COMPUTATIONAL FLUID DYNAMICS MODELING OF UNDERGROUND COAL LONGWALL GOB VENTILATION SYSTEMS USING A DEVELOPED MESHING APPROACH

by

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ABSTRACT

Mining accidents related to ventilation problems that often occur deep within a mine are costly events in terms of production loss, equipment loss, public relations, and ultimately, the cost of human lives. Although the mining process has become safer over the years through mechanical extraction, the operation still requires human control, monitoring, and repair at or near the mining face. Larger operations use the longwall mining process to extract coal by cutting a 3 to 4 foot wide swath out of a long, continuous block of coal. During the operation, the extraction face is ventilated where miners control the cutting process, while the roof is temporarily held up by hydraulic supports called shields. As the shields advance following the cut-out face, the roof behind collapses into a rubblized region called the gob. Air flowing across the face may permeate into the gob, and mine gases (primarily methane) liberated from the overlaying, fractured strata or the mine floor enter the mine ventilation system inside the gob. Continuous monitoring and adjustment of mine ventilation is required to prevent hazardous conditions such as explosive or irrespirable atmospheres. The inaccessibility of the gob prevents any effective monitoring or direct measurements of gas concentration, pressure, velocity or flow characteristics. Research has shown that fresh air from the mine ventilation system can enter the gob where it may create explosive methane-air mixtures. Also, with certain coals, ingress of oxygen into the gob can promote spontaneous combustion of remnant coal.

The interaction of mine gas liberation and oxygen ingress into the gob is examined with a Computational Fluid Dynamics (CFD) modeling tool developed during this project to predict hazardous operating conditions and to help design ventilation systems to avoid these hazards. This tool will be used to model the ventilation of a bleeder-ventilated, underground longwall coal panel to assess the development of the explosive methane-air mixtures, in contrast to the current regulatory view that this condition is not recognized as a hazard in
a properly working bleeder-ventilated gob system.

This dissertation research employed the CFD modeling software package ANSYS® Fluent® along with the output of a previous model developed using the geomechanical software package FLAC³D, to determine the permeability of the gob. Earlier studies have examined the explosive mixture location and total explosive volume found in the gob and near the face, gob caving characteristics, as well as the ingress of oxygen (Gilmore et al., 2013; Marts et al., 2013; Wachel, 2012; Worrall, 2012). This research addresses the challenges of applying CFD to model multiple mine ventilation layouts with the development of a modular meshing approach. This modeling approach incorporates the variations in mine lithology through the development of multiple gob flow characteristics that can be applied across a wide range of panel dimensions, and the challenges of modeling large scale mine networks and panel lengths through the application of the modular meshing approach.

The modular meshing approach developed in this research project is used to build the CFD models of a longwall gob ventilation system flexible enough to model a variety of different mine layouts, mine ventilation schemes, and gob flow parameters. This is accomplished by the creation of a library of meshed geometry modules that are interfaced together to build the ventilation network surrounding the gob. The CFD mesh is tested by creating several ventilation schemes and various mining conditions. Common operating conditions that meet the mine ventilation regulatory statutes are used as the model boundary conditions. The gob flow characteristics are then validated against a tracer gas study. A mesh module repository is developed to help the mining industry create CFD models that match their mine geometry, allowing access to models with fast compute times, and therefore, removing what once hindered wide spread use of CFD simulations in underground ventilation. This dissertation also presents a methodology used to determine the porosity and permeability parameters, scalable in panel length and width, from the output of a FLAC³D model using a combination of polynomial and exponential functions to fit the data.
The modeling tool and methods developed in this research enable mining engineers to design safer longwall mine ventilation systems and to predict results of ventilation changes, thereby preventing conditions that may become hazardous. The resulting work is a significant, progressive step towards prevention of mine fire and explosion disasters related to longwall gob ventilation, which have resulted in the loss of human life. This is accomplished through modeling the commonly used bleeder-ventilated gob ventilation scheme and demonstrating its failure to eliminate the explosive conditions that persist throughout the mine models.
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LIST OF SYMBOLS

Feet ................................................................. ft
Meter ............................................................... m
Porosity ............................................................. \( n, \varepsilon, \gamma, \varphi \)
Volume of fluid .................................................. \( V_{\text{fluid}} \)
Volume of solid .................................................... \( V_{\text{solid}} \)
Volume of a cell .................................................. \( V \)
Pore size length scale ............................................ \( p \)
Domain size length scale ....................................... \( L \)
REV size length scale ............................................ \( D \)
Velocity component in the \( x \)-direction ..................... \( u \)
Pressure ............................................................ \( P \)
Viscosity ............................................................ \( \mu \)
Permeability ......................................................... \( K \)
Particle diameter .................................................. \( D_{p2} \)
Particle diameter stochastic function ......................... \( h(D_p) \)
Velocity: Free fluid .............................................. \( u_f \)
Velocity: Porous medium ....................................... \( u_m \)
Velocity component in the \( y \)-direction ..................... \( v \)
Velocity component in the \( z \)-direction ..................... \( w \)
Beavers and Joseph constant .................................. \( \alpha_{BJ} \)
Stress ................................................................. $\sigma$

Empirical stress parameter ........................................... $a$

Empirical stress parameter ........................................... $b$

Properties constant of overburden .................................. $c$

Strain ................................................................. $\epsilon$

Time ................................................................. $t$

Subsidence function of time ......................................... $W(t)$

Subsidence: Final .................................................. $W_o$

Subsidence: Dynamic ............................................... $K_{Dyn}$

Subsidence: Final .................................................. $K_{Final}$

Time coefficient ................................................... $c$

Radius of influence ................................................. $r$

Face advance rate .................................................. $V_p$

Permeability of the gob ............................................. $k_{gob}$

Permeability ....................................................... $k$

Volumetric strain ................................................... $\epsilon_{Vol}$

Cross-sectional area ............................................... $S$

Pressure .......................................................... $p$

Pressure drop distance ............................................. $L$

Volumetric flow rate ............................................... $Q$

Seam height ......................................................... $H_{coal}$

Cave height ......................................................... $H_{cave}$

Porosity of host rock .............................................. $n_{inherent}$
Permeability of the gob \( K_{gob} \)

Base permeability of the rock \( K_o \)

Sulfur hexafluoride \( \text{SF}_6 \)

Oxygen gas \( \text{O}_2 \)

Carbon dioxide gas \( \text{CO}_2 \)

Temperature in degrees Celsius \( ^\circ \text{C} \)

Temperature in degrees Kelvin \( \text{K} \)

Velocity vector \( \mathbf{V} \)

Substantial derivative operator with respect to variable: \( t \) \( \frac{D \mathbf{V}}{D t} \)

Gradient operator with respect to variable: \( V \) \( \nabla \mathbf{V} \)

Partial derivative operator with respect to variable: \( x \) \( \frac{\partial \mathbf{V}}{\partial x} \)

All velocity components using Einstein index notation \( u_i \)

Subscript of Einstein index notation \( i \)

Unit vector in the \( x \)-direction \( \mathbf{e}_x \)

Unit vector in the \( y \)-direction \( \mathbf{e}_y \)

Unit vector in the \( z \)-direction \( \mathbf{e}_z \)

Mass \( m \)

Density \( \rho \)

Relative velocity vector \( \mathbf{V}_r \)

Vector normal to a surface \( \mathbf{n} \)

Divergence operator on vector: \( \mathbf{V} \) \( \text{div} \mathbf{V} \)

Divergence operator on vector: \( \mathbf{V} \) \( \nabla \cdot \mathbf{V} \)

Force \( \mathbf{F} \)
Acceleration ................................................................. \( a \)

Area ................................................................. \( A \)

Stress Tensor ................................................................. \( T' \)

Gravity ................................................................. \( g \)

Volume dilation constant ................................................................. \( \kappa \)

Reynolds Number ................................................................. \( Re \)

Free stream velocity ................................................................. \( U \)

Pipe diameter ................................................................. \( D \)

Hydraulic diameter ................................................................. \( D_H \)

Kinematic viscosity ................................................................. \( \nu \)

Longer dimension of a rectangular duct ................................................................. \( a \)

Shorter dimension of a rectangular duct ................................................................. \( b \)

Thermal diffusivity ................................................................. \( \alpha \)

Specific heat capacity ................................................................. \( C_p \)

Thermal conductivity ................................................................. \( k_T \)

Turbulent CFD model ................................................................. \( k - \varepsilon \)

Kinetic energy production rate in CFD turbulence modeling ................................................................. \( k \)

Energy dissipation rate in CFD turbulence modeling ................................................................. \( \varepsilon \)

Relationship between turbulence kinetic energy to the mean velocity gradient ................................................................. \( G_k \)

Turbulent viscosity ................................................................. \( \mu_t \)

Effective viscosity ................................................................. \( \mu_{eff} \)

Modulus of the mean rate of strain tensor ................................................................. \( S \)

Generation of kinetic energy due to buoyancy ................................................................. \( G_b \)
Dilatation dissipation effect in compressible flows \( Y_m \)

User defined source term in kinetic energy production equation \( S_k \)

User defined source term in turbulent dissipation rate equation \( S_\varepsilon \)

Inverse effective Prandtl number in turbulent dissipation rate equation \( \alpha_\varepsilon \)

Inverse effective Prandtl number in kinetic energy production equation \( \alpha_k \)

Constant in turbulent dissipation rate equation \( C_{1\varepsilon} \)

Constant in turbulent dissipation rate equation \( C_{2\varepsilon} \)

Constant in differential viscosity model equation \( C_v \)

Constant in standard \( k-\varepsilon \) turbulent model equation \( C_\mu \)

Swirl constant \( \alpha_s \)

Turbulent viscosity without swirl modification \( \mu_{t0} \)

Characteristic swirl number \( \Omega \)

Molecular viscosity \( \mu_{mol} \)

Constant in inverse Prandtl number equation \( \alpha_0 \)

2nd order turbulent dissipation rate term \( R_\varepsilon \)

Modulus of mean rate of strain dependence in 2nd order turbulent dissipation rate term \( \eta \)

Constant in 2nd order turbulent dissipation rate term \( \eta_0 \)

Constant in 2nd order turbulent dissipation rate term \( \beta \)

Coefficient of thermal expansion in turbulent buoyancy term \( \beta \)

Gravity field in z-direction \( g_z \)

Temperature \( T \)

Turbulent Prandtl number \( Pr_t \)
Turbulent intensity ................................................................. $I$
Turbulent length scale .............................................................. $l$
Root mean squared of the average turbulent velocity ......................... $u'$
Mean flow velocity ........................................................................ $u_{avg}$
Relevant geometric flow length ....................................................... $L$
Species mass fraction of the $i$-th species ...................................... $Y_i$
Mass diffusion flux of the $i$-th species ........................................... $J_i$
Net production rate from chemical reaction of the $i$-th species ............. $R_i$
Rate of creation from phase change of the $i$-th species ...................... $S_i$
Diffusion coefficient of the $i$-th species in the $j$-th species ................ $D_{ij}$
Thermal diffusion coefficient of the $i$-th species ............................. $D_{T,i}$
Molecular weight of the $i$-th species ............................................ $M_{w,i}$
Mean molecular weight of the mixture ......................................... $M_{w,m}$
Species molecular fraction of the $i$-th species ................................. $X_i$
Binary mass diffusion coefficient of the $i$-th species in the $j$-th species  $\mathcal{D}_{ij}$
Mass diffusion matrix ..................................................................... $[A]$  
Mass diffusion matrix ..................................................................... $[B]$  
Turbulent mass diffusion coefficient ............................................. $D_{t,eff}$
Mass diffusion coefficient of the $i$-th species in the mixture ............... $D_{i,m}$
Turbulent Schmidt number ............................................................ $Sc_t$
Turbulent diffusivity ....................................................................... $D_t$
Deviatoric stress tensor for viscous heating ................................... $\tau_{ij,eff}$
Viscous resistance matrix (inverse of permeability) ......................... $D$
Inertia resistance matrix \( C \)

Viscous resistance term (inverse of permeability) \( C_2 \)

Cell type quality constant \( C \)

Angle of made my two elements of a cell \( \theta \)

Angle for an equiangular face or cell \( \theta_e \)

Maximum angle in the face or cell \( \theta_{max} \)

Minimum angle in the face or cell \( \theta_{min} \)

Pre-exponential coefficient for curve fitting VSI data \( b_{ijkl} \)

Exponential coefficient for curve fitting VSI data \( c_{ijkl} \)

Operating pressure set in Fluent \( p_{op} \)

Universal gas constant \( R \)

Mixture heat capacity \( c_p \)

Viscosity kinetic theory mixture term \( \phi_{ij} \)

Absolute pressure \( p_{abs} \)

Diffusion collision integral \( \Omega_D \)

Boltzmann constant \( k_B \)

Chemical species energy well depth \( \varepsilon \)

Lennard-Jones characteristic length scale \( \sigma \)

Scalar quantity \( \phi \)

Scalar quantity in the neighboring cell \( \phi_{nb} \)

Scalar quantity at the face \( \phi_f \)

Diffusion coefficient for scalar, \( \phi \) \( \Gamma_\phi \)

Coefficient at the cell center for the variable, \( \phi \) \( a_p \)
Coefficient at the neighboring cell for variable, $\phi$ \hspace{1cm} $a_{nb}$

Cell center \hspace{1cm} $c_0$

Cell center \hspace{1cm} $c_1$

Position vector \hspace{1cm} $r_i$

Area of a face \hspace{1cm} $A_f$

Velocity at a face \hspace{1cm} $V_f$

Residual of a system of linearized equations \hspace{1cm} $R_P$

Friction velocity \hspace{1cm} $U_T$

Friction velocity \hspace{1cm} $u_r$

Wall shear stress \hspace{1cm} $\tau_w$

Dimensionless distance from the nearest wall \hspace{1cm} $y^+$

Dimensionless mean velocity \hspace{1cm} $U^*$

Empirical constant \hspace{1cm} $E$

Carman constant \hspace{1cm} $\kappa$

Subscript, wall-adjacent cell \hspace{1cm} $P$

Dimensionless distance from the wall \hspace{1cm} $y^*$

Roughness function \hspace{1cm} $f_r$

Surface roughness slope intercept term \hspace{1cm} $\Delta B$

Physical roughness height \hspace{1cm} $K_s$

Dimensionless roughness height \hspace{1cm} $K_s^+$

Roughness constant \hspace{1cm} $C_s$

Species transport wall function \hspace{1cm} $Y^*$

Jayatilleke formula for species transport for smooth walls \hspace{1cm} $P_c$
Dimensionless species sublayer thickness \( y_c^* \)
Jayatilleke formula for species transport for rough walls \( P_{c,\text{rough}} \)
Empirical wall function constant for rough walls \( E' \)
Actual velocity of the methane inlet \( V_{\text{methane}} \)
Pressure contribution of velocity at the methane inlet \( V_{\text{pressure}} \)
Density gradient contribution of velocity at the methane inlet \( V_{\text{density}} \)
Strata height from the top of the gob to the coal seam \( \Delta h \)
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algebraic Multi-Grid</td>
<td>AMG</td>
</tr>
<tr>
<td>Atmospheric Monitoring Systems</td>
<td>AMS</td>
</tr>
<tr>
<td>Computational Fluid Dynamics</td>
<td>CFD</td>
</tr>
<tr>
<td>Code of Federal Regulations</td>
<td>CFR</td>
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<tr>
<td>Commonwealth Scientific and Industrial Research Organisation</td>
<td>CSIRO</td>
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<tr>
<td>Colorado School of Mines</td>
<td>CSM</td>
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<tr>
<td>Direct Numerical Simulation</td>
<td>DNS</td>
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<tr>
<td>Explosive Gas Zone</td>
<td>EGZ</td>
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<tr>
<td>General Purpose Graphics Processing Unit</td>
<td>GPGPU</td>
</tr>
<tr>
<td>Gob Ventilation Borehole</td>
<td>GVB</td>
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<tr>
<td>Headgate</td>
<td>HG</td>
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<tr>
<td>Mining Safety and Health Administration</td>
<td>MSHA</td>
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<tr>
<td>Monotonic Upstream-Centered Scheme for Conservation Laws</td>
<td>MUSCL</td>
</tr>
<tr>
<td>National Institute for Occupational Safety and Health</td>
<td>NIOSH</td>
</tr>
<tr>
<td>Portable Batch System</td>
<td>PBS</td>
</tr>
<tr>
<td>Pressure Staggering Option</td>
<td>PRESTO!</td>
</tr>
<tr>
<td>Quadratic Upstream Interpolation for Convection Kinematics</td>
<td>QUICK</td>
</tr>
<tr>
<td>Random Access Memory</td>
<td>RAM</td>
</tr>
<tr>
<td>Representative Elementary Volume</td>
<td>REV</td>
</tr>
<tr>
<td>Renormalization Group Theory</td>
<td>RNG</td>
</tr>
</tbody>
</table>

```
Semi-Implicit Method for Pressure-Linkage Equations .......................... SIMPLE
Simple Linux Utility for Resource Management ................................. SLURM
Society of Mining, Metallurgy and Exploration ................................. SME
Tailgate  ......................................................................................... TG
Text User Interface  .......................................................................... TUI
User Defined Function  ....................................................................... UDF
Volumetric Strain Increment ............................................................. VSI
Before Common Era ...................................................................... B.C.E.
Control Volume  .............................................................................. CV
Control Surface  .............................................................................. CS
ACKNOWLEDGMENTS

I would like to thank my advisor, Dr. Bogin for his willingness to take on a new project and the long discussions that ensued. I would also like to thank my co-advisor and Principle Investigator, Dr. Brune for sharing his knowledge of the mining industry and his continual support of my efforts to improve this research, write papers and present my work at conferences.

Special thanks to Dr. Grubb for initiating this research, writing the proposal and connecting this research to the coal mining industry in the Western United States. This research project would not have been possible without the financial support of the National Institute for Occupational Safety and Health (NIOSH) under contract number 200-2009-31409.

Thanks also to Dr. Worrall for completing the first CFD models in this research area, and to the CSM High Performance Computing group for their administrative support of Mio and upgrades in disk performance.

This research would not be possible without the work of Jon Marts who completed the refined FLAC3D model that provided the data necessary to determine the gob flow characteristics used throughout the CFD simulations. Thanks for completing the early testing of the meshing approach by developing the progressively sealed gob models and back return modeling approach, and for the long modeling discussions over the years.

Finally special thanks to my wife, Andine, for her continuous support, enabling me to finish the work required to complete my degree.
I dedicate this work to the miners and their families.
The coal mining industry remains an essential part of electrical power generation in the United States. Mine ventilation challenges arise from a system consisting of dozens of miles of underground pathways and the inability to take direct measurements in abandoned regions. While mine operators seek to monitor and maintain the mines’ ventilation systems to eliminate the accumulation of explosive mixtures of methane gas an improper ventilation design, incorrect ventilation control or any change in ventilation pattern can cause severe consequences including fires and explosions, the loss of the mine, equipment, and ultimately the loss of miners’ lives.

Generally the approach to prevent methane explosions has been to dilute the methane to concentrations below 1%, which creates a margin of safety to the lower explosive limit of 4.5% methane in air. Hazards also exist from fresh air or oxygen passing through reactive coal that may cause spontaneous combustion in some mines.

Ventilation hazards are often the result of operators’ uncertainty about the ventilation system response to system changes. The Computational Fluid Dynamic (CFD) modeling tool can provide insight into the effectiveness of the ventilation system; these insights can result in safer working conditions and more productive mines.

1.1 Motivation for Longwall Mining Ventilation Research

The coal mining industry supplies the United States with 38% of its electricity (U.S. Energy Information Administration, 2015), through which society bears the significant cost of miners’ lives lost. A total of 10,031 mining fatalities due to coal mine explosions have occurred since the beginning of the twentieth century, in the United States, according to United States Mine Rescue Association, 2013.
Two significant mining tragedies occurred as recently as April 5, 2010, when a methane and coal explosion at Upper Big Branch Mine in West Virginia took the lives of 29 miners. Another methane explosion occurred later that year at the Pike River mine in New Zealand, killing 29 more miners. These two accidents were preceded by 104 coal mining deaths from 1980 to 2009 due to methane related explosions in the United States United States Mine Rescue Association, 2013. Most of the accidents from methane related explosions occurred in mines operating with a bleeder-ventilated gob system.

Currently, mine operators’ often have a reactive response to hazardous conditions. When detector measurements trend towards hazardous conditions, a planned response goes into effect in an attempt to avoid possibly catastrophic events. An automatic or manual de-energizing of the mining machinery is the common response, after which the workers may need to be evacuated from the mine. However, the response may not be fast enough when explosive methane mixtures ignite and propagate into a coal dust explosion extending throughout the mine. Furthermore, a response to high carbon monoxide levels, which is a product of self-heating coal, requires the immediate reduction of oxygen in the vicinity. This slow response process often takes hours to implement. This response can cause severe consequences, even possibly resulting in the total loss of the mine. This research seeks provide a predictive tool capable of optimizing a response strategy and a tool capable of designing the initial ventilation system to avoid the onset of problems well in advance.

Ventilation modeling tools currently available to mine operators and ventilation engineers, such as VnetPC and Ventsim, are limited to one-dimensional ventilation network analysis of the mine and are used to predict changes in new scenarios. However, limiting the domain to linear network flows using a laminar flow assumption does not provide any insight to flow patterns in the three-dimensional, inaccessible regions of the mine.

This research provides a viable alternative to modeling large-scale mining operations involving flow patterns deep within the mine, as well as giving mine operators’ the ability to evaluate hazardous gas compositions related to spontaneous combustion and explosive
methane-air mixtures. The tools created in this project support increased use of CFD modeling to study ventilation effects. The modular meshing approach and scalable gob flow characteristics developed for this project can be adapted by future modelers to evaluate proposed changes to the ventilation system, promoting miners’ safety. This project seeks an objective baseline to evaluate and implement safer ventilation operating conditions and designs for mines in the United States. A review of current literature in the area of mine ventilation research is presented in Chapter 2 to properly place this work in context.

1.2 Introduction to Underground Longwall Coal Mining

In the United States, 49% of the underground coal production is by longwall mining. The longwall mining method produces 95% of the coal mined underground in the Western United States (U.S. Energy Information Administration, 2015). This process yields higher extraction rates compared to room-and-pillar mining. The longwall mining process begins by driving development gateroads in a “U” shape around a solid block of coal, called a panel, as shown in Figure 1.1(a). The primary haulage gateroad, called the headgate, is also the ventilation intake from the main development section, called the mains, and the secondary gateroad, called the tailgate, is either a return airway or a secondary intake depending on the ventilation layout. The development gateroads are mined by continuous mining machines and become the headgate and tailgate of the outlined panel. The headgate and tailgate are connected to the mains, where fresh air is distributed and exhaust air leaves the mine.

![Figure 1.1: Longwall Mining Plan View Layout (The Davies Family Website, 2013)](image-url)
The longwall panel consists of a solid block of coal, typically ranging from 3,000 m to 6,000 m (10,000 ft to 20,000 ft) in length and from 240 m to 460 m (800 ft to 1,500 ft) in width. The height of a typical longwall mined coal seam ranges from 2.7 m to 3.4 m (9 ft to 11 ft) in the Western United States, and 1.5 m to 2.4 m (5 ft to 8 ft) in the Eastern United States. Mining of the longwall panel starts at the end opposite from the mains, where the longwall mining equipment is installed in a special startup entry along the panel width. The panel will be extracted in 0.9 m to 1.2 m (3 ft to 4 ft) increments by moving a shearer, which cuts across the panel width as the longwall face retreats towards the mains. A cross-section of the coal face is presented in Figure 1.1(b): Section View XX, showing the major elements of the longwall mining equipment: the shearer, the armored face conveyor, and a series of hydraulic supports or longwall shields. In the right of the figure, as coal is extracted, the roof rock collapses and forms the gob. The ventilation air provided to workers at the coal face, flows through this “U” shaped ventilation system and traverses the longwall through the cross-section shown in Figure 1.1(b). A discussion of ventilation system details are in Section 1.4.

The longwall mining equipment, as shown in Figure 1.2: A, and the expanded view Figure 1.2: C, spans the width of the coal panel using about 150 to 250 shields with each shield approximately 1.5 m to 2 m (5 ft to 6.6 ft) wide. The shearer cuts across the coal face as it traverses its width, while the shields advance into the newly created space to maintain roof support. Also shown in Figure 1.2: A are the development entries (gateroads) on both the headgate and tailgate sides in the upper and lower part of the Figure. These gateroads are held open by the blocks of coal forming pillar supports. The area of collapsed roof behind the shields, called the gob, is shown in the center of the Figure and is better seen in the section view of Figure 1.2: B.

The gob consists of various sizes of rock blocks from the failing overlying roof material, filling the void of the mined out coal seam. The crushing weight of the overburden compacts the gob further leaving behind a rubblized zone filled with rocks ranging from large boulders.
Figure 1.2: Longwall Miner Layout, (A) Plan View, (B) Section View, (C) Shearer (Karacan, 2008)
to finely crushed gravel. The harsh environment and the inaccessibility of the gob zone make
direct measurements of any kind nearly impossible.

Fresh air is supplied to the face where mine personnel operate the shearer and retreat the
shields. The cross-section view in Figure 1.2: B shows the seam height and overlying rock
strata (overburden) supported by the shields. The immediate mine roof caves into the space
behind the shields as they retreat, and the remaining rock above fractures as it subsides,
creating cracks and fissures that may allow methane from the upper strata to migrate into
the gob.

Hydraulic roof support shields, shown in Figure 1.3(a), are matched to the height of the
c coal seam and overburden load. The shield design height can vary from 1.2 m to 5.5 m (4 ft
to 18 ft) depending on the geology surrounding the coalbed and the extraction height. Each
shield is designed to support the roof with two hydraulic jacks. To retreat a shield, it is
lowered and then pulls itself backwards by a hydraulic ram, called the relay bar, attached to
the armored face conveyor. This connection can be seen on the left of Figure 1.3(b), with
the shearer on the right cutting the coal face.

1.3 Description of Mines – Mines C, E, and W

The modeling data comes from two Western United States underground longwall coal
mines and from observations made by the research team during mine visits. The geome-
chnical model developed by Wachel, 2012, refined and validated by Marts et al., 2014b is
used to determine the gob flow characteristics of Mine C and E. The gob flow characteristics
of Mine W are from Wachel’s geomechanical model based on Mine C data and adapted by
Worrall, 2012 for use in the first iteration of CFD modeling. A review of background work
in geomechanical model is in Section 2.2, and the scalable implementation into Fluent is
discussed in Section 4.3

The coal seam at Mine C is 3.35 m (11 ft) with a depth of cover of 138 m (453 ft) and
an immediate roof consisting of weak mudstone and shale layers forming the gob material.
The rock diameter in the gob directly behind the shields and in the fringe of the gob is
approximately 1 m (3 ft) in size and smaller. The final subsidence, expressed as a percentage of extraction height, was 77%, with a panel width of 304 m (1,000 ft).

The coal seam at Mine E is assumed to be a uniform 2.9 m (9.5 ft) with a depth of cover of 123 m (404 ft). However, the coal seam joins a rider seam increasing the thickness occurring under a mountain where the depth of cover increases to 240 m (800 ft). This large shift in parameters is not included in the geomechanical models. The immediate roof consists of strong, massive sandstone, which occasionally produces large boulders in the gob thereby producing a large rock size distribution. The final subsidence is 58%, with a panel width of 380 m (1,250 ft).

1.4 Mine Ventilation – Bleeder-ventilated Gob Systems and Progressively Sealed Panels

There are two general types of ventilation systems used in underground longwall coal mining operations: bleeder-ventilated gobs and progressively sealed gobs, sometimes called bleederless gobs. The first method, typically used only in the United States, involves the
intake of fresh air into the development entries surrounding the gob in order to ventilate the gob area in a controlled manner. The process aims to dilute any methane inside the gob to levels below the explosive range. The second ventilation method, uses a progressive sealing process around the gob and is often combined with inertizing the gob atmosphere with nitrogen or other inert gases. Progressively sealed gobs are commonly used throughout the rest of the world, but only with special permits in the United States.

Figure 1.4 shows an example of a bleeder-ventilated gob system. Fresh air, shown in blue, is supplied from the mains at the bottom of the figure to the active longwall face. The air then splits in three directions: down the active face, returning out with the conveyor belt (called neutral air shown in green), and inby the face to the bleeder fan (direction heading deeper into the mine). Once the air travels the length of the face to the tailgate, there are several options for design possible. Shown in the Figure 1.4 is a “back return” at the tailgate, where the air is directed one-crosscut inby and returns further inby the bleeder to the bleeder fan with addition fresh air added at the tailgate. This is the more common design option for the tailgate side to supply fresh air and force all the return air to exhaust out the bleeder fan. Further details of the modeling environment used are in Chapter 4.

The progressively sealed system in Figure 1.5 shows how the ventilation is isolated from the gob area with concrete seals in the crosscuts along the headgate side, inby the longwall face. Additionally, nitrogen may be injected through these seals at various locations to inertize the gob atmosphere. For seals that separate the main ventilation system for the gob the completed longwall panels have seals that encase a balance chamber filled with nitrogen. This is to prevent oxygen-rich mine air from leaking into the gob by maintaining a pressure differential between the chamber and the mine air (shown on the left of Figure 1.5). Mine C, studied during this research, uses two headgate nitrogen injection locations, one tailgate injection point and balancing chambers. This mine also uses Gob Ventilation Boreholes (GVBs) drilled from the surface into the fractured zone to extract methane from the gob. The GVBs are equipped with vacuum pump systems to assist the mine ventilation system.
in withdrawing methane from the mine. The additional cost of this ventilation system over using a bleeder-ventilated gob system is estimated by Grubb et al., 2015 to be 25 cents per ton of coal produced.

1.4.1 Design of Ventilation Systems for Fire and Explosion Prevention

The choice of ventilation design for an underground longwall mining operation depends on suspected ventilation hazards of methane gas and the particular coal’s propensity for spontaneous combustion. For example, coal mines in the Eastern United States are typically gassy mines, which have coal’s not generally prone to spontaneous combustion and therefore use the bleeder-ventilated gob systems to dilute the methane gas, as required by law under the Code of Federal Regulation (CFR) Title 30, Part 75.334 (United States Department of Labor, Mine Safety & Health Administration, 2012). The goal of the bleeder system is to dilute the methane inside the gob into the non-explosive range before it reaches an area with potential ignition sources. This is done by providing as much air as necessary in all entries surrounding the gob.

Bleeder systems present problems in underground coal mines in the Western United States. The coal found in the West is often more prone to spontaneous combustion, and excess oxygen in the gob may react with the coal left behind. Therefore, some Western United States mining operations use a progressively sealed ventilation design to avoid spontaneous combustion hazards.

The progressively sealed gob ventilation system has the additional benefit of helping limit oxygen penetration into the gob with the injection of nitrogen, thereby further reducing the possibility of spontaneous combustion events. Details about spontaneous combustion are reviewed in Section 2.4.

1.5 Computational Fluid Dynamics – Fluent Software

Computer simulation of fluid flows using equations of flow physics in a discretized volume of fluid is termed Computational Fluid Dynamics or CFD. There are a number of available
Figure 1.4: Bleeder-ventilated Gob Layout (Grubb, 2008)

Figure 1.5: U-Type Progressively Sealed Ventilation Layout (redrawn for clarity and modified for Mine C) (Grubb, 2008; Smith et al., 1994)
mathematical models for fluid, heat, mass transfer, and chemical reaction modeling. The use of this modeling approach has gained momentum with the lowered cost and increased availability of high powered computing in desktop computers. Also, the use of multi-core, multi-node supercomputers and the available software package integration has become more common in business settings, and is no longer limited to research facilities. CFD modeling is used in combustion applications for engines, open flames, coal fired power plants, and in other energy technologies such as fuel cells, wind turbines, and nuclear power.

The use of the commercially available CFD software package, Fluent, is uniquely suited for this project, because the model settings are integrated into a convenient Graphics User Interface (GUI). Also, through customizable subroutines, the user can alter the model settings as well as boundary and zone conditions in user defined functions (UDF). Details of this code are included in Appendix B.

Fluent software is successfully used by researchers at the National Institute for Occupational Safety and Health (NIOSH), Commonwealth Scientific and Industrial Research Organisation (CSIRO), University of Ostrava (Taraba & Michalec, 2011), University of Nottingham (Lowndes et al., 2005), University of Kentucky (Wala et al., 1997) and the University of Utah (Calizaya & Duckworth, 2004) for longwall mine ventilation modeling. The support of Colorado School of Mines faculty, access to resources, and previously developed models makes Fluent the most logical software choice for this project.

In addition, the geometry modeling and meshing for use in the integrated parametric study analysis tools in ANSYS® Workbench™ software with remote supercomputing solver options allows for even greater availability to mine operators in the utilization of this project’s results. Some mine operators have CFD modeling trained engineering staff, giving them the capacity to access the technologies involved in this project, increasing its practicality. For the scope of this project, the Colorado School of Mines supercomputer, Mio, is the main model solver and post-processor. Details of the fluid dynamics physics used by the ANSYS solver are reviewed in Chapter 3.
The three-dimensional mesh creation and manipulation available with ANSYS products offers great flexibility to control the geometry solved with Fluent. Many ventilation scenarios can be created by assembling mesh parts or suppressing existing parts. For example, a large model mesh encompassing a full longwall panel can be created from individual high quality, low skewness mesh modules to be assembled and solved on a supercomputer. Figure 1.6 shows a mesh made from eight individual mesh modules, creating the desired geometry.

![Figure 1.6: Example of Panel Mesh](image)

Through UDFs in Fluent, custom output variables are generated based on properties solved in the model. For example, a graphical output scheme is created that translates methane and oxygen concentrations into a color coded explosive range plot, shown in Figure 1.7, called a gob gas analysis plot. This quickly identifies the Explosive Gas Zones (EGZs) through the application of Coward’s triangle (Coward & Jones, 1952). This figure is recreated by applying the same boundary conditions from Worrall, 2012 and nitrogen injection, but a new mesh is used with a greater panel length. Details of the gob gas analysis and the color scheme used, which changed blue to dark-green, are found in Sections 5.5–5.6.

1.6 Research Objective and Hypothesis

The objective of this research is to provide the mining industry with a CFD predictive modeling tool for in-house evaluation of the effects of proposed, planned and unexpected changes to the mine ventilation system, and mitigation of hazardous gob gas compositions. The CFD modeling results can then be used for planning and risk assessment to build a customizable risk management plan for the mine.
The modeling approach developed in this research is flexible to a variety of geometry options through the creation of an easily modifiable mesh geometry library to enable simulations of actual mine ventilation layouts. This modeling approach is fully adaptable to underground longwall gob ventilation when combined with a scalable equation for gob compaction to determine the gob flow characteristic parameters of porosity and permeability, including variables to change the host rock properties involved in the conversion.

Using a trend-based analysis of potential hazardous ventilation changes that may not represent actual conditions, but rather provides insight into the overall response of the system, this research examines the explosive gas mixture development in longwall gobs and the surrounding ventilation networks. It is known that methane must follow the dilution path from fuel-rich through an explosive zone to fuel-lean (see Section 5.5), therefore this research asks the question: Do EGZ exist in bleeder-ventilated gobs, and if so, where are they located and how large is the explosive gas volume?
This research considers the following hypothesis:

- EGZs exist in a bleeder-ventilated gob, then EGZs will be found in CFD modeling results when using acceptable regulatory operating conditions in bleeder-ventilated gobs.

1.7 Specific Aims and Research Tasks

The specific aims of this research project are to mitigate hazardous ventilation conditions in underground coal mines, helping the mining industry achieve their goal to reduce fire and explosion accidents to zero. This project will benefit mine workers, companies, and stakeholders in the industry by decreasing risks related to ventilation accidents, which has the added benefit of improving public perception of underground mining operations. The following sections present the related tasks to reach these aims: development of a modular meshing approach, creation of a scalable equation fit for gob permeability, and building the CFD model to guide mine ventilation systems design.

1.7.1 Universal Mesh Assembly for Multiple Mine Geometries

One of the most challenging parts of CFD simulations is creating a mesh that can be solved under a variety of conditions. In this project, a library of mesh files of basic geometric parts is prepared. The creation of high quality, low skewness meshes facilitates the reduction in simulation time, increase stability, and reduces overall resources needed to converge to a solution. The meshes can be assembled into a layout mimicking the ventilation network surrounding any longwall gob area.

The mesh library consists of mesh parts or modules (see Figure 1.6) that can be interchanged and scaled as needed to match a specific mine layout. A basic layout, for example, contains the parts for the ventilation airways of the headgate, face and shields, tailgate, and any crosscuts or connecting entries with the option to include regulators. It also contains the gob, open fringe surrounding the gob, upper and lower strata, and GVB parts. These
modules can be assembled into an interfacing network of mesh connections for the CFD solver.

The mesh module creation follows the guidelines provided by ANSYS for quality and skewness. The ventilation airways that often contain turbulent flows are modeled with a combination of inflation layers and tetrahedral mesh elements, while the porous regions that dominate the simulation contain hexahedral elements, only. The hexahedral element is ideal for modeling slow moving flow. This combination of mesh types ensures faster simulation times, which have previously taken many hours to solve on dedicated processors; this makes it possible to achieve reasonable solution times employing desktop resources. Using this approach maintains a higher quality mesh ensuring stability under a variety of operating conditions. Details of the mesh creation process are in Chapter 6.

The modular mesh library is tested using several mining scenarios including progressively sealed gobs optimizing nitrogen injection (Marts et al., 2015), active face ventilation schemes (Marts et al., 2014a), modeling a large bleeder-ventilated gob panel (Gilmore et al., 2014), and multiple panel bleeder-ventilated gobs. More details are in Section 7.2.

1.7.2 Piece-wise Scaled Equation Fit Implementation of FLAC\textsuperscript{3D} Output

A geomechanical model created by Marts et al., 2014b is used to determine the gob flow characteristics required to solve the flow inside the gob as it responds to changes in the ventilation system. The FLAC\textsuperscript{3D} (Itasca Consulting Group, 2013) output of volumetric strain increment (VSI) describes the change in the porosity inside the gob. Detailed in Section 4.3, a piece-wise equation is built, which is applicable in certain bounds within the gob. This approach permits scaling of the mine geometry in length and width enabling a comparison of different mine lithologies; the resulting EGZs within the gob are presented in Chapter 8.

A previous project completed the FLAC\textsuperscript{3D} modeling and refined and calibrated it to known conditions Marts et al., 2014b. The approach to calculating the porosity and permeability from the VSI follows the work of previous researchers Esterhuizen et al., 2010; Lolon
& Calizaya, 2009; Wachel, 2012; Worrall, 2012; Yuan & Smith, 2010. Where the conversions from VSI take place after the equation fits enabling greater control to the modelers. The equation fits are in the form of a set of piece-wise equations bounded to a sectional area of the gob. In addition, the VSI conversion to porosity and permeability yields parameters that can be adjusted by the modeler for a given mine’s caving characteristics. A review of porous media modeling is presented in Section 2.2.

1.7.3 Computational Fluid Dynamics Gas Flow Model

A Fluent CFD model is assembled using a group of repeating modular mesh files to model a bleeder-ventilated gob network surrounding a large gob area in a steady-state case. The approximation of a steady-state analysis is considered valid under the circumstances of an advancing longwall face because the rate of advance is small, 9 m to 30 m per day (30 ft to 100 ft), relative to the hundreds of meters of the panel length. This is also applicable during longwall maintenance periods when the face advance is stopped.

The bleeder-ventilated gob model is calibrated to acceptable operational parameters at the inlets and outlets of the ventilation as provided by statutory requirements. Section 7.1 presents model comparison of predicted velocities inside the gob to the velocity of a tracer gas release study for validation.

The CFD simulation results of the formation of EGZs in bleeder-ventilated gobs are discussed in Chapter 8. Safety concerns and suggestions for future work follow in Chapters 9 and 10, respectively.
CHAPTER 2
BACKGROUND

A review of ventilation safety technologies commonly found in the mining industry and the federal regulations that govern the operation of underground coal mines are introduced in this chapter. A review of research conducted to determine the gob flow characteristics begins with an examination of the roof caving process. This is followed by a review of the ventilation research and CFD studies, and a brief overview of the chemical reaction of spontaneous combustion. This chapter concludes with proposed improvements for mine ventilation safety.

2.1 Ventilation Safety Technologies

Mine ventilation systems dilute the explosive gases released during the mining process, which consists of primarily methane. In addition to dilution, explosion hazards may also be controlled through inertization, e.g., injecting nitrogen. Companies use mine atmospheric monitoring to detect harmful gases and to analyze changes in gas composition and resulting trends. There are a variety of monitoring systems available to use throughout the mine, from handheld systems to continuous monitoring systems. A review completed by Grubb, 2008 outlines the safety and operational risks for the efficacy of many of these technologies in mining operations, and recommends the use of tube bundles, progressive sealing and nitrogen inertization in longwall mining operations.

2.1.1 Ventilation Regulatory Standards

The United States CFR, Title 30 covers all mandatory safety standards for the mining industry including underground, surface, hardrock, coal, metal, and non-metal mining. Sections dealing with mine ventilation and air standards in underground coal mining are found in 30 CFR, Part 75.300 and the following parts. These standards include sections regulating
breathable air in the mine and measurement locations, gas concentration limits, dust control, temperature and inertization (Mine Safety & Health Administration, 2012).

For example, where miners work and travel oxygen content must be greater than 19.5%, with carbon-dioxide less than 0.5% (30 CFR §75.321), and methane less than 1% (30 CFR §75.321). The maximum allowable methane concentration is 1.5% or 2% in certain return airways, including bleeder entries (30 CFR §75.323(d) and (e) 2012).

2.1.2 Monitoring and Measurements Technologies

The monitoring of the mine atmosphere is required under 30 CFR §75.360, which specifies locations in the mine where air quality must be monitored pre-shift, and at certain intervals of the shift, day, week, or month. These points are marked in the ventilation plans by the mine operator and are measured and recorded. The monitoring equipment used to measure quality parameters may include handheld gas monitor devices, continuous atmospheric monitoring systems (AMS), gas bag sampling and the use of tube-bundle monitoring systems.

A handheld gas monitor is typically capable of measuring the concentration of oxygen, carbon monoxide, methane, carbon dioxide, and, as needed, hydrogen sulfide and other gases. Air quality data from bleeder-ventilated gob systems are usually gathered with handheld devices during the weekly inspections conducted by certified mine examiners.

The continuous AMS are most commonly used on the headgate and tailgate drive areas of the longwall armored face conveyor and on the shearing machine. The AMS measurements can sound alarms and de-energize the mining equipment if hazardous concentrations of methane are detected.

Gas bag samples are taken manually and are typically analyzed with a gas chromatograph. The samples are analyzed for the main components of common explosive gases found in mines and spontaneous combustion products, typically consisting of the following gases: hydrogen, methane, oxygen, nitrogen, carbon dioxide, carbon monoxide, ethylene and acetylene.

A tube-bundle system continuously draws gas samples through tubes from locations within the mine unreachable by other sampling techniques, including from behind seals.
These samples are drawn to the surface for analysis of methane, oxygen, nitrogen, carbon dioxide and carbon monoxide concentrations.

2.1.3 Gob Ventilation Boreholes (GVBs)

The objective of GVBs is to remove methane by means other than ventilating it through the mine. GVBs are similar in fashion to natural gas wells, except that the fracturing of the rock occurs from undermining the gas reservoir with the longwall operation. Figure 2.1 shows a cross-section of the strata layers of a coal mine. The active mining face at the bottom is ventilated with fresh air; the methane comes from the reservoir in the strata and desorption from the coal seams. A bore hole is drilled from the surface to within 12 m to 24 m (40 ft to 80 ft) above the coal seam with approximately 60 m (200 ft) of slotted casing at the bottom. The optimum size, locations and depth of GVBs for the Pittsburgh Coalbed are modeled by Karacan et al. (2007a), recommending the addition of GVBs for mines with a wider longwall panel width.

![Figure 2.1: Gob Ventilation Borehole Capture System (Karacan, 2009c)](image-url)
2.2 Gob Porosity and Permeability

Much research has been done in the field of defining fluid flow in porous media in the past decade. The works of Nield & Bejan, 2013, “Convection in Porous Media”, Bird et al., 2007, “Transport Phenomena” and De Lemos, 2012, ”Turbulence in Porous Media: Modeling and Applications” guide the discussion of this topic. This section presents a review of porous media modeling and the assumptions that define its use. Additionally, the process of gob formation, compaction and surface subsidence is reviewed; and finally, the geomechanical numerical modeling results and ranges of permeability are presented.

2.2.1 Flow through Porous Media

A porous medium is defined as a region containing a distribution of solid particles and interconnecting void spaces. The percentage of connecting voids is termed the porosity, \( n \) (ANSYS, 2014b documentation uses \( \varepsilon \) and \( \gamma \), and mathematical derivation is often \( \varphi \)). Therefore, the volume of fluid, \( V_{\text{fluid}} \) is given in Equation 2.1, and the volume of solid, \( V_{\text{solid}} \) is given in Equation 2.2

\[
V_{\text{fluid}} = V \times n \quad (2.1)
\]

\[
V_{\text{solid}} = V \times (1 - n) \quad (2.2)
\]

In Table Table 2.1 some values of porous materials are given. The predicted values based on Karacan, 2010 experimental work for gob material from two Eastern United States coal mines are shown. The initial uncompacted porosity ranges from 0.629 to 0.711 and the final compacted porosity ranges from 0.216 to 0.383 after applying a correction factor from the laboratory scale.

Figure 2.2 shows a Representative Elementary Volume (REV) in the center with length scale, \( D \), the pore size length scale on the right, \( p \), and the domain length scale, \( L \), on the right (Teruel & Uddin, 2008). At the pore scale, the flow variables will have large fluctuations, but space-averaged across many pores on the REV scale, the variables become steadier. A
Table 2.1: Porous Materials

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Porosity, $n$</th>
<th>Gob Material (Karacan, 2010)</th>
<th>Porosity, $n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Media</td>
<td>&lt; 0.6</td>
<td>Test A &amp; B (Initial)</td>
<td>0.629</td>
</tr>
<tr>
<td>Cubic Packing</td>
<td>0.476</td>
<td>Test B &amp; D (Initial)</td>
<td>0.711</td>
</tr>
<tr>
<td>Coal</td>
<td>0.02–0.12</td>
<td>Test A (Loaded)</td>
<td>0.225</td>
</tr>
<tr>
<td>Granular Crushed Rock</td>
<td>0.45</td>
<td>Test B (Loaded)</td>
<td>0.216</td>
</tr>
<tr>
<td>Limestone</td>
<td>0.04–0.1</td>
<td>Test C (Loaded)</td>
<td>0.383</td>
</tr>
<tr>
<td>Sandstone</td>
<td>0.08–0.38</td>
<td>Test D (Loaded)</td>
<td>0.269</td>
</tr>
</tbody>
</table>

Figure 2.2: Representative Elementary Volume and Porous Media Length Scales (Teruel & Uddin, 2008)

A thorough derivation is presented by Whitaker, 1999. This scaling of a porous media assumes that the relationship given in Equation 2.3 is true.

\[ L \gg D \gg p \]  

(2.3)

Another method of deriving flow through porous media uses a statistical averaging across possible pore structures that maintain a macroscopic equivalent relationship. This method uses fractals after the work of Mandelbrot & Van Ness, 1968 and the self-similarity of the solution across length scales, agreeing with the solution of the spatial approach when fluctuations are neglected. Karacan & Luxbacher, 2010 used this method to determine a relationship for gob permeability. The results are similar using the simpler method developed by Esterhuizen et al. 2010 for steady-state flows.
2.2.2 Porous Media Model

The flow velocity through a volume of the porous medium is termed the superficial velocity, also referred to as the seepage, filtration or Darcy velocity, based on Darcy (1856) law of fluid flow through a porous media, given in simplified form in Equation 2.4

\[ u = -\frac{K \partial P}{\mu \partial x} \]  

(2.4)

where \( u \) is the velocity component in the \( x \)-direction across some pressure gradient \( P \), and \( \mu \) is the fluid viscosity. This law defines the permeability unit of Darcy’s, \( K \), equal to \( 0.987 \times 10^{-12} \, m^2 \). The value of permeability is related to the porosity and particle diameter, \( D_{p2} \), by the Carman-Kozeny relationship given in Equation 2.5

\[ K = \frac{(D_{p2})^2 n^3}{180(1-n)^2} \]  

(2.5)

where \( D_{p2} \) may be represented by a stochastic model of the density function, \( h(D_p) \), of the form given in Equation 2.6

\[ D_{p2} = \frac{\int_0^\infty (D_p)^3 h(D_p) dD_p}{\int_0^\infty (D_p)^2 h(D_p) dD_p} \]  

(2.6)

The constant of 180 in Equation 2.5 is based on a tortuosity of 2.4, a slightly higher value than the value of 2, which would approximate spherically shaped particles. A refinement by including a second term for inertial damping is suggested for use by ANSYS (2014b) using the Ergun approach in Section 3.7.

Figure 2.3 presents the work of Ward, 1964 that identifies the two major flow regimes, Darcy flow and Forchheimer flow, and the smooth transition that occurs in experiments. This smooth transition, shown as modeled, uses the Ergun approach. Darcy’s law holds for values of Reynolds numbers less than 0.1, where the Reynolds number scale with the square root of the permeability and the friction factor remains linear. In the Forchheimer (1852–1933) region, the friction factor remains constant with increasing Reynolds numbers. Other length scales for the Reynolds number are suggested by Bird et al., 2007 based on the pore scale instead of the permeability. Since the transition to the region of non-linear drag
is smooth, it should be noted that this is not an effect of turbulence, and the flow in the pores remains laminar (Bird et al., 2007).

The recommendation given by Nield & Bejan (2013) is that “until further experimental work is carried out, the simple quadratic expression for the form drag be used, on the understanding that the coefficient is not necessarily given by the Ergun formula.”

2.2.3 Porous Media Boundary Condition

There is considerable debate regarding the matching of the interface between the Navier-Stokes free fluid flow solution, as discussed in Chapter 3, and the solution obtained in the porous medium. The problem is illustrated in Figure 2.4 by the lack of the development of a boundary layer in the velocity profile. The velocity at the impermeable wall at the top is well defined, as discussed in Section 5.3.3; however, the permeable interface at the bottom, a relationship between the free fluid velocity, $u_f$ and the velocity in the porous medium, $u_m$ must be defined.

In the case of a liquid medium exposed to air, the boundary condition may be expressed with the following relationship given by Equation 2.7
\[
\frac{\partial v}{\partial y} = 0 \text{ at } y = 0 \quad (2.7)
\]

Beavers & Joseph, 1967 proposes that in the case of the same fluid saturating the medium, the relationship may be expressed by Equation 2.8

\[
\frac{\partial u_f}{\partial y} = \frac{\alpha_{B,J}}{K^{1/2}}(u_f - u_m) \quad (2.8)
\]

where \( u_f \) is evaluated at some small distance into the free fluid, \( y = 0^+ \) from the plane at \( y = 0 \), and \( u_m \) is evaluated at \( y = 0^- \) in the porous media. The constant \( \alpha_{B,J} \) may range from 0.1 to 4 and depends on the geometry of the porous media and problem being considered. The most recent work by Nabovati & Amon, 2013 uses a lattice-Boltzmann approach that considers the colliding particles on the surface of the porous medium and predicts results similar to parameters used in experimentation.

![Porous Media Boundary Flow](image)

Figure 2.4: Porous Media Boundary Flow (Nield & Bejan, 2013)

### 2.2.4 Porous Media with Turbulence

De Lemos, 2012 discusses the treatment of turbulence and buoyancy in a porous medium, as well as an impinging jet onto a porous layer, among many other porous media flow cases. The author presents the coupling of the turbulence equations with the porous media model assumption using a double-decomposition model based on volume averages that include both
spatial deviations and time fluctuations. The algorithms presented in De Lemos, 2012 are not mentioned in ANSYS, 2014b, release and remain an area of ongoing research.

2.2.5 Gob Formation

The gas flow characteristics identified in the gob depend on the rock strata that ultimately will form the gob and overburden that compacts it, crushing the rock and reducing the particle size. Numerical modeling, direct stress measurements, tracer gas and laboratory block modeling have all been used to study the gas flow characteristics of the material that forms the gob behind the retreating longwall mining machine. These studies predict the formation, structure and variability that create the porosity and permeability used in flow models.

The gob formation occurs as the longwall shields retreat out, allowing the roof to collapse into the void of the extracted coal seam. Initially, the gob consists of loose rock and rubble with a high porosity and permeability. The gob formation from the roof caving process causes failure and delamination in the upper strata rock and creates three distinct regions as shown in Figure 2.5: a rubble zone of broken pieces of rock or gob, a zone of fractured rock that is being supported by the gob, and a strata bending and delamination zone extending to the surface (Peng & Chiang, 1984; Singh & Kendorski, 1981). The surface subsidence, defined as the downward movement with respect to the original elevation (dotted line), is also shown in Figure 2.1. Once the coal is removed, the overburden load redistributes across the gob. As the face advances farther, the overburden load compacts the gob material and reduces the porosity and permeability.

The height of each zone shown in Figure 2.5 depends on the geological conditions of the mine site: lithology of the overburden strata, mine depth and mine extraction height. The height of the caved zone of the gob is dependent on the overburden strength and the orientation, rotation and stacking of the falling blocks and their bulking factor (Esterhuizen & Karacan, 2007). The gob height is typically 3 to 6 times the extraction height (Esterhuizen & Karacan, 2005). The fractured zone above extends from 30 to 60 times the extraction...
height and consists of bedding plane separation and vertically aligned fractures. This zone may be shaped as an arch or saddle depending on overburden properties (Bai et al., 1995).

### 2.2.6 Gob Compaction

Studies have been conducted to understand the compaction of the gob material for both porosity and permeability. An indicator for the compaction is surface subsidence that must be considered for building damage estimates or continuing ground movement (Karmis et al., 1984; Landsberg, 1936). Gob compaction depends on the following two factors: the bulking factor describing how a block initially falls into place, and the rock fragment strength (Karacan et al., 2007a; Yavuz, 2004).

The bulking factor is determined from shape, falling height of the rock fragments, size of the fragments, and size distribution of rock fragments. The bulking factor initial value is determined by the fall height created by the removed coal, and decreases to zero as the fall height decreases within the caving zone (Karacan et al., 2007a; Yavuz, 2004). The bulking factor is inversely proportional to gob compaction (Esterhuizen & Karacan, 2007), which will result in a maximum bulking factor directly behind the shields and near the gate roads, and reduced bulking toward the center of the gob with higher compaction. Pappas & Mark, 1993b determined that the initial void ratio is 30% to 45% in laboratory tests.

The compacting gob receives the majority of the load from the strata a short time after the face retreats. Once the initial load compacts the gob, the gob material begins to respond with strain hardening and stiffening behavior; this crushes the rock and leads to a non-elastic, irreversible response. An estimate of the gob material response to loading is first presented as a hyperbolic curve given in Equation 2.9 (Salamon, 1990)

\[
\sigma = \frac{a \epsilon}{b - \epsilon}
\]  

where \(a\) and \(b\) are empirical parameters, and \(\epsilon\) is the amount of plastic-volumetric-strain. The value of \(a\) is the stress before the material begins to harden, which occurs when \(\epsilon\) equals twice the value of \(b\). The value of \(b\) is the initial value of the bulking factor when the gob
forms, and limits the maximum compaction of the material found in the gob.

Strain hardening has been studied and determined for common rock types. The strength of the rock fragments in the gob is taken from initial values identified by several researchers (Esterhuizen et al., 2010; Pappas & Mark, 1993b; Ray et al., 2006; Salamon, 1970; Yavuz, 2004). The empirical value of $b$ ranges from 0.4 to 0.45, while the value of $a$ is used as a calibration parameter to match stresses and subsidence. The final value of subsidence is commonly measured by mine operators.

Gob compaction is determined using the numerical rock mechanics modeling software package FLAC$^{3D}$ by Badr et al., 2002; Esterhuizen et al., 2010; Karmis et al., 1984; Kiusalaas & Albert, 1983; Palchik, 2003; Styler, 1984; Yasitli & Unver, 2005; Yavuz, 2004. Two-dimensional simulations (Morsy & Peng, 2002; Mukherjee et al., 1994), and early supercomputers (Park & Gall, 1989) used other modeling code. FLAC$^{3D}$ provides significant advancement in modeling capability in that a double-yield model can be introduced to allow for the simulation of granular material behavior. The strength of the gob material varies widely between mine sites. The FLAC$^{3D}$ numerical model uses the surface subsidence, stress abutments taken near the gate road, and overall profile of the resulting subsidence as a guide to calibrating the final results (Marts et al., 2014b).

### 2.2.7 Subsidence Profile

The profile of subsidence down the length of the panel during an actively mining longwall face is reported by Campoli et al., 1993 as shown in Figure 2.6. This confirms early work by Salamon, 1989 using a mathematical predictive Gaussian distribution function model. The gob compaction results have been shown to have a similar shape to that of the subsidence profiles, as discussed further in Section 4.3 and Appendix A.

Initial work by Knothe, 1957, predicted dynamic subsidence and resulted in a differential equation dependent on time in Equation 2.10 with its solved form in Equation 2.11

\[
\frac{dW(t)}{dt} = c(W_o - W(t)) \tag{2.10}
\]
Figure 2.5: Vertical Cross-section of the Disturbance above a Longwall Panel (Karacan et al., 2007b)

Figure 2.6: Subsidence Profile along the Center Line (top), and Generalized Vertical Stress Distribution (bottom) Campoli et al., 1993
\[ W(t) = W_0(1 - e^{-ct}) \]  

where \( W(t) \) is the subsidence at time \( t \), and \( W_0 \) is the final subsidence at any given point, and the constant, \( c \), represents the properties of the overburden. The mining extraction rate relates to the subsidence rate (Cui et al., 2001), confirming a modification to the Knothe equations results in Equation 2.12

\[ K_{Dyn} = K_{Final} \left( 1 - e^{\frac{ct}{V_p}} \right) \]  

where \( K_{Final} \) is the final subsidence, \( K_{Dyn} \) is the dynamic subsidence value, \( c \) is a time coefficient, \( r \) is the radius of influence, and \( V_p \) is the face advance rate (Peng et al., 1992).

The immediate roof rock strata properties play an important role in the final form of the gob and the dynamic gob compaction. Two caving response cases studied by Hill, 1995 discuss, parting-plane controlled and bulking controlled caving response. He notes that when the roof contains thick, strong rock, the roof tends to hang and fracture at the parting-plane in large pieces as it falls. If the roof is composed of weak rock, the block rotation and stacking (bulking factor) play a greater role in the formation of the gob. The final formation of the gob may contain a void between the broken strata layers and the gob, or it may completely fill. More often though, there are combinations of the two formations, and direct observation will only determine the size and shape of the void (see Section 4.2.2).

### 2.2.8 Volumetric Strain Increment (VSI)

The volumetric strain increment (VSI) is a measure of the change from the initial porosity of a granular material. Laboratory tests performed by Jozefowicz, 1997, proposed a modification to the Pappas & Mark test. Tri-axially loaded samples of sandstone, shale, or gritstone were compressed uniformly in a Hoek-Cell acting as permeameter shown in Figure 2.7, where the sample is compressed in all directions.

During the compression process, nitrogen gas is injected at a known pressure, while the flow rate of gas is monitored. Darcy’s law is used to develop the intrinsic permeability at each
compressive pressure. As a result, a relationship between volumetric strain and permeability determined the constants in Equation 2.13

$$k_{gob} = -4 \times 10^{-16} \epsilon_{Vol}^3 - 6 \times 10^{-15} \epsilon_{Vol}^2 - 7 \times 10^{-14} \epsilon_{Vol} + 1 \times 10^{-11} \{m^2\} \quad (2.13)$$

where $\epsilon_{Vol}$ is the volumetric strain, and $k_{gob}$ is the gob permeability.

A coefficient of permeability from direct in-situ rock property measurements is first introduced by Szlazak, 2001, in a study of gob air flow patterns and spontaneous combustion. Assuming a laminar flow in the gob, the coefficient of permeability is derived from linear porous media filtration as given in Equation 2.14

$$k = \mu \frac{L \Delta Q}{S \Delta p} \{m^2\} \quad (2.14)$$

where $\mu$ is the coefficient of absolute viscosity of air, $S$ is the cross-sectional area, $\Delta p$ is the pressure drop across the distance, $L$ and $\Delta Q$ is the volumetric flow in the gob.

The porosity of the gob material is initially assumed to be $40 - 50\%$ (Pappas & Mark, 1993b), depending on the host rock of the roof. The Pappas & Mark value of initial porosity
is derived from the void volume in the cave zone, which is the ratio of extracted seam height over the caving height of the gob, plus the inherent porosity value of the rock material that makes up the host rock forming the gob, \((H_{\text{coal}}/H_{\text{cave}} + n_{\text{inherent}})\) equals the initial porosity value. This initial porosity value minus the compaction value of VSI, \((n_{\text{initial}} - VSI)\), equals the final porosity of the gob material. The Carman-Kozeny relationship between permeability and porosity, expressed in Equation 2.15

\[
K_{\text{gob}} = \frac{K_o}{0.241} \left( \frac{n^3}{(1 - n)^2} \right)
\]  

(2.15)

where \(K_o\) is the base permeability of the rock, and \(n\) is the porosity. Equation 2.15 is used to relate the output of FLAC\(^3\)D and the inputs required to complete the flow characterization of the gob. This relationship is used by Esterhuizen & Karacan, 2007; Lolon & Calizaya, 2009; Wachel, 2012 and is generally accepted among researchers.

A complete range of permeability values used by researchers is given in Table 2.2, and summarizes the range of minimum and maximum values. The work completed previous by CSM researchers Wachel, 2012; Worrall, 2012 for Mine C became the first models of Western United States mines.

Table 2.2: Comparison of Gob Permeability Findings

<table>
<thead>
<tr>
<th>Source</th>
<th>Max Perm [mD]</th>
<th>Min Perm [mD]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brunner, 1985</td>
<td>(1.01 \times 10^9)</td>
<td>(1.01 \times 10^8)</td>
</tr>
<tr>
<td>Ren &amp; Edwards, 1997</td>
<td>n/a</td>
<td>(1.01 \times 10^8)</td>
</tr>
<tr>
<td>Szlazak, 2001</td>
<td>(1.01 \times 10^9)</td>
<td>(5.07 \times 10^8)</td>
</tr>
<tr>
<td>Wendt &amp; Balusu, 2002</td>
<td>n/a</td>
<td>(1.00 \times 10^9)</td>
</tr>
<tr>
<td>Whittles et al., 2006</td>
<td>(5.07 \times 10^8)</td>
<td>(1.01 \times 10^7)</td>
</tr>
<tr>
<td>Esterhuizen &amp; Karacan, 2007</td>
<td>n/a</td>
<td>(1.00 \times 10^9)</td>
</tr>
<tr>
<td>Lolon &amp; Calizaya, 2009</td>
<td>(4.74 \times 10^8)</td>
<td>(8.10 \times 10^5)</td>
</tr>
<tr>
<td>Karacan, 2009c</td>
<td>(3.55 \times 10^7)</td>
<td>(1.52 \times 10^7)</td>
</tr>
<tr>
<td>Karacan, 2009d</td>
<td>(1.27 \times 10^7)</td>
<td>(5.07 \times 10^6)</td>
</tr>
<tr>
<td>Ren et al., 2011</td>
<td>(2.00 \times 10^9)</td>
<td>(2.00 \times 10^6)</td>
</tr>
<tr>
<td>Worrall, 2012 Mine C</td>
<td>(6.99 \times 10^9)</td>
<td>(2.03 \times 10^8)</td>
</tr>
<tr>
<td>Marts et al., 2014b Mine C</td>
<td>(5.17 \times 10^9)</td>
<td>(2.03 \times 10^8)</td>
</tr>
<tr>
<td>Marts et al., 2014b Mine E</td>
<td>(6.99 \times 10^9)</td>
<td>(2.03 \times 10^9)</td>
</tr>
</tbody>
</table>
Recent work by Marts et al., 2014b used FLAC$^{3D}$ to model the mining operation of two mines following the work of Esterhuizen & Karacan, 2007, to validate the gob material strength against the subsidence data provided by the mines. The values shown in Table 2.2 for Mine C (Marts et al., 2014b) represent a mine that is highly compacted, while the values for Mine E represent a more loosely compacted gob. Table 2.2 presents a wide range of values within an order of magnitude and illustrates the vast change in the gob properties that must be considered for an effective ventilation design.

2.3 Ventilation Studies using Computational Fluid Dynamics

The section presents the use of CFD code in mine ventilation research, some of the general ventilation problems that have been studied, and then details regarding the specific study of gob ventilation. This discussion covers a brief overview of methane emission and the related work on GVB performance, then the work on progressively sealed gob ventilation systems, and finally tracer gas studies to determine ventilation network connectivity.

2.3.1 Codes used in General Ventilation Problems

Initial CFD studies in mining began in Japan by Uchino et al., 1980 with a coal mining ventilation requiring coolers on the face air. The researchers used a one-tenth scale physical model of the 100 m (330 ft) wide longwall panel to evaluate gob conditions and the effect of air flow and patterns along the face, and headgate curtain effect on gas ingress simulated on a two-dimensional representative mesh. As computational processing power increased in the early 1990s, the focus shifted to face ventilation in mining development sections as studied by Gong & Bhaskar, 1992 in a three-dimensional flow model of an active continuous miner machine to predict the effects of exhausting, blowing, brattice, or tubing schemes of auxiliary fans. Later, Banik et al., 1993 studied general flow models in natural mine airways for friction flow coefficients estimated in mine entries and compared to standard pipe flow models using surface roughness and Reynolds number to relate friction flow coefficients on a Moody chart. Discrepancies were found and attributed to the great randomness in placement
and size of wall roughness values, but fractal analysis was suggested to correlate values for mine airways.

### 2.3.2 Models used for Gob Ventilation Problems

Initial modeling of air flow in longwall gobs began with Ren et al., 1997 using a two-dimensional Fluent model for the control of methane transport from the strata and gob to the gate road airways. The gob properties were taken from a rock sample test using a tri-axial stress condition to determine permeability and porosity changes of the overlying strata to simulate the undermining of the longwall mining operation. Shown in Figure 2.8 are the results of static pressure and velocity contour plots of a vertical cross-section of the strata and gateroads. The two gateroads can be seen in the lower left and right of the figures. This begins to suggest the flow patterns that might be found in the gob. Wendt & Balusu, 2002 used CFD modeling to examine the effect of overburden and rock types on the flow patterns in the gob, advancing the work of Karacan & Okandan, 2000.

Balusu et al., 2005a is the most comprehensive study using gas monitoring, as shown in Figure 2.9, to analyze the effects of ventilation schemes, mine layouts, and GVB design with respect to gob gas composition. In addition, tracer gas studies (see Section 2.3.6) from two different mines, as shown in Figure 2.10, validate computer modeling efforts. A CFD code and coupled geomechanical gas flow software, COSFLOW (Yeh et al., 1997), optimized the ventilation schemes for the safety of methane-air mixtures in the ventilation system. The methane is both collected as ventilation air methane, and coal mine methane through GVBs as useful gas production. These two complete mine gob ventilation studies and their simulation efforts comprise the earliest retrieved publications.

The largest CFD model of mine ventilation by Ren et al., 2011 used the mine geometry shown in Figure 2.11, which shows an active face in the lower left-hand corner with several sealed gobs. A CFD analysis of the area and the active panel using various ventilation schemes were modeled. One of the results is shown in Figure 2.12, where a nitrogen injection point is placed at 200 m (660 ft) and 80 m (260 ft) behind the face. The oxygen concentration
Figure 2.8: Fluent Modeling of Methane Transport to Gate Road Airways: Pressure and Velocity Contour Plots (Ren et al., 1997)

Figure 2.9: Typical Gob ("goaf") Gas Monitoring System in Underground Longwall Panels (Balusu et al., 2005a)
Figure 2.10: Tracer Gas First Arrival Times at Different Locations in the Gob for Two Mines

is reduced through the gob area at 200 m (660 ft), but increases at the face when compared with the 80 m (260 ft) placement injection point. The oxygen concentration reported in these models is useful for reducing the potential for spontaneous combustion, however, they fail to identify the EGZ location and size.

Worrall, 2012 used a gob gas composition algorithm to compute the explosive hazard based on Coward’s Triangle, as shown previously in the gob gas analysis plot Figure 1.7. The mine geometry used for the CFD study is taken at the recovery room with additional ventilation to the face through two special entries, called recovery chutes. The recovery of the longwall shields is modeled in a five-step removal process where the nitrogen injection is optimized for each step. Other studies published by Marts et al., 2013 and Gilmore et al., 2013, show the effect of face ventilation quality and nitrogen injection amounts in the tailgate or headgate on the explosive volumes, tailgate concentrations of methane, and the oxygen ingress as related to spontaneous combustion potential.
Figure 2.11: Ventilation Scheme with Regulator Applied in the New Longwall Tailgate on LW9 upon Sealing (Ren et al., 2011)
Figure 2.12: Effect of Nitrogen Injection at Various Locations behind the Face (Ren et al., 2011)
2.3.3 Methane Emission Studies

The primary source of methane emission in underground coal mines is from the disturbance of a gas reservoir in an overlying or underlying coal seam, and the in-situ methane contained in the coalbed being mined may also be a significant source. The methane enters the mine ventilation at the assumed concentration of 100%, diluting into the airways as shown in Figure 2.13. Previous studies used models of an underlying gas reservoir by Balusu et al., 2005b for Australian mines, and an overlying gas reservoir, used by Worrall, 2012.

![Figure 2.13: Methane Liberation from a Feeder Crack into a Mine Ventilation Airway (not to scale)](Kissell, 2006)

According to a study by Saghafi et al., 1997, the worldwide methane emission from underground coal mining is believed to be 30% of the human industrial contribution. The recovery of useable methane is increasing with GVB use in ventilation designs. The production of coal in highly gassy mines is predicted to produce up to 50 cubic meters of methane per metric ton of coal mined. Using a comparison of production rates in Australian coal mines for gassy and non-gassy mines, the authors used an empirical relationship to predict foreign coal mines salable methane gas as shown in Table 2.3. The percentage of utilized methane comes from GVBs, and the total is the emissions liberated as ventilation air methane, or freely venting GVBs. The United States is the third highest emitter of methane, with less than 10% utilization. As recently reported, Poland has improved recovery to 20%, and the mines in Poland are some of the deepest in the world, with some as deep as 1,200 m (4,000 ft) below the surface. Poland has achieved 20% recovery only with great efforts spent in the removal of methane before and after mining (Uszko et al., 2013).
Table 2.3: Methane Emission from Underground Coal Mining and Utilization in 1993 (Saghafi et al., 1997)

<table>
<thead>
<tr>
<th>Country</th>
<th>Total Production $Mt$</th>
<th>Underground Production $Mt$</th>
<th>Underground $CH_4$ Emissions $Mm^3$</th>
<th>$CH_4$ Utilized $Mm^3$</th>
<th>% Utilized</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>1047</td>
<td>994.7</td>
<td>10837</td>
<td>205</td>
<td>2</td>
</tr>
<tr>
<td>USA</td>
<td>774.2</td>
<td>348.4</td>
<td>5871</td>
<td>459</td>
<td>8</td>
</tr>
<tr>
<td>CIS (Russia)</td>
<td>420.4</td>
<td>218.6</td>
<td>6169</td>
<td>234</td>
<td>4</td>
</tr>
<tr>
<td>India</td>
<td>238</td>
<td>73.8</td>
<td>389</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Africa</td>
<td>187.4</td>
<td>112.4</td>
<td>596</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Australia</td>
<td>180</td>
<td>50.4</td>
<td>752</td>
<td>67</td>
<td>9</td>
</tr>
<tr>
<td>Poland</td>
<td>130.6</td>
<td>130.6</td>
<td>1321</td>
<td>168</td>
<td>13</td>
</tr>
<tr>
<td>UK</td>
<td>67.5</td>
<td>55.4</td>
<td>711</td>
<td>154</td>
<td>22</td>
</tr>
<tr>
<td>Germany</td>
<td>64.2</td>
<td>64.2</td>
<td>1553</td>
<td>353</td>
<td>23</td>
</tr>
<tr>
<td>Canada</td>
<td>59</td>
<td>3.9</td>
<td>62</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Indonesia</td>
<td>28.6</td>
<td>2.9</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Czech Republic</td>
<td>23.9</td>
<td>23.9</td>
<td>385</td>
<td>125</td>
<td>32</td>
</tr>
<tr>
<td>Colombia</td>
<td>21.7</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Spain</td>
<td>18.2</td>
<td>14.1</td>
<td>82</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>France</td>
<td>9</td>
<td>9.0</td>
<td>176</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Japan</td>
<td>7.2</td>
<td>6.4</td>
<td>147</td>
<td>13</td>
<td>9</td>
</tr>
<tr>
<td>Turkey</td>
<td>2.7</td>
<td>2.7</td>
<td>68</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total World</strong></td>
<td><strong>3384.8</strong></td>
<td><strong>2179.1</strong></td>
<td><strong>30,068</strong></td>
<td><strong>1778</strong></td>
<td><strong>6</strong></td>
</tr>
</tbody>
</table>
Examining the reported discharge of methane in the United States from 1980 to 2009, from the Annual Energy Review, 2015, as shown in Figure 2.14, coal mining releases the second highest emissions of methane, only surpassed by natural gas systems. The recovery of this methane is modeled by Jan et al., 2002, in an effort to capture the coalbed methane reservoirs in the San Juan Basin.

![Energy Sources by Type 1980-2009](image)

Figure 2.14: United States Methane Emission (U.S. Energy Information Administration, 2015)

Further modeling work by Schatzel et al., 2006, predicts the methane emissions associated with increasing the longwall face length in coal mines. Karacan & Diamond, 2006 published a handbook for controlling mining methane for safety applications, including: the measurement of coal’s gas content, forecast of emissions from the geological formation data, prediction of gas storage of the strata, implementation of GVB monitoring to forecast future emissions, and prediction of gas emissions during mining operations.
2.3.4 Gob Ventilation Borehole Studies

In a United States Bureau of Mines study by Diamond, 1994, methane drainage techniques for control in underground mines were reviewed for pre-mining and post-mining drainage to reduce the methane that enters the ventilation system. In Australia, Xue & Balusu, 2002, studied designs for optimal GVB methane production. Flow simulations coupled with geomechanical modeling of horizontal GVBs by Kelsey et al., 2003, suggest the optimal spacing when drilling pre-mining drainage systems in Tower Colliery, UK.

Mines in the Pittsburgh coalbeds are the subject of extensive studies in methane drainage, geomechanical modeling, and flow simulations. Karacan et al., 2007b, studied the placement and design of GVBs and suggested 60 m (200 ft) of slotted casing with a drilling depth to just above the formation of the gob in the fractured zone. These recommendations were based on flow simulation and geomechanical modeling verified by mine data from drill holes. Also Karacan et al., 2007a found that the impacts of longwall panel width on emissions in the GVBs result in further fracturing and production of methane. The strata layers above a coalbed seam are highly influential in the production and release of methane as reported by Karacan et al., 2008. Additional experimental data gathered by multi-rate drawdown well tests are used to study the flow characteristics of coalbed methane reservoirs (Karacan, 2009c). Karacan’s work is applied in flow modeling of methane removal (Karacan, 2009d) to prevent mine explosions. Coalbed methane reservoir life is simulated using intelligent computing methods by training an algorithm with a partial data set and comparing the predicted result with the actual well life span (Karacan, 2009a,b). The algorithm suggested an optimum operating condition of future wells. Karacan & Luxbacher, 2010 used stochastic modeling of the strata geological formation modeling the heterogeneous rock properties, which can affect GVB performance.

The application of CFD modeling in optimizing the positioning and operation of GVBs to reduce methane in Australian mines is published by Ren, 2009, suggesting the drilling of GVBs in a cross-measure roof borehole to drain the tailgate corner more effectively. Down-
hole measurements for methane production by flow meters and cameras are conducted by Wierzbicki, 2013 in Poland to better understand the rock fractures and methane producing strata.

The removal of salable methane from GVBs as a production method and as a mitigation strategy for mining coal has over a decade of profitability (Schraufnagel et al., 1994). The full implementation of profitable methane sales for many coal mining operations is limited by distance to the end user, and therefore methane is often freely vented or flared off instead of being captured for sale.

2.3.5 Studies of Progressively Sealed Ventilation Systems

Ren et al., 2005 used Fluent to simulate the inertization practices in bleederless coal mine gobs. The mine geometry for an active face, recovery room and the sealing of the panel were modeled. The methane inlet is defined as a constant velocity inlet at 10 m (32.8 ft) below the mine floor. The mesh is generally hexahedral with refinements near the face. The model extended 1,000 m (3280 ft) inby and is 250 m (820 ft) wide using a “U-type” ventilation system.

The nitrogen injection locations from a gas boiler at a rate of 0.5 m$^3$/s (1060 cfm) are optimized for the minimum amount of oxygen penetration into the gob. During active mining, the effects of two different nitrogen injection locations are modeled. The first location is just inby the face, and the second is three crosscuts inby the face. Figure 2.15 shows the resulting oxygen contour plots. The near face injection may reduce the oxygen near the face, but high levels of oxygen still remain inby to the second crosscut. Using the third crosscut as the injection point reduces the penetration depth, and reduces the remaining gob oxygen concentration to levels that will stop the self-heating process.

In the recovery room, the ventilation T-splits at the tailgate and the oxygen surrounding the shields has breathable air quality, as shown in the base model in the top of Figure 2.16, with no nitrogen injection. The following oxygen contour plots show the effect of nitrogen injection at 30 m (98 ft), 110 m (360 ft), and 200 m (660 ft) behind the face. The oxygen
Figure 2.15: Oxygen Distribution Pattern in the Gob following Inert Gas Injection (Ren et al., 2005)
reduction on the headgate side is most significant with the 200 m (660 ft) nitrogen injection location. The effects of the permeability are shown in the shape of steep oxygen gradients.

Further research by Ren & Balusu, 2009, on the effects of nitrogen injection in a GVBs showed that if the tailgate becomes inaccessible, then a GVB may be used to inject nitrogen to reduce the oxygen directly behind the face, sufficiently, to prevent spontaneous combustion. Trevits et al., 2010 determined that 10 hours are needed to reach an inert atmosphere below 10% oxygen using a 0.26 $m^3/s$ (560 scfm) flow of nitrogen injection after the longwall shield recovery and sealing of the panel.

2.3.6 Tracer Gas Mine Ventilation Analysis

A tracer gas study examines gas flow communication between a release point and measuring point along the gob or from GVBs. The gas of choice is sulfur hexafluoride ($SF_6$), a nontoxic, colorless, odorless, nonflammable gas, and easily detectable at extremely low concentrations. In a study of the Pittsburgh coal seam by Diamond et al., 1999, tracer gas is released from one GVB in-taking, and detected at GVBs further inby, suggesting communication between these GVBs. Also, tracer gas released into the gob generally remained in the gob except when a GVB is shut down due to low methane levels. Tracer gas released into the ventilation followed bleeder paths to the mine exit bleeder fan. Another study in the Pittsburgh coal seam by Mucho et al., 2000, used tracer gas in an effort to understand and improve GVB production and to limit the amount of methane liberated through the bleeder-ventilated gob system.

Xu et al., 2013 used tracer gas release to build a CFD model based on the mine geometry and predict the status of ventilation controls after a mine explosion. This modeling approach could be useful when the mine is not accessible in other ways.

2.4 Chemical Reactions of Coal - Spontaneous Combustion

The self-heating of coal or spontaneous combustion can take place in the stockpile and in the gob, when coal is left behind. This primarily occurs under conditions when the oxygen
Figure 2.16: Recovery Room Oxygen Concentration Contours with Varying Nitrogen Injection Locations (Ren et al., 2005)
concentration is high enough to sustain the reaction, and the air is stagnant enough that the generated heat is not removed. The spontaneous combustion of coal has led to several accidents resulting in the loss of production, equipment, and even the loss of life (Bessinger et al., 2005; Grubb, 2008). The following list of events from recent years in Table 2.4 shows the significance of spontaneous combustion events.

Table 2.4: Significant Spontaneous Combustion Events (Grubb, 2008)

<table>
<thead>
<tr>
<th>Year</th>
<th>Mine</th>
<th>Consequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>1972</td>
<td>Box Flats (Australia)</td>
<td>18 Fatalities (Cliff et al., 1996)</td>
</tr>
<tr>
<td>1975</td>
<td>Kianga (Australia)</td>
<td>13 Fatalities (Cliff et al., 1996)</td>
</tr>
<tr>
<td>1991</td>
<td>Ulan (Australia)</td>
<td>Loss of $60 million (Cliff et al., 1996)</td>
</tr>
<tr>
<td>1994</td>
<td>Moura No. 2 (Australia)</td>
<td>11 Fatalities (Cliff et al., 1996)</td>
</tr>
<tr>
<td>1997</td>
<td>Galatia (U.S.A.)</td>
<td>Loss of $38 million</td>
</tr>
<tr>
<td>1997-1998</td>
<td>North Goonyella (Australia)</td>
<td>Loss of longwall</td>
</tr>
<tr>
<td>1999</td>
<td>Sanborn Creek (U.S.A.)</td>
<td>Mine idled 9 months</td>
</tr>
<tr>
<td>2000</td>
<td>West Elk (U.S.A.)</td>
<td>Loss of $50 million</td>
</tr>
<tr>
<td>2003</td>
<td>Southland (New Zealand)</td>
<td>Mine closed</td>
</tr>
<tr>
<td>2006</td>
<td>Dartbrook (Australia)</td>
<td>Mine closed</td>
</tr>
<tr>
<td>2010-2011</td>
<td>Signal Peak (U.S.A.)</td>
<td>Mine idled 9 months</td>
</tr>
<tr>
<td>2012</td>
<td>Oxbow (U.S.A.)</td>
<td>Mine closed</td>
</tr>
</tbody>
</table>

The propensity for spontaneous combustion varies regional with coal deposits. Coal’s tendency for self-heating is often determined from the coal’s classification or rank as determined by the carbon content, and the higher the rank the more prone it is to self-heating. For example, Western United States coal mines often have a higher ranked coal and are more prone to self-heating than Eastern United States mines. Based on Table 2.4, many mines in Australia are highly prone to spontaneous combustion. When a mine has both a high propensity for self-heating and is high in methane emissions, special attention is required for the ventilation system design. The oxygen ingress concentration and its penetration distance into the gob must be carefully controlled to prevent self-heating, and the methane released
into the face must avoid the explosive range. The risk of spontaneous combustion heightens during slow mining or when a complete halt is required.

Studies by Banerjee, 1985; Cliff et al., 1996; Feng et al., 1973; Funkemeyer & Kock, 1989; Highton, 1979; Kaymakci & Didari, 2002; Mitchell, 1973 highlight the dangers of insufficient cooling of spontaneous combustion prone coal via air velocity, described as the critical velocity. Over a sufficient time frame, a lack of critical air velocity can initiate the self-heating reaction. The reaction is known to slow at oxygen levels below 6%. However, some coals can continue to react in as little as 2% oxygen (Highton, 1979).

Wang et al., 2003 studied the spontaneous combustion reaction pathway and the dependence on the transport of oxygen to reaction sites within a coal particle. A variety of factors have been determined to influence the possible reactivity of the coal such as composition, history of weathering, particle size, temperature, partial pressure of oxygen and moisture content. However, the carbon content or coal ranking is the only agreed upon factor for propensity of self-heating.

The chemical pathways proposed for the reaction sequence of coal oxidation are shown in Figure 2.17. The chemisorption sequence is known to occur, but falls short of the total amounts of heat and gas produced. The overall production rates require another mechanism of burn off, although the full extent is still not known. Modeling efforts are therefore limited to only a few variables due to the complexity of this reaction sequence.

High levels of carbon monoxide are a known indicator of a heating event. NIOSH has modeled a simplified one-step reaction using CFD (Yuan & Smith, 2006, 2008a,b,c, 2009a,b, 2010). The models use the following reaction pathway: \( \text{Coal} + O_2 \rightarrow CO_2 + 0.1 CO + \text{Heat} \) (Smith & Lazzara, 1987). The effects of nitrogen injection for Eastern United States coal mines are modeled using progressively sealed gobs. This is the most comprehensive work on spontaneous combustion modeling, but it does not explore the methane-air mixture results inside the gob.
The classification of coal for self-heating is studied primarily by an adiabatic oven test, the $R_{70}$ test, with a pre-dried sample of coal. This process fails to take into account the effects of water on the overall reaction, which can either help or hinder heating. Recent research to introduce a new standard is discussed by Beamish & Beamish, 2011; Beamish et al., 2013. The testing of several coals in Figure 2.18 shows the wide range of times that coal exposed to oxygen takes to heat. The moisture inherent in the coal is shown to influence heat significantly, as compared to a sample that is dried first. However, the researchers could not draw a direct relationships to possible catalyst components such as pyrite content to moisture.

The reactions for self-heating follow a set of stages. The first is the oxygen sorption mechanism heating the coal to 70°C. This is followed by the production of hydrocarbon such as benzene in the temperature range of 70°C to 150°C, where the release of combustion products starts to occur. The accelerated heat generation begins from 150°C to 230°C, and this transforms into full thermal runaway if the process is not stopped. During thermal runaway, the coal content may contain sufficient oxygen or may be hot enough to liberate oxygen from surrounding water sources to continue the spontaneous combustion process.
Although some studies focus on spontaneous combustion reaction pathways for simple modeling work, a specific mine ventilation system with the added variable of coal ranking is not applicable to an industry useful general gas flow model. The concentration of oxygen in the gob and the reduction of ingress distance are better suited for general CFD modeling results and the ventilation design comparisons in this research.

2.5 Improvement of Previous Research

Other researchers have primarily focused on oxygen ingress or methane concentration in the gob, and on limiting the application of the research to spontaneous combustion control measures and tailgate methane control. This research provides the first look at the explosive nature of bleeder-ventilated gobs and offers hazard mitigation strategies.

The modular mesh assembly approach developed for this project makes it possible to study multiple mine ventilation layouts, efficiently and quickly. This approach also provides faster solution times on larger ventilation networks than previously modeled by Worrall, 2012,
and makes it possible to construct other ventilation networks for comparison to previous research results by Balusu et al., 2005b; Ren & Wang, 2013; Yuan & Smith, 2010. For example, a back return and T-split options on tailgate ventilation design is modeled by Marts et al., 2014a using progressively sealed gob ventilation.

The development of scalable equation fits for porosity and permeability are additional improvements to the established research. The transparent nature of implementation of the equation fits offers the ability to match a given overburden depth, host rock properties and panel size are important improvements to mine ventilation modeling.

The accessibility of this research is further improved by the creation of a panel scale model ventilation network and by the accompanying library of mesh files that provide a modeling environment capable of running on standard desktop computers available to anyone.
CHAPTER 3
INTRODUCTION TO COMPUTATIONAL FLUID DYNAMICS

This chapter summarizes the equations used in fluid dynamics following the work of White, 2010 and Tu et al., 2008 for the history and fluid physics derivations, and the FLU-ENT Theory Guide, ANSYS, 2014b for the final equation form. The notation used throughout follows that of ANSYS, 2014b when discrepancies between reference sources exist.

Fluid flow modeling began with Archimedes (285–212 B.C.E.) describing the laws of buoyancy, and continued with the addition of one-dimensional conservation of mass by da Vinci (1452–1519) defined in steady-state flow. Newton (1642–1727) postulated the laws of motion and defined the law of viscosity in what is now called Newtonian fluids. Bernoulli (1700–1782) made further developments in theoretical fluid motion with a principle describing inviscid flow conservation named after him, Euler (1707–1783) explained the more general integrated form of the differential equations of motion. (White, 2010)

The vast difference between theory and experimental results drove engineers to develop the science of hydraulics. Weber (1871–1951), Hagen (1797–1884), Poiseuille (1797–1869), Darcy (1803–1858), Manning (1816–1897), and many others conducted foundational work in this area. The experimental work by William (1810–1879) and Robert Froude (1846–1924) codified the laws of scaling or similitude of modeling, and further work by Rayleigh (1842–1919) developing of dimensional analysis built strong connections between experimental results and theory. Reynolds (1842–1912) expanded his predecessors work with a pipe experiment showing that flow regimes can be characterized with his dimensionless Reynolds number. The theoretical work continued to advance with developments by Navier (1785–1836) and Stokes (1819–1903) studying viscous relationships in the differential form of the equations of motion. At the time the Navier-Stokes equations were too complex, so their solutions could not be easily applied.
Modern fluid mechanics began with Prandtl’s (1875–1953) division of flow into bulk fluid motion and flow near a surface in a thin viscous region, called boundary layer theory. The random motion of fluid in development of turbulent eddies had been observed in earlier research, but was first modeled by Kolmogorov (1903–1987) who developed length scales in 1941. In 1972, Launder and Spalding first proposed the standard $k-\varepsilon$ turbulent model.

Over the last four decades, there have been many refinements in modeling with the increasingly available computational power and linear system solver algorithms. This chapter presents a summary of the fluid transport equations used in this research.

### 3.1 Mathematical Notation

The mathematical notation of vectors and indices are presented in this section to facilitate the writing of fluid dynamics. The substantial derivative with respect to time, $t$, is defined in Equation 3.1

$$\frac{D\mathbf{V}}{Dt} \equiv \frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot (\nabla \mathbf{V})$$  (3.1)

where $\mathbf{V}$ is the velocity vector with three Cartesian coordinate components as given in Equation 3.2

$$\mathbf{V} = u \mathbf{e}_x + v \mathbf{e}_y + w \mathbf{e}_z$$  (3.2)

where $u$, $v$, and $w$ are the velocity scalar quantities in the unit direction vectors of $\mathbf{e}_x$, $\mathbf{e}_y$ and $\mathbf{e}_z$. This may also be written using Einstein index notation as

$$\mathbf{V} = u_i$$  (3.3)

where the subscript, $i = x, y, z$ referring to each of the terms in Equation 3.2. This notation is used to refer to a summation over all the coordinate components of a vector or used to refer to all species involved in the formulation of a given solution. Therefore, Equation 3.1 expands into the following three Equations 3.4–3.6

$$\frac{Du}{Dt} = \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z}$$  (3.4)
\[
\frac{Dv}{Dt} = \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} \quad (3.5)
\]
\[
\frac{Dw}{Dt} = \frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} \quad (3.6)
\]

These equations written using Einstein notation are given in Equations 3.7–3.9

\[
\frac{Du}{Dt} = \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x_i} \quad (3.7)
\]
\[
\frac{Dv}{Dt} = \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x_i} \quad (3.8)
\]
\[
\frac{Dw}{Dt} = \frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x_i} \quad (3.9)
\]

### 3.2 Conservation of Mass

For an arbitrary deforming shaped portion of fluid inside a defined region or control volume (CV), the rate of change of mass within the system is equal to the mass flux on the control surface (CS) as stated in integral form in Equation 3.10 (White, 2010)

\[
\left( \frac{dm}{dt} \right)_{\text{system}} = 0 = \frac{d}{dt} \left( \int_{CV} \rho \, dV \right) + \int_{CS} \rho (\mathbf{V}_r \cdot \mathbf{n}) \, dA \quad (3.10)
\]

where the \( m \) is the mass, \( \rho \) is the fluid density, \( V \) is the volume, \( \mathbf{V}_r \) is the relative velocity on the surface normal, \( \mathbf{n} \) and \( A \) is the surface area. Applying Gauss’s divergence theorem defined in Equation 3.11

\[
\frac{d}{dt} \int_{CV} \rho \mathbf{V} \, dV = -\int_{CS} \rho (\mathbf{V} \cdot \mathbf{n}) \, dA \quad (3.11)
\]

to the control surface integral over the surface area to a volume integral divergence of the vector transforms Equation 3.10 into a combined control volume integral form as given in Equation 3.12

\[
\int_{CV} \left( \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) \right) \, dV = 0 \quad (3.12)
\]

Considering a differential control volume the integrand is constant over the volume and Equation 3.12 can be written as Equation 3.13 (Tu et al., 2008)
\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0 \] (3.13)

A physical meaning of each of the terms in Equation 3.13 can be identified as the change in mass or density in the control volume due to temperature or phase fluctuation over time, and the mass flux in and out of the control volume. Using the chain rule to expand the second term in Equation 3.13 results in Equation 3.14

\[ \frac{\partial \rho}{\partial t} + \rho \nabla \mathbf{V} + \mathbf{V} \cdot \nabla \rho = 0 \] (3.14)

Using Equation 3.2 to replace each velocity vector gives the following full vector expansion in Equation 3.15

\[ \frac{\partial \rho}{\partial t} + u \frac{\partial \rho}{\partial x} + v \frac{\partial \rho}{\partial y} + w \frac{\partial \rho}{\partial z} + \rho \frac{\partial u}{\partial x} + \rho \frac{\partial v}{\partial y} + \rho \frac{\partial w}{\partial z} = 0 \] (3.15)

Now simplifying this using the substantial derivative, Equation 3.1, with density as the variable gives the condensed Cartesian coordinates mass conservation in Equation 3.16

\[ \frac{D \rho}{Dt} + \rho \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right) = 0 \] (3.16)

For incompressible flows and steady-state fluid flows this can be simplified into Equation 3.17

\[ \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \] (3.17)

generally referred to as the incompressible continuity equation, or written using Einstein index notation as Equation 3.18

\[ \frac{\partial u_i}{\partial x_i} = 0 \] (3.18)

3.3 Navier-Stokes Momentum Equation

The definition of the governing equations of motion start with Newton’s second law of motion applied in a Cartesian coordinate reference frame as given in Equation 3.19

\[ \mathbf{F} = m \mathbf{a} \] (3.19)
where \( \mathbf{F} \) is the force acting on the body of fluid, \( \mathbf{a} \) is the acceleration as defined by the time derivative of velocity and considering a fluid system with the momentum, \( m \mathbf{V} \), as the transport variable in the Reynolds transport theorem (see Section 5.2) in a non-conservative system. An arbitrary volume of fluid in Equation 3.19 with the forces acting on the system expands into a CV and CS integral as given in Equation 3.20 (White, 2010)

\[
\mathbf{F} = \frac{d}{dt}(m \mathbf{V})_{\text{system}} = \frac{d}{dt} \left( \int_{CV} \mathbf{V} \rho \, dV \right) + \int_{CS} \mathbf{V} \rho (\mathbf{V} \cdot \mathbf{n}) \, dA
\]  

(3.20)

Applying Gauss’s divergence theorem in a control volume fixed in space, Equation 3.20 becomes

\[
- \nabla p + \nabla \cdot (\mathbf{T}') + \rho \mathbf{g} + \mathbf{F} = \frac{\partial}{\partial t}(\rho \mathbf{V}) + \nabla \cdot (\rho \mathbf{V} \mathbf{V})
\]  

(3.21)

where the forces on the left hand side are expanded into the static pressure \( p \), the gravitational forces \( \rho \mathbf{g} \), and the sum of external body forces \( \mathbf{F} \), which later includes the source term for the porous media model. The stress tensor \( \mathbf{T}' \) is given in Equation 3.22

\[
\mathbf{T}' = \begin{pmatrix}
2\mu \frac{\partial u}{\partial x} + \nabla \cdot \mathbf{V} & \mu \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) & \mu \left( \frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \right) \\
\mu \left( \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right) & 2\mu \frac{\partial v}{\partial y} + \nabla \cdot \mathbf{V} & \mu \left( \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \right) \\
\mu \left( \frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} \right) & \mu \left( \frac{\partial w}{\partial y} + \frac{\partial v}{\partial z} \right) & 2\mu \frac{\partial w}{\partial z} + \nabla \cdot \mathbf{V}
\end{pmatrix}
\]  

(3.22)

where \( \mu \) is the laminar molecular viscosity, and \( \nabla \cdot \mathbf{V} \) is the effects of volume dilation.

Expanding the Navier-Stokes equation for each of the Cartesian coordinate gives Equations 3.23–3.25

\[
\begin{align*}
- \frac{\partial p}{\partial x} & + \frac{\partial}{\partial x} \left[ 2\mu \frac{\partial u}{\partial x} + \kappa \nabla \cdot \mathbf{V} \right] + \frac{\partial}{\partial y} \left[ \mu \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \right] + \frac{\partial}{\partial z} \left[ \mu \left( \frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \right) \right] + \rho g \\
\text{pressure gradient} & + \text{diffusion} \\
\rho g & + \frac{\partial}{\partial t} \left( \rho u \right) + \rho \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right) \text{local acceleration} \\
\text{gravity} & + \text{other forces} + \text{advection}
\end{align*}
\]  

(3.23)
The chaotic and random motion of fluids and the formation of swirls into eddies describes the characteristics of turbulent flow. In comparison to laminar flow, which is fully defined by continuity and momentum equations, turbulent flows require numerical solutions. The flow regime can be identified by the Reynolds number that is defined by the ratio of inertial forces to viscous forces in a pipe as given by Equation 3.26

\[ \text{Reynolds Number} \equiv \frac{\rho U D}{\mu} = \frac{v D H}{\nu} \]  
\[ (3.26) \]

where \( U \) is the free stream velocity, \( D \) is the pipe diameter, \( D_H \) is the hydraulic diameter given by \( \frac{2ab}{a+b} \) for a rectangle of dimensions \( a \) by \( b \) and \( \nu \) is the kinematic viscosity defined as \( \frac{\mu}{\rho} \). The flow is laminar when the Reynolds number is below 2,100, transitional between 2,100 – 4,000, and fully turbulent above 4,000.

The full-resolution of unbounded turbulent flow by Direct Numerical Simulation (DNS) in real time is achieved on a two-dimensional plane using NVIDIA sample code (Goodnight, 2012) run on their General Purpose Graphics Processing Units (GPGPUs), however, three-dimensional flows over large domains require turbulent flow approximation. The standard \( k-\varepsilon \) turbulent model by Launder and Spalding (1972) provides sufficient flow resolution of
turbulent flows in most cases. The addition of renormalization group theory (RNG) turbulent modeling resolves a wider range of cases.

3.4.1 Description of $k - \varepsilon$ RNG Models

The RNG turbulent model improvement over the standard $k-\varepsilon$ model includes an additional term in the formulation of turbulent energy dissipation that improves simulation accuracy in rapidly strained flows and includes swirling flow modeling. RNG also provides analytical formulation of turbulent Prandtl numbers compared to constant user specified values in the standard $k-\varepsilon$ model. Furthermore, the standard $k-\varepsilon$ model is valid only in high Reynolds number flows, while the RNG model provides differential formulation for an effective viscosity in low Reynolds number flows. The use of RNG model is chosen over the realizable turbulent model for this reason (Worrall, 2012).

The Prandtl number is defined by the ratio of molecular diffusivity of momentum to heat transfer as given by the following Equation 3.27

$$Pr = \frac{\text{Molecular diffusivity of momentum}}{\text{Molecular diffusivity of heat}} = \frac{v}{\alpha} = \frac{\mu C_p}{k_T} \quad (3.27)$$

where $\alpha$ is the thermal diffusivity or ratio of heat conductivity to thermal capacity ($\frac{k}{\rho C_p}$), $k_T$ is the thermal conductivity and $C_p$ is the specific heat capacity.

The two-equation models use two transport equations for the definition of turbulent kinetic energy $k$ and turbulent dissipation $\varepsilon$. These two variable then calculate a turbulent viscosity $\mu_t$ that is added to the laminar viscosity in the momentum Navier-Stokes Equations 3.23–3.25. The formulation of $k$ and $\varepsilon$ are two additional non-linear equations requiring solutions every iteration. The turbulence transport equations are the turbulent kinetic energy given in Equation 3.28

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u)}{\partial x} + \frac{\partial(\rho k v)}{\partial y} + \frac{\partial(\rho k w)}{\partial z} = \frac{\partial}{\partial x} \left( \alpha_k \mu_{eff} \frac{\partial k}{\partial x} \right) + \frac{\partial}{\partial y} \left( \alpha_k \mu_{eff} \frac{\partial k}{\partial y} \right) + \frac{\partial}{\partial z} \left( \alpha_k \mu_{eff} \frac{\partial k}{\partial z} \right) + G_k + G_b - \rho \varepsilon - Y_M + S_k \quad (3.28)$$
and the turbulent dissipation in Equation 3.29

$$\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \varepsilon u)}{\partial x} + \frac{\partial (\rho \varepsilon v)}{\partial y} + \frac{\partial (\rho \varepsilon w)}{\partial z} = \frac{\partial}{\partial x} \left( \alpha_k \mu_{eff} \frac{\partial \varepsilon}{\partial x} \right) + \frac{\partial}{\partial y} \left( \alpha_\varepsilon \mu_{eff} \frac{\partial \varepsilon}{\partial y} \right) + \frac{\partial}{\partial z} \left( \alpha_\varepsilon \mu_{eff} \frac{\partial \varepsilon}{\partial z} \right) + C_1 \varepsilon \frac{\varepsilon}{\kappa} \left( G_k + C_3 \varepsilon G_b \right) - C_2 \rho \varepsilon^2 - R_\varepsilon + S_\varepsilon \quad (3.29)$$

where $G_k$ is the relationship between turbulence kinetic energy to the mean velocity gradient given as $G_k = \mu_t S'^2$, $S'$ is the modulus of the mean rate of strain tensor given as $S' = \sqrt{2} S_{ij} S_{ij}$, $G_b$ is the generation of turbulent kinetic energy due to buoyancy, $Y_M$ is the dilatation dissipation effect in compressible flows, which is neglected for incompressible turbulent modeling, $S_k$ and $S_\varepsilon$ are user defined source terms, $\alpha_k$ and $\alpha_\varepsilon$ are the inverse effective Prandtl numbers and the constants are analytically derived as $C_1 = 1.42$ and $C_2 = 1.68$.

The effective viscosity given as $\mu_{eff} = \mu + \mu_t$ is the result of the scale elimination procedure in RNG theory defined by Equation 3.30

$$d \left( \frac{\rho^2 k}{\sqrt{\varepsilon \mu}} \right) = 1.72 \frac{\mu_{eff} / \mu}{\sqrt{(\mu_{eff} / \mu)^3 - 1 + C_v} \ d (\mu_{eff} / \mu)} \quad (3.30)$$

where $C_v$ is approximately 100. This allows the RNG turbulence model with the “Differential Viscosity Model” enabled to accurately predict low-Reynolds number. In the high-Reynolds number flow limit the solution to Equation 3.30 gives Equation 3.31

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \quad (3.31)$$

where $C_\mu$ is 0.0845, which is approximately the value use in the standard $k-\varepsilon$ model.

The RNG model in three-dimensional flows accounts for swirl in the mean flow with a modification to the turbulent viscosity as given in Equation 3.32

$$\mu_t = \mu_{t0} \cdot f \left( \alpha_s, \Omega, \frac{k}{\varepsilon} \right) \quad (3.32)$$

where $\mu_{t0}$ is the turbulent viscosity without swirl modification, $\alpha_s$ is a swirl constant dependent on the flow being dominated by swirl and $\Omega$ is a characteristic swirl number calculated within Fluent.
The inverse effective Prandtl numbers $\alpha_k$ and $\alpha_\varepsilon$ are calculated using the following relationship in Equation 3.33

$$
\left| \frac{\alpha - 1.3929}{\alpha_0 - 1.3929} \right|^{0.6321} \left| \frac{\alpha + 2.3929}{\alpha_0 + 2.3929} \right|^{0.3679} = \frac{\mu_{mol}}{\mu_{eff}}
$$

(3.33)

where $\alpha_0 = 1.0$, and $\mu_{mol}$ is the molecular viscosity. High-Reynolds numbers yield ($\mu_{mol}/\mu_{eff} \gg 1$) and therefore $\alpha_k = \alpha_\varepsilon \approx 1.393$.

The $R_\varepsilon$ term is a positive or negative influence on the standard $k-\varepsilon$ model second-order turbulent dissipation rate as given in Equation 3.34

$$
R_\varepsilon = \frac{C_\mu \rho \eta^3 (1 - \eta/\eta_0) \varepsilon^2}{1 + \beta \eta^3} \frac{1}{k}
$$

(3.34)

where $\eta \equiv S k/\varepsilon$, $\eta_0 = 4.38$, and $\beta = 0.012$.

### 3.4.2 Buoyancy in Turbulence $k-\varepsilon$ Model

The production and dissipation of turbulence due to buoyancy is accounted for by the $G_b$ term in the transport Equations 3.28 and 3.29 in the $z$-direction resulting from temperature, and therefore density gradients is given by Equation 3.35

$$
G_b = \beta g_z \frac{\mu_t}{P_{rt}} \frac{\partial T}{\partial z}
$$

(3.35)

where $g_z$ is the gravitation field acting in the $z$-direction, $P_{rt}$ is the turbulent Prandtl number equal to $1/\alpha_{k,\varepsilon}$ given in Equation 3.33 but with $\alpha_0 = 1/Pr$, $T$ is the fluid temperature and $\beta$ is the coefficient of thermal expansion defined by Equation 3.36

$$
\beta = -\frac{1}{\rho} \left( \frac{\partial \rho}{\partial T} \right)_p
$$

(3.36)

which reduces for an ideal gases to Equation 3.37

$$
G_b = -g_z \frac{\mu_t}{\rho P_{rt}} \frac{\partial \rho}{\partial z}
$$

(3.37)

The constant $C_{3\varepsilon}$ in the transport equation for $\varepsilon$ is neglected by default in Fluent. When enabled the constant is defined by Equation 3.38

$$
C_{3\varepsilon} = \tanh \left[ \frac{w}{v} \right]
$$

(3.38)

where $w$ is the velocity parallel to gravitational forces and $v$ is a velocity component perpendicular to gravitational forces.
3.4.3 Turbulence Boundary Conditions

The turbulent flow conditions at the model boundaries (i.e. inlets and outlets) must have initial values based on the flow conditions entering the CFD domain to be computed or have backflow conditions set when the flow re-enters the CFD domain. However, for the large scale modeling of an underground mine, this is shown to be relatively insensitive to these settings (Worrall, 2012). The $k-\varepsilon$ model in Fluent uses one of three methods to define the turbulent flow characteristics:

1. Specifying $k$ and $\varepsilon$ values directly
2. Turbulent Intensity, $I$, and hydraulic diameter
3. Turbulent Intensity and Length Scale, $l$

The first method is impossible to know without prior modeling results. The second is for fully developed internal flows such as the mine entries, and the third can be used for external flows. Fluent guidelines for estimating turbulent intensity is given by Equation 3.39

$$I \equiv \frac{u'}{u_{avg}} \approx 0.16 \left(Re_{D_H}\right)^{-1/8} \quad (3.39)$$

where $u'$ is the root mean squared of the average turbulent velocity fluctuation and $u_{avg}$ is the mean flow velocity. The length scale is define by $l = 0.07L$, where $L$ is the relevant geometric flow length that for this research is the hydraulic diameter of the entries.

3.5 Species Conservation

Molecular species transport is governed by a conservation law stating that species cannot be created or destroyed. However, chemical reactions within a control volume may change the concentration of different species from one to the next following element conservation between species. In this research project, chemical reactions between species are not considered as there is no combustion occurring in the gob. Therefore, modeling is only concerned with species transportation. On a mass fraction $Y_i$ basis the species conservation is given in Equation 3.40
\[ \rho \frac{DY_i}{Dt} = -\nabla \cdot J_i + R_i + S_i \]  

(3.40)

where \( S_i \) is the rate of creation from phase change, \( R_i \) is net production rate from chemical reactions and \( J_i \) is the mass diffusion flux of species \( i \) in laminar or turbulent flow. Conservation of species allows for \( N - 1 \) species equations to fully define the transport of \( N \) total species.

### 3.5.1 Mass Diffusion

Species mass diffusion flux, \( J_i \) of species \( i \) is driven by gradients of concentration and temperature. For laminar flows, Fick’s law expands with Maxwell-Stefan multicomponent diffusion into Equation 3.41

\[ J_i = -\sum_{j=1}^{N-1} \rho D_{ij} \nabla Y_j - D_{T,i} \frac{\nabla T}{T} \]  

(3.41)

where \( D_{T,i} \) is the thermal diffusion coefficient for the \( i \)-th species and \( D_{ij} \) is the diffusion coefficient calculated using the solution to the following system of Equations 3.42

\[
\begin{align*}
D_{ij} &= [D] = [A]^{-1}[B] \\
M_{w,m} &= \sum_{i=1}^{N} \frac{Y_i}{M_{w,i}} \\
A_{ii} &= -\left( \frac{X_i M_{w,m}}{\mathcal{D}_{iN} M_{w,N}} + \sum_{j=1}^{N} \frac{X_i M_{w,m}}{\mathcal{D}_{ij} M_{w,i}} \right) \\
A_{ij} &= X_i \left( \frac{1}{\mathcal{D}_{ij} M_{w,j}} - \frac{1}{\mathcal{D}_{iN} M_{w,N}} \right) \\
B_{ii} &= -\left( X_i \frac{M_{w,m}}{M_{w,N}} + (1 - X_i) \frac{M_{w,m}}{M_{w,i}} \right) \\
B_{ij} &= X_i \left( \frac{M_{w,m}}{M_{w,j}} - \frac{M_{w,m}}{M_{w,N}} \right)
\end{align*}
\]  

(3.42)

where \([A]\) and \([B]\) have matrix dimensions of \((N-1) \times (N-1)\), \(M_w\) is the molecular weight, where the subscript \( m \) is used for the mixture mean molecular weight, \( X_i \) is the species molecular fraction and \( \mathcal{D}_{ij} \) is the binary mass diffusion coefficient of species \( i \) in species \( j \).
For turbulent flows the mass diffusion is given by the following Equation 3.43

\[ \mathbf{J}_i = -D_{t,\text{eff}} \nabla Y_i - D_{T,i} \frac{\nabla T}{T} \]  

(3.43)

where in the standard and realizable k–\( \varepsilon \) models the effective turbulent diffusion coefficient \( D_{t,\text{eff}} \) is given by \( \rho D_{i,m} + \frac{\mu_t \text{Sc}_t}{\rho D_t} \) where \( D_{i,m} \) is the mass diffusion coefficient for species \( i \) in the mixture and \( \text{Sc}_t \) is the turbulent Schmidt number defined as \( \frac{\mu_t}{\rho D_t} \) where \( D_t \) is the turbulent diffusivity. The Fluent default turbulent Schmidt number is 0.7. Turbulent diffusion is orders of magnitude greater than laminar diffusion in turbulent flows and the details of full multicomponent diffusion are often unnecessary to model.

The RNG turbulent model uses a difference formulation for the effective turbulent diffusion coefficient given in Equation 3.44

\[ D_{t,\text{eff}} = \alpha \rho \mu_{\text{eff}} \]  

(3.44)

where \( \alpha \) is calculated using Equation 3.33 with the value of \( \alpha_0 = 1/\text{Sc} \) where \( \text{Sc} \) is the molecule Schmidt number.

3.6 Energy Transport

The energy transport equation is not solved due to constant temperature boundary conditions and no significant temperature gradients appearing in the solutions when it is enabled. Also, in the Fluent pressure-based solver the viscous heating term \( \tau_{ij,\text{eff}} \) the deviatoric stress tensor is not computed by default.

3.7 Treatment of Porous Media

The flow through porous media as modeled in Fluent is an empirically determined resistance or momentum sink that is added to the governing momentum Equations 3.23–3.25. The physical presence of the material producing the porous media is not represented in Fluent. Therefore, a superficial velocity, which is based on the volumetric flow rate, is used in the convection and diffusion terms in the momentum equations. This formulation may be changed by using the physical velocity porous media model, which may produce more
accurate results when velocity values and gradients are important. The superficial velocity porous formulation generally provides a sufficiently accurate representation of the bulk pressure loss needed for flow evaluation. A unique pressure interpolation scheme is always used in the porous media zone, which calculates the necessary pressures at the faces for the transport equations (see Section 5.2.2).

The porous media momentum source term contains two terms. The first term, Darcy’s Law is a viscous loss term linear with velocity, and the second term, varies with the square of velocity as given in the following Equation 3.45

\[
S_i = - \left( \sum_{j=1}^{3} D_{ij} \mu v_j + \sum_{j=1}^{3} C_{ij} \frac{1}{2} \rho \|v\| v_j \right)
\]  

(3.45)

where \(S_i\) is the source term for the \(i\)-th direction momentum equation, \(\|v\|\) is the velocity magnitude, \(D_{ij}\) is a user defined prescribed matrix for viscous resistance and \(C_{ij}\) is a user defined prescribed matrix for inertia resistance. The porous media source term contributes to the pressure gradient in relationship to the fluid velocity.

In the simple homogeneous case Equation 3.45 becomes Equation 3.46

\[
S_i = - \left( \frac{\mu}{K} v_i + C_2 \frac{1}{2} \rho \|v\| v_i \right)
\]

(3.46)

where \(K\) is the permeability and \(C_2\) is the inertial resistance factor. Fluent uses the input in cell resistance, which is the inverse of permeability. The value of \(K\) is calculated by Equation 2.15 and discussed further in Section 4.3.

### 3.8 Solvers

Fluent has two numerical solvers available: pressure-based and density-based. The pressure-based solver was initially developed for low-speed incompressible flows, while the density-based solver was better suited for high-speed compressible flows. Currently, both handle a wider range of flow problems.

The final solution of the velocity field using either solver is obtained from the momentum equations. The density-based solver obtains the density field from the continuity equation.
and then the pressure field from an equation of state such as the ideal gas law. The pressure-based solver obtains the pressure field from a pressure correction equation, which is derived from the combination of the continuity and momentum equation. Both solvers, then calculate the solutions to other scalar equation such as turbulence, species and energy equations.

The Fluent solver uses the following steps in a control volume based approach:

- Mesh or grid creation of discrete control volumes dividing the domain into cells (see Chapter 6)
- Governing equations integrated over the cells creating algebraic discrete dependent variables (velocity, pressure, temperature, species, turbulence k–ε)
- Discretization of equations creating a linear equation system solved for the updated values of the variables (see Section 5.2)

The choice of using the pressure-based solver over the density-based solver is clear as the flow velocity is expected to be sub-sonic and dominated by flow in the gob, which is primarily driven by Darcy’s law (pressure differentially driven flow).

3.8.1 Pressure-Based Solver

The pressure-based solver algorithm constrains mass conservation of the velocity field variable through the use of a pressure correction equation. The pressure correction equation derived from the governing equations of continuity and momentum has the solution such that the velocity field when corrected by the pressure must satisfy the continuity equation. The governing equations are nonlinear in nature and coupled, and therefore a solution proceeds by iteratively solving the governing equations until the largest change per iteration reaches a required minimum. This change per iteration is termed a residual, and a converged solution is said to be reached when at least a three-order of magnitude drop is achieved. There are two options for the pressure-based solver algorithms: segregated and coupled.

The segregated algorithm solves the governing equations in a sequential fashion. Thus, being memory efficient and relatively fast per iteration, but slower to solution convergence
due to the decoupling of the governing equations. Figure 3.1 shows the segregated solution process in the following steps:

1. Update the fluid cell properties from a current solution or initialized values

2. Solve the momentum equations in sequence using updated mass fluxes at the face and pressure values

3. Solve the pressure correction equation using the velocity field and mass fluxes from step 2

4. Apply the pressure correction solution to correct the mass flux, pressure and velocity field

5. Solve other governing equations such as energy, turbulence and species

6. Check if the equation residuals meet the set convergence criteria

The coupled algorithm solves the momentum and the pressure-based continuity equation in a single coupled step, thus, replacing steps 2 and 3 in the segregated solver process with a single step as shown in Figure 3.1. The solver then continues to solve the other governing equations. The coupled solver may converge in fewer iterations with increased time per iteration due to the coupled solver step. In addition, the memory storage requirement increases 1.5 to 2 times the segregated solver usage due to solving the velocity and pressure fields simultaneously. Improvements in iteration times is shown to be beneficial as published by Gilmore et al., 2015a with the use of GPGPU processing units.

3.9 Domain Meshing

CFD requires discretization of the fluid domain into control volumes or cells. This is considered by many to be the most challenging part of the modeling process, since as the creation of the mesh impacts solution stability, iteration time and the resolution of gradients of the transport equations. Therefore, many mesh quality reporting statistics are available,
Figure 3.1: Pressure-Based Solution Method (ANSYS, 2014b)
describing the cells in the mesh. These qualities include: cell quality, orthogonal quality, skewness, aspect ratio, warp angle and smoothness. These may also have a dependence on the flow field in the resulting solution. The guidelines from ANSYS recommend the use of the statistics of quality and skewness as reported by ANSYS® Meshing™ software.

The cell quality is a composite quality metric ranging from 0 to 1, where a value of 0 is a poorly formed cell and a value of 1 is a perfectly formed cell. For three-dimensional cells, this mesh statistic is computed using Equation 3.47

$$Quality = C \left( \frac{volumen}{\sqrt[3]{\sum (edgelength^2)}} \right)$$

(3.47)

where the value of $C$ is selected for the cell type found in Table 3.1. The ANSYS meshing guidelines recommend a minimum cell quality greater than 0.01 for all individual cells, with an overall average much higher.

Table 3.1: Values of C for Computing Quality

<table>
<thead>
<tr>
<th>Element Type</th>
<th>Value of C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tetrahedron</td>
<td>124.70765802</td>
</tr>
<tr>
<td>Wedge</td>
<td>62.35382905</td>
</tr>
<tr>
<td>Pyramid</td>
<td>96</td>
</tr>
</tbody>
</table>

The cell skewness is a mesh metric based on either the optimal cell size or a normalized angle. The method for calculating the cell skewness is chosen to match the type of cell. For example, Figure 3.3 shows the ideal skewness for a triangle and quadrilateral cell, and the corresponding highly skewed cell for each. The range of values for skewness is listed in Table 3.2 with their cell quality ranking. ANSYS Meshing guidelines recommend a skewness below 0.95.

For example, for triangles and tetrahedral cells the equilateral volume method is calculated by using Equation 3.48

$$Skewness = \frac{Optimal \, Cell \, Size - Cell \, Size}{Optimal \, Cell \, Size}$$

(3.48)
Figure 3.2: Example Tetrahedral Cell Vectors used to Compute Orthogonal Quality (ANSYS, 2014b)

Figure 3.3: Ideal (left) and Skewed (right) Triangles and Quadrilaterals (ANSYS, 2014b)
Table 3.2: Mesh cell skewness

<table>
<thead>
<tr>
<th>Value of Skewness</th>
<th>Cell Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>degenerate</td>
</tr>
<tr>
<td>0.9–&lt;1</td>
<td>bad</td>
</tr>
<tr>
<td>0.75–0.9</td>
<td>poor</td>
</tr>
<tr>
<td>0.5–0.75</td>
<td>fair</td>
</tr>
<tr>
<td>0.25–0.5</td>
<td>good</td>
</tr>
<tr>
<td>&gt;0–0.25</td>
<td>excellent</td>
</tr>
<tr>
<td>0</td>
<td>equilateral</td>
</tr>
</tbody>
</table>

For other cell and face shapes the deviation from a normalized equilateral angle is calculated by using Equation 3.49

\[
Skewness = \max \left[ \frac{\theta_{\text{max}} - \theta_e}{180 - \theta_e}, \frac{\theta_e - \theta_{\text{min}}}{\theta_e} \right]
\] (3.49)

where \(\theta_{\text{max}}\) is the largest angle in the face or cell, \(\theta_{\text{min}}\) is the smallest angle in the face or cell and \(\theta_e\) is the angle for an equiangular face or cell (i.e., 60 for a triangle, and 90 for a square). If the cell is a three-dimensional pyramid consisting of a quadrilateral base and four triangular faces or if the cell is wedge shaped, then the maximum of the two methods is reported.
CHAPTER 4
MODELING ENVIRONMENT

This chapter describes the modeling environment of the mine ventilation layout, geometric representation, and flow characteristics used in the simulations. The model construction creates a complete bleeder-ventilated longwall panel from startup room to the active face location 3,109 m (10,200.0 ft) in length. As shown in Figure 1.4 the active panel has regulated flow into the bleeder entries leading to the bleeder shaft and fan. This ventilation layout is further discussed in Section 4.1. The active mining at the face is assumed stopped for a sufficiently long period of time to consider steady-state simulation a good approximation.

The construction of a CFD model of the ventilation layout begins with the sketching of individual sections approximating the geometry that represents the mine entries, face, gob, etc. This is done in the ANSYS native software suite using ANSYS® DesignModeler™ software in order to facilitate geometry changes. All models were create in feet with the exact dimension noted throughout this chapter. A discussion of each geometry section is in Section 4.2. The unknown flow characteristics of the gob are then estimated using the geomechanical simulation data from FLAC³D (Marts et al., 2014b) and fitted to the length, width, and the mine’s stratigraphic type. The resulting porosity and viscous resistance, equation fits and Fluent implementation are discussed in Section 4.3.

4.1 Ventilation Layout

The CFD simulation models the mixing of ventilation air and methane released from the overlaying strata. Figure 4.1(a) shows the ventilation plan map of a bleeder-ventilated gob with labeled Points A through F, and regulators at Point 1 and 2. Figure 4.1(b) shows the ventilation network system that supplies 47 m³/s (100,000 cfm) to the panel at Point A. This air is split to provide 33 m³/s (75,000 cfm) across the face to Point B and 12 m³/s (25,000 cfm) inby the headgate entry to Point E. The headgate (HG) is on the right, and the
tailgate (TG) on the left in Figure 4.1. The Point D and C receives 4.7 m$^3$/s (10,000 cfm) and 7 m$^3$/s (15,000 cfm), respectively, in an H-Type ventilation pattern used for most of the simulations in this research.

This ventilation simplification is made bounding the CFD domain to commonly known measurement points. The headgate entries inby the face are simplified as a single combined entry (Point E). The model outlets are the regulators at the startup room at Point 1, and just before Point F. The methane gas inlet to the mine is placed at the top of the gob, with no overlaying strata included in the model. The permeability jump from strata to gob is four orders of magnitude, and no flow is expected to penetrate a significant distance into the strata without the assistance of a GVB pressure sink.
The model methane liberation rates are set to 2% of the total incoming ventilation air and must be diluted to 2% at both the tailgate and headgate regulator. These regulators are generally considered the examination points for bleeder effectiveness as defined in CFR 30. However, the regulators at Point 2, as shown in Figure 4.1(a), are generally constructed to restrict accidental personnel access to the startup room, and not considered as an essential ventilation control. This project includes a study of the EGZs that form in response to the ventilation controls at Point 1 and 2.

4.2 Geometry

The geometry of the mine dimensions are simplified to common dimensions of mine entries. For example, the width of the development entries is assumed to be 6.1 m (20.0 ft). The geometry models are sketched and dimensioned in the units of feet using constraining relationships where possible in order that a simple parameter can be changed to create the next model. An origin point is chosen for each part as noted in the following sections.

4.2.1 Overview of Geometry Sections

The mine geometry is broken down into repeatable sections to represent the fluid domain of the ventilation system. Figure 4.2 shows the plan view of a panel with a three-dimensional exploded view zooming in on the tailgate side of the panel. The geometry pieces consist of the longwall face, tailgate and headgate, gob, void or gob-fringe, crosscuts and entries. The gob height is 12.8 m (42.0 ft) and slanted at the headgate and tailgate sides to match the observed angle and the formation of the gob-fringe as discussed by Worrall, 2012.

4.2.2 Void or Gob-fringe

The void or gob-fringe is formed as the roof collapses to form the gob and incompletely fills the gateroads on either side of the longwall panel. This behavior is observed in 3 out of 4 of the Western United States coal mines in visited by Grubb (2008) and again observed by the research group behind the headgate in Mine C and E. Figure 4.3 shows a picture
of a gob-fringe, and the estimated geometry that might form. The back return ventilation pattern shown in Figure 1.4 requires the construction of a large trapezoidal opening. This was originally modeled by Marts et al. (2014a) in a paper on U-type ventilation and the effects of a back return, and is adapted into the bleeder-ventilated longwall panel modeled for this research.

The continuous void surrounding the gob is initially modeled by Worrall (2012). Figure 4.4 shows the sketch dimensions and origin point. The origin shown in the figure has x-zero at the void interface to the gob, y-zero at the void interface to the headgate and z-zero at the mine floor. The void is 0.9 m (3.0 ft) at the base, 0.3 m (1.0 ft) at the top, and 12.8 m (42.0 ft) in height, with an offset of 4.7 m (16.0 ft) to tilt the gob-fringe. The length can be adjusted to any panel length and is 3,109 m (10,200.0 ft).

Figure 4.5 shows the back return modeling the tailgate as it remains open to the first crosscut inby. The origin is located at the center of the panel, at the gob interface to the face and at the mine floor. This is the same origin as the final model. The panel width is 305 m (1,000.0 ft) and the tailgate end is located at minus 152 m (−500.0 ft) from the origin.
Figure 4.3: Gob-fringe Model (Worrall, 2012)

Figure 4.4: Gob-fringe Geometry
The bottom of the trapezoid is 8.8 m (29.0 ft), and the top is 3 m (10.0 ft). The height and the inby shape remain the same as the continuous void shape.

### 4.2.3 Longwall Shields and Coal Face

The ventilated longwall face, as shown in Figure 1.3, allows leakage through the shield into the gob area. This is modeled using the approach developed by Worrall, 2012 where it is assumed that a gap area of 0.093 m$^2$ (2.5 ft$^2$) accumulates for every 5 shields. Figure 4.6 shows the geometry of a 6 m (19.5 ft) face depth in a 3.4 m (11.0 ft) tall coal seam offset by the shield leakage gap depth of 0.15 m (0.5 ft). The gaps are modeled by a window placed in the center of the coal seam approximately every 9.1 m (30.0 ft). The gap is 0.76 m (2.5 ft) tall and 0.3 m (1.0 ft) wide. The longwall face width is 293 m (960.0 ft); and when including the headgate and tailgate entries, the total width is 305 m (1,000.0 ft). The origin and global axis shown in Figure 4.6 has x-zero at the center of the panel, y-zero at the face geometry interface to the gob and z-zero at the mine floor.

The face model is improved by modeling individual shields, but is not included in this research due to the computational complexity of the physics needed to define the flow and
the number of cells required to capture the geometry. This work is the subject of a study by Gilmore et al., 2015a conducted with the use of GPGPU.

Figure 4.7 shows the geometry of the headgate entry. The headgate side longwall face entry is modeled with a single leakage gap connecting the face ventilation to the gob-fringe located next to the gob. The origin has coordinates of x-zero at the outer edge of the gob (or 500.0 ft from the panel center), y-zero at the gob to face interface and z-zero at the mine floor. The same offset of 0.15 m (0.50 ft) is used from the shield gap model, which connects the headgate to the gob-fringe. The entry length is 28.7 m (94.0 ft) from the origin point. This geometry can be used for the tailgate entry by rotating it on the y-axis.

The headgate geometry used in this project is a simplification of the air pathway of an actual mine headgate. The actual mine headgate entry would include following: the air split to the belt of neutral air shown in green in Figure 4.1(a), the conveyor belt, crusher, stage loader and headgate drive for the armored face conveyor. These details would require extensive mesh refinements to resolve and would result in localized effects not within the scope of this research.
4.2.4 Crosscuts into Gob-fringe

The crosscuts as shown in Figure 4.2, connect the center development entry to the gob by interfacing with the gob-fringe and entries. Figure 4.8 shows the origin location of x-zero at the gob-fringe interface with the gob, y-zero at gob to face interface (see blue void sketch for reference) and z-zero at the mine floor. The geometry part extends from the face in the negative y-direction. The geometry is offset by the bottom width of the gob-fringe of 0.9 m (3.0 ft) as the interfacing face must have the same slope as the gob-fringe. The width is 15 m (50.0 ft) across the bottom that places the entries on 21 m (70.0 ft) centers.
4.2.5 Mine Entries

The mine entries’ geometry has a constant cross-section of the coal seam height of 3.4 m (11.0 ft) with a width of 6.1 m (20.0 ft). Figure 4.9(a) shows a 18 m (60.0 ft) mine entry extending in the positive y-direction, while Figure 4.9(b) shows a 67 m (220.0 ft) mine entry extending in the negative y-direction. The origin shown in the figures has coordinates of x-zero where the geometry extends in the positive x-direction and z-zero at the mine floor. The entries connect with the crosscuts to make the airway network of the bleeder system. This process is further discussed by the modular mesh approach in Chapter 6. Also, a third tailgate entry, with a length of 34 m (110.0 ft), interfaces with the back return void section and the face, thus modeling the open tailgate entry inby the shields.

![Figure 4.9: Mine Development Entry Geometry](image)

(a) Mine Development Entry – 60 ft Segment

(b) Mine Development Entry – 220 ft Segment

Figure 4.9: Mine Development Entry Geometry
4.2.6 Gob Geometry

The gob geometry represents the fluid zone of the rubblized, collapsed roof rock. The Fluent porous media model (see Section 3.7) is applied to this zone using the developed equation fit in Section 4.3. Figure 4.10 shows the geometry of the gob, including the geometries applied as mesh refinements. Figure 4.10(a) shows a 240 m (800.0 ft) long gob. A 1-foot refinement geometry is shown in the figure applied at 168 m (550.0 ft) inby the face with a 45 degree sloping to 46 m (150.0 ft) from the tailgate and headgate sides and is 46 m (150.0 ft) inby the face. The 1-foot refinement geometry height is equal to that of the coal seam, 3.4 m (11.0 ft). A 2-foot refinement geometry zone is centered in the middle of the gob extending 61 m (200.0 ft) inby the 1-foot refinement zone. The gob is mirrored across the panel center and is 152 m (497.0 ft) from the center to the tailgate side totaling 300 m (994.0 ft) when completed. This width, when added to the gob-fringes of 0.9 m (3.0 ft) each, is 305 m (1,000.0 ft) at the widest points from headgate to tailgate. The origin and global coordinates are set for use for the porous media equation fit of x-zero at the center of the panel, y-zero at the face and z-zero at the mine floor.

Figure 4.10(b) shows a 1,500 m (5,000.0 ft) gob using the same refinement regions, but with the 1-foot region extending the depth of the panel. These geometry pieces are mirrored across the panel center. Figure 4.11 shows a close-up of the tailgate with the specially shaped gob geometry with the included refinement regions and the back return gob-fringe cut out in red. This gob-fringe models the open tailgate gateroad that remains open to the first crosscut inby.

The total modeled panel length is 3,100 m (10,200.0 ft), which includes the specially shaped gob for the back return, 61 m (200.0 ft), and two 1500 m (5,000.0 ft) gob sections. This is a short panel as compared to some actual mines in the Western United States that use 4,830 m to 8,050 m (3-mile to 5-mile) long panels, although the flow and trends for each should be similar.
4.2.7 Startup Room and Entries

The startup room section spans the panel width of 305 m (1,000.0 ft). This is modeled using an open entry interfaced with the back of the gob. This is similar to the face section without the leakage window gaps for the shields. Under normal conditions in a mine, the startup room collapses into the gob and may have a similar shape of the gob-fringe or void that forms when the roof collapses into the gateroads, however, the details are simplified to a single open entry. The startup room is interconnected with one additional entry inby with connecting crosscuts.

The crosscuts into the startup room at Point 2 in Figure 4.1(a) are separate geometry sections that include a regulatory geometry restriction. This regulatory restriction is added by using the Fluent “mark region” tool to add a new zone that becomes a separated, interior fluid zone, which then can be modeled as a porous jump region or as a solid zone leaving a window.

4.3 Model Porosity & Permeability – Equation Fitting

The gob porosity and permeability is calculated from the VSI output from the FLAC$^{3D}$ modeling, as described by Marts et al., 2014b. Before the equation fitting process is applied, the panel is broken up into scalable parts in order to fit any size longwall gob. The equation fitting tool box in Matlab, cftool, is used to match the primary curve features of the data. The 3D data set for position x, y, and VSI is fit using a least-squares approach to determine the coefficients of a custom equation. The goodness of fit is determined by comparing the R-square values, the number of coefficients, and by visually matching the shape. The custom equations combine a series of polynomials and exponentials to reduce the number of coefficients in each fitted section of the panel. The Knothe subsidence Equation 2.11 is used to expand exponentials and polynomials to find an optimal number of coefficients to recreate the given data.
4.3.1 Matlab Equation Fitting Overview

Figure 4.12 shows the section splits, mirrored locations and dimensions for each. The recovery gateroad corner and startup gateroad corner are fixed in width, 60 m (197 ft), and fixed in length, 300 m (980 ft) and 190 m (620 ft), respectively. The recovery room panel center and startup room panel center are fixed in length with the same dimensions of the adjacent section but extendable in width. The gateroad panel center is fixed in width and extendable in length, while the panel center is a constant value. This allows the equations to be applied to their respective panel locations for any size super-critical panel width and length.

Figure 4.13 shows the equation fits of four sections at the startup room. The minor jumps between equations shown in the figure are resolved using a blending of the two equations. The blending takes place over 5 m to 25 m (17 ft to 82 ft) based on the resulting smoothness, and then a percent of each equation is scaled based on the distance.

This process is followed for three FLAC$^{3D}$ data sets and resulted in the equation fits of Mine C, Mine E and a sub-critical panel not modeled for this research (see the UDF code in Appendix B). Mine W is also included from (Wachel, 2012; Worrall, 2012) fit for porosity that, when translated back to the original VSI values, represents a mine fixed in length and width.

The VSI equations were implemented using an execute-on-demand UDF in Fluent. This calculates the VSI values for each cell within the gob zone. The values for porosity and permeability are determined using the Carman-Kozeny relationship discussed in Section 2.2. The code detailing the curve fitting process using the Matlab cftool box is in Appendix A.

4.3.2 Equation Fit for Mine C

The Mine C VSI uses a starting porosity value of 40% and an initial porosity of 25% for the host rock. Figure 4.14(a) shows that the viscous resistance (the inverse of permeability) begins at $1.45 \times 10^5$ 1/m$^2$ and 40% porosity, and is limited to $5 \times 10^6$ 1/m$^2$ and 19% porosity.
in the center of the gob. The steep gradients near the gateroads suggest that this fit may represent a mine that quickly caves into the gateroads and has a weak roof material that compacts tightly.

4.3.3 Equation Fit for Mine E

The Mine E VSI uses a starting porosity of 50% and an initial porosity of 25% for the host rock. Figure 4.14(b) shows that the viscous resistance is significantly less than Mine C. Starting at the same value of $1.45 \times 10^5 \text{1/m}^2$, but only compacting to $5 \times 10^5 \text{1/m}^2$. The porosity range is smaller from 50% to 32%. The gradients near the gateroads are shallow and the final value of viscous resistance is an order of magnitude less than Mine C.

4.3.4 Volumetric Strain Increment Equations and Coefficients

The VSI equation and the corresponding coefficients are defined in the following section. The following subscripts $i, j, k, l$ are used to notate the powers of $x$ and $y$, where $i$ and $j$ correspond to the pre-exponential powers of $x$ and $y$, and $k$ and $l$ correspond to the powers of $x$ and $y$ inside the exponential function as given in following Equation 4.1

$$(xy)^f \sum b_{ijkl}x^iy^je^{-c_{ijkl}x^ky^l} \quad (4.1)$$

where $b_{ijkl}$ is the pre-exponential coefficient, $c_{ijkl}$ is the coefficient inside the exponential function, and $f$ is a fractional exponent or zero.

The permutations from 0 to 2 of $ijkl$ are used in fitting the equations, and then through a process of elimination the terms with the largest exponential coefficient are removed. This process is repeated until the equation is no longer capable of a reasonable match to the contours of the data. An term elimination threshold value of about 3,200 was observed during this iterative process. Further improvements are made to the equation fit by fixing values of previously unknown coefficients, thereby, simplifying the overall equation that the Matlab tool box must solve. This process is used on three FLAC$^3$D data sets with reproducible success. The Mine E and Mine C equation fits are expressed in Equation 4.2 with coefficients given in Table 4.1.
The previous research on this topic developed the code and fit for both porosity and permeability. Since the relationship between the two values is known, a simplified application was developed for comparison. Figure 4.15 shows the fits for viscous resistance and porosity. The figure shows that the equations do not exhibit the super-critical behavior in both the panel width and length. The viscous resistance range is the same as the Mine C fit, but is achieved by limiting the calculations from the porosity values, which range from 50% to 8%. This equation is a previous version of Mine C, which may represent a mine heavily compacted as compared to the validated version developed by Marts et al., 2014b.

### 4.3.6 Using Porosity and Permeability Fits

The VSI is calculated in Fluent after the initialization step by calling the execute-on-demand UDF. This assigns a value to a memory location that is then used by a profile UDF assigned to the viscous resistance in x, y, and z, and the process for assigning the porosity uses a similar method. Currently, no vertical directional dependence is used in the z-direction, but it is an area for future work. The scheme TUI in Fluent assigns variables used in each of these functions to define a scale for the length and width, apply a scalar multiplier to resistance or porosity, specify an initial porosity of the host rock and define initial and limiting values for resistance and porosity. Further details are included in the UDF code in Appendix B.

### 4.4 Summary of Model Assumptions

- The longwall face uses an approximate window gap to model the shields leaking ventilation air into the gob
### Table 4.1: VSI Coefficients

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<td>2.062</td>
<td></td>
<td>0.4457</td>
<td>17.14</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E– Gateroad</td>
<td>0.7157</td>
<td>3.193</td>
<td>-0.1517</td>
<td>3.717</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C– Startup Gate rd</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.2179</td>
<td>3.020</td>
<td>0.3628</td>
<td>2.519</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C– Recovery Gate rd</td>
<td>-27.11</td>
<td>73.60</td>
<td>0.3156</td>
<td>51.90</td>
<td>-0.2532</td>
<td>3.203</td>
<td></td>
<td>-0.01</td>
<td>47.30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C– Gateroad</td>
<td>2.172</td>
<td>4.062</td>
<td>-0.4748</td>
<td>5.389</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
• The tailgate is open to the first crosscut inby in a back return ventilation configuration

• A single panel is modeled and the length is considered sufficiently long

• The mine activity is stopped for a sufficient period of time to consider a steady-state simulation to be a good approximation

• The gob-fringe is modeled as a continuously open geometry on the headgate and tailgate sides of the panel

• The startup room remains open and no gob-fringe forms

• The bleeder entries connecting the headgate and tailgate after the regulators are not modeled

• The three-development entry system on the headgate sides of the panel that reduces to two open entries are modeled as a single open entry
Figure 4.10: Gob Geometry

(a) Gob – 800 ft Segment

(b) Gob – 5000 ft Segment

Figure 4.11: Gob with Open Gob-fringe for a Back Return Geometry
Figure 4.12: Sections of Gob for Equation Fitting

Figure 4.13: Matlab Equation Fit
Figure 4.14: Custom Permeability & Porosity Distribution over Plan View of Longwall Panel
Figure 4.15: Legacy Mine W – Permeability & Porosity
This chapter presents the details of the Fluent model setup, solver settings, methane source considerations, near-wall treatment and treatment of gravity. It also discusses the boundary conditions, EGZ algorithm for post-processing results and development of a supercomputer interface script.

### 5.1 General Solver Settings

The Fluent software settings for the solver are shown in Table 5.1. The pressure-based solver is used when the flow is incompressible, and the velocity formulation can be absolute for slow flowing fluids. The time formulation is set to steady-state, however, transient cases are possible; and the Fluent gravity model is turned off (see Section 5.4).

<table>
<thead>
<tr>
<th>ANSYS Fluent General Settings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
</tr>
<tr>
<td>Velocity Formulation</td>
</tr>
<tr>
<td>Time</td>
</tr>
<tr>
<td>Gravity</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Pressure-Based</td>
</tr>
<tr>
<td>Absolute</td>
</tr>
<tr>
<td>Steady State</td>
</tr>
<tr>
<td>Off</td>
</tr>
</tbody>
</table>

The transport equation model settings are shown in Table 5.2. They were parametrically determined by Worrall, 2012 to produce the best results. Worrall studied the effect of different $k-\varepsilon$ turbulent sub-model settings on the solution results and concluded that the choice of the RNG $k-\varepsilon$ turbulent model made little difference over the standard $k-\varepsilon$ model, but is reputed to be more accurate in a wider range of applications (ANSYS, 2014b). The standard wall function was selected in order to simplify modeling of the entries and the surface roughness of the gob-fringe. Choosing the differential viscosity model enables the solution of the Equation 3.30 for effective viscosity to account for low-Reynolds number
effects. The porous media model is applied to the gob zone using the superficial velocity formulation, which is based on the volumetric flow rate through the cell. The variable viscous resistance (inverse of permeability) and porosity are applied via a Fluent UDF using the equation fitting of FLAC$^3$D data, as discussed in Section 4.3. The additional formulation for porous media inertial resistance term in Equation 3.45 is set to zero for the formulation of an initial solution and trend analysis.

Table 5.2: Fluent Model Settings

<table>
<thead>
<tr>
<th>ANSYS Fluent</th>
<th>Transport Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>On</td>
</tr>
<tr>
<td>Viscous</td>
<td>RNG $k - \varepsilon$, Standard Wall Function,</td>
</tr>
<tr>
<td></td>
<td>Differential Viscosity Model</td>
</tr>
<tr>
<td>Porous Media Model</td>
<td>Zone: Gob</td>
</tr>
<tr>
<td></td>
<td>Porous Formulation: Superficial Velocity</td>
</tr>
<tr>
<td></td>
<td>Viscous Resistance &amp; Porosity from UDF</td>
</tr>
</tbody>
</table>

Fluent material settings for species are shown in Table 5.3. The methane-air mixture species formulation includes five species. For initial modeling of EGZ development, carbon dioxide and water are not included in the model. This is the equivalent of modeling dry-air with no additional sources of carbon dioxide during the mining process. However, sources could exist in a mine from spontaneous combustion, as discussed in Section 2.4, or as a seam gas similar to methane occurs. The three modeled species are methane, oxygen and nitrogen, which requires only the solution for two species transport equations (see Section 3.5). Although, an air species is available in Fluent that would simplify the bleeder-ventilated gob case, the code was built for use with three species.

The species density formulation is an incompressible ideal gas, which models the change in density according to Equation 5.1

$$\rho = \frac{p_{op}}{RT \sum_i \frac{Y_i}{M_{w,i}}}$$  \hspace{1cm} (5.1)

where $p_{op}$ is the operating pressure and $R$ is the universal gas constant (8.134 J/K-mol).
The thermal conductivity is set as a constant 0.0454 W/m-K. The specific heat is formulated using the mixing law, which is defined as the mass fraction average of the pure species heat capacities, $c_p$, calculated by the following Equation 5.2

$$c_p = \sum_i Y_i c_{p,i} \quad (5.2)$$

The viscosity formulation in Fluent is set using the ideal gas mixing law. The solver computes the mixture viscosity based on kinetic theory given by the following Equation 5.3

$$\mu = \sum_i \frac{X_i \mu_i}{\sum_j X_j \phi_{ij}} \quad (5.3)$$

where

$$\phi_{ij} = \left[ 1 + \left( \frac{\mu_i}{\mu_j} \right)^{1/2} \left( \frac{M_{w,i}}{M_{w,j}} \right)^{1/4} \right]^2 \left[ 8 \left( 1 + \frac{M_{w,i}}{M_{w,j}} \right)^{1/2} \right]^{1/2}. \quad (5.4)$$

The mass diffusivity uses the kinetic theory formulation from a modification on the Chapman-Enskog formula to compute the diffusion coefficient as given by Equation 5.5

$$D_{ij} = 0.00188 \left[ T^3 \left( \frac{1}{M_{w,i}} + \frac{1}{M_{w,j}} \right) \right]^{1/2} \frac{1}{p_{abs} \sigma_{ij}^2 \Omega_D} \quad (5.5)$$

where $p_{abs}$ is the absolute pressure and $\Omega_D$ is the diffusion collision integral. The diffusion collision integral is a measure of the interaction of the molecules, which is a function of $T/(\varepsilon/k_B)_{ij}$ where $k_B$ is the Boltzmann constant ($1.3806 \times 10^{-23}$ m$^2$ kg s$^{-2}$ K$^{-1}$) and $\varepsilon$ is the chemical species energy well depth defined from quantum mechanics. The quantity $\varepsilon/k_B$ is defined as the Lennard-Jones energy parameter for each species. The term $(\varepsilon/k_B)_{ij}$ for a mixture is the geometric average given by the square root of the product, $\sqrt{(\varepsilon/k_B)_i (\varepsilon/k_B)_j}$. The Lennard-Jones characteristic length scale, $\sigma$, is given in units of Angstroms for each species and for a binary mixture $\sigma_{ij}$ is the arithmetic average of the species.

5.2 Fluent Discretization and Solver Settings

The choice of gradient interpolation between the cell center and an adjacent face, transport equation derivatives discretization, and segregated or coupled solver are all important
Table 5.3: Fluent Materials Settings

<table>
<thead>
<tr>
<th>ANSYS Fluent</th>
<th>Materials – Methane-air Mixture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Names</td>
<td>Methane, Oxygen, Nitrogen</td>
</tr>
<tr>
<td>Density</td>
<td>Incompressible-ideal-gas</td>
</tr>
<tr>
<td>Specific Heat</td>
<td>Mixing-law</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>0.0454 W/m-K</td>
</tr>
<tr>
<td>Viscosity</td>
<td>Ideal-gas-mixing-law</td>
</tr>
<tr>
<td>Mass Diffusivity</td>
<td>Kinetic-theory</td>
</tr>
</tbody>
</table>

for the accuracy and convergence of the solution. The CFD general modeling approach recommends that once a solution is achieved, then a process of cell refinement and an increase in discretization order is followed to quantify the accuracy of a solution. This is conducted by analyzing the percent change in a variable of interest and reducing it to an acceptable value, or by direct comparison with experimental data. The following sections outline the chosen settings to calculate the initial solution. Further discussion on validation of the results is presented in Chapter 7.

5.2.1 General Scalar for Transportation Equation Discretization

The control volume based technique in Fluent is applied to a general scalar transport equation, yielding an algebraic equation solved numerically. The transport equation is integrated over each control volume producing a discrete equation expressing the conservation law on a control volume basis. Considering a general scalar transport equation for an unsteady conservation law with the scalar quantity $\phi$ in integral form for an arbitrary control volume $V$ is given by the following Equation 5.6

$$\int_V \frac{\partial \rho \phi}{\partial t} dV + \oint_{\partial V} \rho \phi \mathbf{V} \cdot dA = \oint_{\partial V} \Gamma_\phi \nabla \phi \cdot dA + \int_V S_\phi dV \quad (5.6)$$

where $\rho$ is the density, $\mathbf{V}$ is the velocity vector (equal to $u\hat{i} + v\hat{j}$ in 2D), $\mathbf{A}$ is the surface area vector, $\Gamma_\phi$ is the diffusion coefficient for scalar $\phi$, $\nabla \phi$ is the gradient of $\phi$ (equal to $(\partial \phi/\partial x)\hat{i} + (\partial \phi/\partial y)\hat{j}$ in 2D) and $S_\phi$ is the source term per unit volume.
Applying Equation 5.6 to each control volume in the computational domain of meshed cells leads to a two-dimensional discretization of the scalar transport equation. Using the triangular cell shown in Figure 5.1 gives the following discrete Equation 5.7

\[ \frac{\partial \rho \phi}{\partial t} V + \sum_{f} \rho_f V_f \phi_f \cdot A_f = \sum_{f} \Gamma_f \nabla \phi_f \cdot A_f + S_f \phi V \]  

where \( N_{\text{faces}} \) is the number of faces enclosing the cells, \( \phi_f \) is the value of the scalar \( \phi \) convected through the face \( f \), the quantity \( \rho_f V_f \cdot A_f \) is the mass flux through the face, \( A_f \) is the area of the face, \( \nabla \phi_f \) is the gradient of the scalar quantity at the face, \( V \) is the cell volume and \( \frac{\partial \rho \phi}{\partial t} V \) is the temporal discretization.

![Figure 5.1: Control Volume Discretization](image)

The discretized form of general scalar transport, Equation 5.7, represents the value of \( \phi \) at the cell center and its relationship to the surrounding neighboring cells. The system of equations is, generally, a non-linear problem, it can be represented in linear form as written in Equation 5.8

\[ a_p \phi = \sum_{nb} a_{nb} \phi_{nb} + b \]  

where \( a_p \) is the coefficient at the cell center for the variable \( \phi \), the subscript \( nb \) refers to the neighboring cell for coefficients \( a_{nb} \), and \( b \) for the variable \( \phi_{nb} \). The number of coefficients depends on the mesh type and is equal to the number of faces shared with interior neighboring...
cells or exterior cells representing boundary conditions. A complete system results in a set of algebraic equations with a sparse coefficient matrix solved using a point implicit (Gauss-Seidel) linear equation solver with an imbedded algebraic multi-grid (AMG) method.

The AMG solver settings and speed-up in Fluent using the coupled velocity-pressure solution method are the subject of a recent publication by Gilmore et al. (2015a). This paper explores the limitations and benefits of using GPGPUs for mine ventilation research aided by CFD simulations.

The solution variables $\phi$ are computed and stored at the cell centers, $c_0$ and $c_1$, as shown in Figure 5.1, and the face values $\phi_f$ must be interpolated. By default in the porous medium, the solver calculates the solution at every cell face. The upwind scheme interpolation options available in Fluent are first-order, second-order, power-law, Quadratic Upstream Interpolation for Convection Kinematics (QUICK) and third-order Monotonic Upstream-Centered Scheme for Conservation Laws (MUSCL). It is also necessary to compute the gradients and derivatives in the solution process in the convection and diffusion terms in the flow conservation equations. Fluent offers three schemes: Green-Gauss, cell-based; Green-Gauss, node-based and least squares, cell-based.

5.2.2 Fluent Solution Settings

The Fluent solution method settings are given in Table 5.4. The Semi-Implicit Method for Pressure-Linkage Equations (SIMPLE) is used to couple the pressure-velocity field. This sets the solver to use the iterative solution process outlined for the pressure-based segregated algorithm as shown in Figure 3.1.

The default gradient setting in Fluent, least squares cell based, selection is kept. This method assumes the solution varies linearly and the relative accuracy is comparable to the node-based gradient, but less expensive, computationally. The change in a cell value between $c_0$ and $c_1$ (see Figure 5.1) along the position vector between the two cell centroids can be expressed as Equation 5.9

\[
(\nabla \phi)_{c_0} \cdot \Delta r_i = (\phi_{c_i} - \phi_{c_0})
\]  

(5.9)
Table 5.4: Fluent Solution Method

<table>
<thead>
<tr>
<th>ANSYS Fluent</th>
<th>Solution Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure-Velocity Coupling</td>
<td>SIMPLE</td>
</tr>
<tr>
<td>Spatial Discretization</td>
<td></td>
</tr>
<tr>
<td>Gradient</td>
<td>Least Squares Cell Based</td>
</tr>
<tr>
<td>Pressure</td>
<td>PRESTO!</td>
</tr>
<tr>
<td>Momentum</td>
<td>1&lt;sup&gt;st&lt;/sup&gt; Order Upwind</td>
</tr>
<tr>
<td>Turbulent Kinetic Energy</td>
<td>1&lt;sup&gt;st&lt;/sup&gt; Order Upwind</td>
</tr>
<tr>
<td>Turbulent Dissipation Rate</td>
<td>1&lt;sup&gt;st&lt;/sup&gt; Order Upwind</td>
</tr>
<tr>
<td>Species</td>
<td>2&lt;sup&gt;nd&lt;/sup&gt; Order Upwind</td>
</tr>
<tr>
<td>Energy</td>
<td>1&lt;sup&gt;st&lt;/sup&gt; Order Upwind</td>
</tr>
<tr>
<td>Under-Relaxation Factors</td>
<td>Default</td>
</tr>
</tbody>
</table>

Thus, the gradient becomes a function of mesh geometry. The various setting effects on the final solution were determined by Worrall (2012) to have little impact.

The pressure spatial discretization choice is governed by the domination of the domain by a porous media. The recommended setting is PRESTO! (PRESSure STaggering Option), which computes the face pressure as well as the cell pressure. PRESTO! is more computationally intensive, but is required for an accurate solution in porous media flows (Patankar, 1980). The PRESTO! scheme uses the discrete continuity balance for a control volume about the face to compute the pressure. Note that for triangular and tetrahedral meshes, comparable accuracy is obtained using a similar algorithm, and therefore PRESTO! is available for all mesh types.

In Fluent Version 15.0 and greater, PRESTO! is intrinsically used by the solver for all porous media cell zones allowing the user to select a discretization scheme for the remaining fluid zones. Therefore, a first-order, second-order or QUICK scheme can be used in the mine entries to more accurately resolve the solution. PRESTO! was the scheme used for this research as most solutions were obtained using Version 14.5 of the software.

The remaining transport equations are first-order discretization except species. A noticeable difference is observed in the species contour plots between first-order and second-order. A higher order discretization is recommend by Fluent, however, solution stability and con-
vergence issues remain a challenge for future work.

The energy equation may be de-selected as there is no significant heat transfer in the model with the temperature boundary conditions set to 300 K. As observed in final solutions, the temperature ranges from 299.8 K to 300.6 K with no noticeable impact on the other transport equations.

5.2.3 First-order and Second-order Accuracy

The first-order scheme assigns the field variable at the cell faces by assuming the field variable at the cell centroid represents a cell average value. Thus, in a first-order upwind scheme, the face value \( \phi_f \) is equal to the value of \( \phi \) from the upwind cell centroid.

The second-order scheme computes the cell face values using a multidimensional linear reconstruction based on the selected gradient evaluation scheme. Through a Taylor series expansion about the cell centroid, the second-order upwind scheme computes the face value \( \phi_f \) as given in Equation 5.10

\[
\phi_f = \phi + \nabla \phi \cdot \mathbf{r}
\]  

(5.10)

where \( \nabla \phi \) is calculated using Equation 5.9, and \( \mathbf{r} \) is the vector from the upwind cell centroid to the face centroid. For example, \( \mathbf{r}_1 \) as shown in Figure 5.1 when \( c_1 \) is upwind of \( c_0 \).

The solution order of accuracy for first-order and second-order is given in the following Equations 5.11–5.12

\[
\left( \frac{\partial \phi}{\partial x} \right) = \frac{\phi_{i+1} - \phi_i}{\Delta x} + \underbrace{O(\Delta x)}_{\text{Truncation error}} \]  

(5.11)

\[
\left( \frac{\partial \phi}{\partial x} \right) = \frac{-\phi_{i+2} + 4\phi_{i+1} - 3\phi_i}{2\Delta x} + \underbrace{O(\Delta x^2)}_{\text{Truncation error}} \]  

(5.12)

The modeling solution accuracy of mine gas mixtures in large underground bleeder-ventilated gobs varies linearly with the spatial component of the cell size when using the first-order upwind discretization scheme. The scale of the mine is on the order of 4 to 5 miles and the smallest geometric shape is approximated by the shield longwall face model.
shown in Figure 4.6. The mesh face sizing control used to model the shield gaps is one-tenth of a foot and the largest face element size in the center of the gob is 16-feet. As a result, initial solutions have two orders of magnitude linear error from an unknown actual solution. However, as discussed in Chapter 7, this error is significantly reduced through mesh refinement and increases to the second-order scheme.

5.2.4 Solution Approach and Convergence

A steady-state CFD simulation implies that the solution no longer significantly changes with further iterations. Fluent recommends checking the following to determine convergence:

- Discrete conservation equations are solved to a specific tolerance
- Overall mass, momentum, energy and scalar balances
- Decrease in residuals by at least three orders of magnitude
- Energy residual decrease by six orders of magnitude
- Species residual decrease by five orders of magnitude
- Monitor relevant key variables

The specific tolerance to the governing equations is determined by examining the key relevant variable, which in this project is the normalized EGZ size (see Section 5.5). The overall mass balance is reported for all inlets and outlets of the model as $5 \times 10^{-5} \text{kg/s}$, which is four orders of magnitude less than the smallest mass inlet. The momentum and energy balance are not of importance in this simulation as the temperature boundary conditions are uniform and the momentum transfers to a fixed geometry.

Fluent reports the root mean squared average of the global normalized residual to the linearized governing equations in 5.8, where a residual is defined in Equation 5.13

$$R_p = a_p \phi_p - \sum_{NB} a_{NB} \phi_{NB} - b_p$$  \hspace{1cm} (5.13)
which is a measure of how well the linearized system of equations is converged to the solution of the represented non-linear system.

This research solved a steady-state solution using the following process, and then used this solution to re-initialize all following cases. The transport equations are turned on one-by-one and iterated until the residuals convergence criteria are reached. The initial solution for the laminar case is partially solved followed by the turbulent and temperature equations, and then the species transport equations. Figure 5.2 shows this process for 1,500 iterations where the jump in residuals at 300, 700, and 1,000 correspond to each step in the solution approach. The residuals appear steady for species and energy, but further reduction in the velocity and turbulent residuals are needed before a final solution is reached, which is determined by calculating the percent change in EGZ size.

![Figure 5.2: Initial CFD Simulation Residuals](image)

Figure 5.2 shows the residuals starting from a previously solved data set solved for 5,000 iterations more after a change in boundary conditions. These residuals suggest that the convergence criteria can be set to $1 \times 10^{-4}$ for continuity, $1 \times 10^{-5}$ for the velocities, $1 \times 10^{-6}$ for the energy, 0.001 for turbulence and $1.3 \times 10^{-4}$ for the species equations. The solution appears to converge with 1,300 iterations although the EGZ is still changing. Figure 5.4 shows the normalized EGZ and the percent change in EGZ. Using the EGZ as the determining variable for convergence the solution can be considered converged at approximately 3,200 iterations when the percent change in EGZ drops below 0.5%. This process is used for all final results.
of the bleeder-ventilated gob system of Mine E, C and W. The parametric studies presented in the results used only 600 iterations between cases to observe the effects of a parameter.

5.3 Turbulence Modeling

The choice of a turbulent model in studies by Worrall, 2012 is shown to have little effect on the overall change in both the location and size of the EGZ found in the gob. Geometry simplification and the resulting mesh are limiting factors for resolving the effects of turbulence. The boundary conditions and near-wall treatments are selected following the recommendation of the Fluent manuals and Worrall, 2012.
5.3.1 Boundary Conditions

The boundary conditions of the models at the inlets and outlets are match to regulatory conditions when using common ventilation quantities. The model boundaries are at common measurement points for flow quantity and gas concentrations. Therefore, the predicted flow within the model would represent an operational mine to the extent that the geometry and mesh represent the ventilation system.

The inlets are defined as velocity-inlets in Fluent, which sets the flow rates to the measured quantities typically found in bleeder-ventilated gobs. The inlets of the model are the headgate entry supplying air to the face (Point A), the entry on the headgate side supplying air inby the face (air flowing past Point A), tailgate entry supplying air to the face (Point C), and tailgate center entry supplying air inby the face (Point D) as shown in Figure 4.1. Each inlet is set with a velocity magnitude normal to the boundary as listed in Table 5.5. The hydraulic diameter of 4.3 m (14 ft) and turbulent intensity of 3% are calculated from Equations 3.26 and 3.39. The species mole fraction is set for the composition of air as 20.95% oxygen, with the remainder as nitrogen and ignoring the 1% other gases normally contained in air. The outlet of the model is set to a pressure outlet with zero gauge pressure and backflow conditions same as the inlets.

Table 5.5: Inlet Boundary Conditions

<table>
<thead>
<tr>
<th>Name</th>
<th>Velocity, m/s</th>
<th>Air Quantity, m³/s (cfm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>inlet_hg</td>
<td>1.732</td>
<td>35.4 (75,000)</td>
</tr>
<tr>
<td>inlet_hg-entry60ft_y+</td>
<td>0.577</td>
<td>11.8 (25,000)</td>
</tr>
<tr>
<td>inlet_tg</td>
<td>0.231</td>
<td>4.72 (10,000)</td>
</tr>
<tr>
<td>inlet_tg-gentry60ft_y+.1</td>
<td>0.346</td>
<td>7.07 (15,000)</td>
</tr>
</tbody>
</table>

5.3.2 Methane Sources

Methane may come from three main locations: upper or lower coal seams and the seam being mined. This project neglects seam gases produced during active mining; therefore, the
model is simplified to a longwall panel that is complete, or is inactive. The methane source is modeled as an upper rider seam well above the caved zone. The methane must enter the mine ventilation system through the partially intact strata layers above the gob. The rider seam supplies methane from an infinitely larger reservoir that readily refills the cleated coal structure. This is evident as the permeability of the coal seam is orders of magnitude higher than the surrounding strata. As a result, this produces an evenly distributed methane source at the bottom of the rider coal seam.

The methane source may further be simplified by allowing the methane inlet to be moved to the top of the gob, when neglecting the operation of GVBs located in the strata. The choice to locate the methane inlet boundary condition at the top of the gob is further supported when considering the orders of magnitude difference in permeability between the intact strata and the gob. Further consideration of methane sources is discussed by Worrall (2012).

The volume of the methane inlet was calibrated to supply a concentration of 2% methane at the bleeder outlets (Point 1 and Point F), which is the concentration limit in a bleeder entry. The top of the gob has an area of 911,600 m$^2$ (9,812,000 ft$^2$) on a 3,109 m (10,200.0 ft) long panel, with a constant velocity inlet of $1.31 \times 10^{-6} m/s$ producing 119 m$^3$/s (2,530 cfm) of methane. The turbulent conditions are set with the intensity of 0.1% and length scale of 0.35 m, however, the solution is insensitive to the choice of these turbulent boundary conditions.

5.3.3 Turbulent Near-Wall Treatment

The ANSYS Fluent Theory Guide 2014b discusses the equations and use of near-wall treatment, and is summarized in the following section. The highest gradients in the flow solution are often near walls where the no-slip boundary condition must be imposed. Also, the walls serve as the main source of vorticity and turbulent production in the formation of the momentum boundary layer. The geometry modeling, mesh refinement and numerical expense required to fully resolve the solution gradients near walls is beyond most CFD
modeling needs. It is important to accurately predict the pressure drop and turbulent effects produced by modeling fluid flow across walls.

Figure 5.5 shows that the near-wall region flow can be subdivided into three layers plotted on semi-log coordinates where $U$ is the free stream velocity, $U_T$ or $u_\tau$ is the friction velocity as defined as $\sqrt{\tau_w/\rho}$, where $\tau_w$ is the wall shear stress and $y^+ \equiv \rho u_\tau/\mu$ a dimensionless distance from the nearest wall. The three regions are the inner viscous sublayer where the flow is almost laminar, which is dominated by the molecular viscosity; the outer fully-turbulent layer where turbulence is the dominating flow factor; and a buffer layer, or blending region, where molecular viscosity and turbulence are equally important. The use of a semi-empirical formula or wall function to calculate the effects of the viscous sublayer and the buffer layer eliminated the need to fully resolve the flow near the wall. The use of a wall function requires that no grid refinements near the wall allow a $y^+$ value below 15, except when using a scalable wall function.

![Figure 5.5: Subdivisions of the Near-Wall Region (redrawn for clarity) (ANSYS, 2014b)](image)

This research uses the standard wall function to calculate near wall effects. This simplified the modeling of mine entry wall roughness and gob-fringe roughness. The use of a wall roughness of 0.15 m (0.5 ft) and a wall constant of 0.6 for the gob-fringe effectively models the surface of the gob and surface of the gob-fringe with the intact strata, while the mine entries remained the default values of a smooth duct. The momentum equations and species
equations defining the law-of-the-wall in the standard wall function are given in Equations 5.14–5.16. For the mean velocity

\[ U^* = \frac{1}{\kappa} \ln \left( E y^* \right) - \Delta B \]  

(5.14)

where,

\[ U^* \equiv \frac{U_P C_{\mu}^{1/4} k_P^{1/2}}{\tau_w/\rho} \]  

(5.15)

is the dimensionless velocity and

\[ y^* \equiv \frac{\rho C_{\mu}^{1/4} k_P^{1/2}}{\mu} y_P \]  

(5.16)

is the dimensionless distance from the wall, \( \kappa \) is the Carman constant of 0.4187, \( E \) is the empirical constant of 9.793, where the subscript \( P \) refers to the wall-adjacent cell, \( U_P \) is the mean velocity of the fluid at the wall-adjacent cell centroid, \( k_P \) is the turbulence kinetic energy at the wall-adjacent cell centroid, \( y_P \) is the distance from the centroid of the wall-adjacent cell to the wall and \( \mu \) is the dynamic viscosity of the fluid.

The recommended range of \( y^* \) values depends on the overall Reynolds number. The lower limit is always in the order of \( y^* \sim 15 \). The upper limit for high Reynolds number flows can be several thousand, while for low Reynolds number flows it may be as small as one hundred. Therefore, ANSYS recommends avoiding the application of wall functions in low Reynolds number flows, as it limits the overall number of nodes, which may be placed in the boundary layer.

The mathematical form of the slope intercept term, \( \Delta B \) in Equation 5.14 has the following form, \( 1/\kappa \ln f_r \) where \( f_r \) is the roughness function. The form of \( f_r \) is determined by the value of the non-dimensional roughness height given in Equation 5.17

\[ K^+_s = \frac{\rho C_{\mu}^{1/4} k_P^{1/2}}{\mu} K_s \]  

(5.17)

where \( K_s \) is the physical roughness height.

There are three flow regimes: hydrodynamically smooth, transitional and fully rough, modeled by Equation 5.18
\[ \triangle B = \begin{cases} 
0, & \text{for } (K_s^+ \leq 2.25) \\
\frac{1}{\kappa} \ln \left[ \frac{K_s^+ - 2.25}{87.75} + C_s K_s^+ \right] \sin \left[ 0.4258 \left( \ln K_s^+ - 0.811 \right) \right], & \text{for } (2.25 \leq K_s^+ \leq 90) \\
\frac{1}{\kappa} \ln \left( 1 + C_s K_s^+ \right), & \text{for } (K_s^+ > 90) 
\end{cases} \] (5.18)

where \( C_s \) is the roughness constant depending on the type of roughness modeled. The roughness constant has the default value of 0.5 for uniform roughness of sand-grains and may range up to 1 for non-uniform roughness.

 Fluent uses the law-of-the-wall for mean velocity and temperature, which is based on \( y^* \) a more robust calculation, rather than \( y^+ \) values. The log-law is used from \( y^* > 11.225 \) values, and when the node has a \( y^* < 11.225 \) then the laminar stress-strain relationship of \( U^* = y^* \) is applied.

For species transport the wall function is calculated using Equation 5.19

\[
Y^* \equiv \frac{(Y_{i,w} - Y_i) \rho C_\mu^{1/4} k_p^{1/2}}{J_{i,w}} = \begin{cases} 
Sc y^*, & \text{for } (y^* < y_c^*) \\
Sc \left[ \frac{1}{\kappa} \ln (E y^*) + P_c \right], & \text{for } (y^* > y_c^*) 
\end{cases} \] (5.19)

where \( Y_{i,w} \) is the mass fraction of species \( i \) at the wall, \( J_{i,w} \) is the diffusion flux of species \( i \) at the wall and \( P_c \) is computed by using the Jayatilleke formula for species for smooth walls in given in Equation 5.20

\[
P_c = 9.24 \left( \frac{Sc}{Sc^l} \right)^{3/4} \left[ 1 + 0.28 e^{-0.007 Sc/Sc^l} \right] (5.20)
\]

The non-dimensional species sublayer thickness, \( y_c^* \) is evaluated at the \( y^* \) value where the linear law and logarithmic law intersect for the molecular Schmidt number of the fluid.

For rough walls the \( P_c \) function in Equation 5.20 is modified to Equation 5.21

\[
P_{c,\text{rough}} = 3.15 Sc^{0.695} \left( \frac{1}{E'} - \frac{1}{E} \right)^{0.359} + \left( \frac{E'}{E} \right)^{0.6} P_c \] (5.21)

where \( E' \) is the wall function constant modified for rough walls as defined by \( E' = E/f_r \).

The turbulence values in the wall function are computed by solving the whole fluid domain with the following boundary condition at the wall, \( \partial k/\partial n = 0 \) where \( n \) is the local coordinate normal to the wall. The source terms in Equation 3.28 and 3.29 for the production of kinetic
energy and the dissipation rate are calculated with the local equilibrium hypothesis with the assumption that they are equal in the wall-adjacent cell. The kinetic energy production is calculated by Equation 5.22

\[ G_k \approx \tau_w \frac{\partial U}{\partial y} = \frac{\tau_w}{\kappa \rho C^1_{\mu}^{1/4} k_P^{1/2} y_P} \] (5.22)

and the dissipation rate is computed by Equation 5.23

\[ \varepsilon = \frac{C^{3/4}_{\mu} k_P^{3/2}}{\kappa y_P} \] (5.23)

The wall boundary conditions used are summarized in Table 5.6. The application of the roughness coefficients to the gob-fringe wall requires that the interface between the crosscuts and the gob-fringe be created, then the remaining wall not in contact with a crosscut surface is assigned the wall boundary conditions. The surface roughness on the interface between the gob, a porous media, and the gob-fringe, a fluid zone, is accounted for in the roughness applied to the gob-fringe wall. The mine entries’ walls are considered smooth. Although to properly model the actual pressure drop across a mine entry, a more complete geometry and roughness would have to be considered. The simplified modeling of the longwall face (as discussed in Section 4.2.3) requires a generalization for the mine entries.

<table>
<thead>
<tr>
<th>Wall</th>
<th>Roughness Constant</th>
<th>Roughness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>Gob-fringe Walls</td>
<td>0.6</td>
<td>0.15</td>
</tr>
</tbody>
</table>

### 5.4 Gravity

The effects of buoyancy of the source term \( G_b \) in the turbulent production equation and in turbulent dissipation rate equation (see Equations 3.28 and 3.29) forming a species separation gradient within a porous media are not fully understood. Attempts to activate gravity in the simulations resulted in un-converged cases. A simple two-dimensional flow simulation suggests that a flow separation will be produced with gravity enabled, but when disabled,
the species gradient becomes dispersed. A U-type ventilation simulation with gravity one-
thousandth of a G, results in the expected flow separation between methane and air. The
methane gradients in the upper layers are most affected, but no difference is noticeable near
the mine floor where results are of primary interest.

The effects of gravity in the mine ventilation system are known to produce a separation
layer between the unmixed methane gas and air at sufficiently low air velocities.

The effects of gravity within the porous media of the gob are not well understood. Fur-
thermore, the turbulent equations solved on the appropriate mesh size for a valid porous
media model assumption fail to resolve the separation layer when applying the superficial
velocity formulation and neglecting the inertia resistance term. A solution might be attain-
able with the inclusion of these models, but this is beyond the scope of this dissertation.

The effects of gravity in the gob can be separated into three cases: the formation of a
stable separation layer trapping unmixed methane near the top without the addition of more
methane; the influx of a sufficient amount of methane to overwhelm the development of a
separation layer; and the development of a highly unstable, turbulent separation layer at low
methane concentrations. This third case is more realistic and likely in the mine ventilation
system based on two-dimensional simulations.

The large, three-dimensional models in this application simplify the methane inlet source
as a constant velocity inlet. This fixes the ratio of methane to air in the model to a mole
fraction of 2% methane. A summary of this modeling choice is discussed by Worrall (2012);
the incoming methane velocity has two components as given in Equation 5.24:

\[ V_{\text{methane}} = V_{\text{pressure}} - V_{\text{density}} \]

where \( V_{\text{methane}} \) is the actual velocity inlet of methane into the mine, \( V_{\text{pressure}} \) is the velocity
developed from the pressure driven flow governed by Darcy’s Law and \( V_{\text{density}} \) is the velocity
driven by the density gradient. A linear approximation of the contribution, which the density
gradient has on the inlet velocity within the strata layer, can be simplified using a finite
difference of Darcy’s Law as given in Equation 5.25:
\[ V_{density} = \frac{k}{\mu} \cdot \frac{\Delta \rho g}{\Delta h} \quad (5.25) \]

where \( k \) is the permeability of the strata (with a uniform porosity of 10\%), \( \mu \) is the viscosity of air, \( \Delta \rho \) is the density difference between air and methane, \( g \) is the gravitational constant and \( \Delta h \) is the strata height from the top of the gob to the rider coal seam, 28 m (92 ft).

\[
V_{density} = \frac{2.9 \times 10^{-16} m^2}{1.71 \times 10^{-5} Pa \cdot s} \cdot \frac{(1.225 kg/m^3 - 0.668 kg/m^3)(9.81 m/s^2)}{28 m} = 3.3 \times 10^{-12} m/s \quad (5.26)
\]

The Equation 5.26 equates to six orders of magnitude lower than the 1.31 \times 10^{-6} m/s, defined as inlet velocity at top of the gob. Fixing the mass flow rate would result in an artificially increased density, and therefore increased pressure at the top of gob, as illustrated in Equation 5.27

\[
\dot{m} = \rho V_{methane}A = \uparrow \rho \downarrow V_{pressure}A \quad (5.27)
\]

Following this analysis, the effects of gravity would be localized, compressing the concentration gradients and resulting in the thinning of EGZ zones near the top of the gob. The effects would further be diminished near the plan view height chosen for result comparisons.

### 5.5 Explosive Gas Zone (EGZ) Mixture Analysis

An algorithm originally developed by Worrall, 2012 is used to combine the results of methane and oxygen concentration in each cell into one easily readable data point. The algorithm based on Coward’s triangle, shown in Figure 5.6, characterizes the mixture and assigns a value corresponding to the appropriate color zone. The color zone classifications are below:

- **Blue** – a cell that may become explosive
- **Yellow** – a cell capable of forming an explosive mixture if diluted with air
- **Green** – a cell not capable of forming an explosive mixture with air (dark green indicates a zone inert to the spontaneous combustion process and not studied in this research)
• Red – a cell that is explosive

• Orange – an arbitrary buffer zone surrounding the red explosive zone

This algorithm aides in the identification of the presence, location and size of EGZs in order to compare results. Figure 5.7 shows a diagram of the algorithm’s use, combining the oxygen concentration and methane concentration into one plot. A thin sliver of EGZ (red) can be identified as being surrounded by an orange buffer zone. An examination of EGZ plots reveals the presence and location of EGZs for comparison.

The resulting size of the EGZ is calculated by assigning a value of 1 to each red cell followed by integrating the total volume of the cell and multiplying by the porosity to calculate the total EGZ gas volume. A normalized EGZ volume is then used to compare the effects of a given parameter on the overall trend, where it is assumed that an actual mine follows the same trends identified in the model. This approach addresses the potentially large variation in mine characteristics and uncertainty in boundary conditions.

Figure 5.6: Color Coded Coward’s Triangle – Modified after (Coward & Jones, 1952)
5.6 Model Result Post Processing

The CFD results are compared on a plan view plane located 1.5 m (5 ft) from the mine floor, which is roughly half the coal seam thickness. The plane passes through all mine entries in order to evaluate the trend in the location of an emerging EGZ. Also, this is the most common location of methane concentration measurements made by mine workers. The results of the simulations are plotted on this plane for the following: oxygen, methane, nitrogen, EGZ, pressure, porosity and resistance (the inverse of permeability). In addition, the area-weighted average of the methane mole fraction and pressure are reported at each inlet, outlet and the plane across the regulators (Point 2 in Figure 4.1). Also the mass flow rate, volumetric flow rate and EGZ volume integral are reported.

5.7 Running on the CSM Mio Supercomputer

The CFD model size is approximately 15.8 million cells and it requires a large amount of memory to solve. Parallel processing and domain partitioning on a multi-node supercomputer architecture are required to solve these models. The NIOSH funded research project
has acquired licensing for four 8-core nodes and two 12-core nodes on the supercomputer research group shared platform, Mio, at CSM. To meet the memory requirement, it is recommended to use the four 8-core nodes with 48 GB of RAM installed, or six 8-core nodes, borrowing time on two additional nodes. The two 12-core nodes with 24 GB of RAM installed are insufficient to complete the final iterations of a converged solution.

5.7.1 SLURM Job Scheduler

The administration of a supercomputer with a job scheduler allows multiple users on a single system to access a large number of resources. CSM has phased out the most common scheduler, Portable Batch System (PBS) with the purchase of two new supercomputer platforms and replaced it with a Simple Linux Utility for Resource Management (SLURM).

5.7.2 GoFluent Usage

A Fluent software custom startup script, GoFluent, was developed in this research to organize results into unique folders, minimize file system space, select the number of nodes and processors, select the job run time and then output the batch startup script and submit it to the SLURM job scheduler. GoFluent takes the following four parameters: number of nodes, number of processors, journal file name and the maximum job run time. A unique SLURM job number folder and files are then created in the user’s working Fluent job name directory. See Appendix D for more detailed information.
CHAPTER 6
MODULAR MESHING APPROACH

This chapter discusses the details of a 2015 paper describing the modular meshing approach developed in this research, published by Gilmore et al., 2015c. The mesh is created with the ANSYS Meshing software in modular parts in order to maintain high quality and low skewness.

The cut-cell meshing method is applied to the gob, with the remaining parts free meshed according to edge and face sizing controls, mapped face controls, and where applicable, match face control for repeated interfaces. Using this approach, the geometry sections are individually meshed using custom controls to achieve a minimum quality of 0.20 and a maximum skewness of 0.85. The mesh used to solve the transport equations affects the accuracy of the solution and the computational time required to converge a solution. Each part has an origin, identified in the Section 4.2, that is translated and rotated into place to complete the fluid domain of the final mesh. Using this method, the mesh files are reused, reducing the need to store large case files. This also eliminates the need to have computers capable of re-generating the entire, larger mesh domain files every time a geometry change is made, which can take days to execute.

The modular meshing approach creates greater control and flexibility over the standard approach. The standard approach involves representing the fluid domain with a complete geometry model. The only requirement is the creation of a separate fluid zone for the porous media; multiple geometries can be interfaced within ANSYS Meshing software not visible to the Fluent solver. ANSYS Meshing software creates a mesh for each geometry part, one after the other, using the previous interfacing part as the input to the next. The advantage is the creation of conformal mesh interface boundaries between parts, however, the non-conformal algorithm used in Fluent is suitable enough for most interfacing modules.
6.1 Mesh Creation Cycle

The modular meshing approach produces solvable mesh files that can easily be adjusted or augmented. The modular meshing of individual, interfacing mesh modules permits quick geometry changes without re-meshing and rebuilding entire models. This results in greater control over the resulting mesh quality and skewness; the pre-meshed modules guarantee a consistent mesh quality. Figure 6.1 shows the model design process, beginning with the creation of individual mesh modules, which are assembled to create the full mesh. Each new module is added to the mesh module library from which the modeler can choose the required components to match the desired mine geometry. The full assembly of modules creates the CFD mesh for the complete computational domain solved by Fluent. Mesh modules can be stretched or compressed within certain bounds to approximate a match for the mine entry geometry. The mesh assembly can be adjusted to match a variety of entry dimensions and configurations. This meshing approach ensures flexibility when changing a geometry or ventilation control for the next modeling task. The user simply removes the module to be changed, and either replaces it with a suitable module from the library or creates a new one.

![Figure 6.1: Mesh Creation Cycle](image)

This process takes advantage of the newly released Fluent Version 16.0, released in 2015, which has Multiple Upstream Mesh systems. Figure 6.2 shows multiple geometries meshed...
individually and connected to a single Fluent solver. This allows completion of a parametric study when only part of the domain needs to be updated. In addition, the meshing mode in Fluent can run a journal file of pre-defined commands to create the mesh assembly. The final mesh assembly consists of the parts shown in Figure 4.2 to create the domain of a bleeder panel with 46 crosscuts similar to Figure 1.6.

A modular meshing approach allows the domain to be meshed using multiple techniques. The cut-cell mesh assembly option creates large domains of ideally shaped hexahedron cells or cubes. The general approach creates tetrahedrons, prism or wedge cells, and may convert these into hexahedrons frequently resulting in some level of skewness. Figure 6.3 shows the use of the two techniques applied to the gob (right) and a mine entry (left). The mine entries contain one layer of inflation that forms wedge cells and forms tetrahedrons in the center. This resolves the boundary condition applied at the wall and turbulence in the center. The gob is meshed with the cut-cell method, which produces only hexahedrons in the center, and slightly skewed cells near the angled edges at the gateroads.
6.2 Mesh Modules

The mesh modules for each geometry section use unique controls to maintain the quality and skewness of mesh. Each mesh file is saved in Fluent mesh file format. The following sections discuss the mesh and metrics for each module used in assembling the bleeder panel.

6.2.1 Gob

The gob mesh consists of two different sections. The main section uses the cut-cell method with 0.3 m (1 ft) face sizing on the interfaces to the gob-fringe mesh, while the 61 m (200 ft) gob section behind the face uses a mesh control method for hexahedrons. Figure 6.4 shows a view looking at the top of the mesh, where the cells at the center have 4.9 m (16 ft) edges and edge size steps down towards the gateroad edges to 0.3 m (1 ft). Also, the effects of the 0.3 m (1 ft) body of influence shown previously in Figure 4.10(a) can be clearly observed. The total number of cells is 2.6 million in a single 1,500 m (5,000 ft) module.

The 61 m (200 ft) gob section, shown in Figure 4.11, uses the same 0.3 m (1 ft) face size control on the interface to the headgate gob-fringe. Figure 6.5 shows the resulting mesh
from the applied methods with 96,000 cells. The minimum quality is 0.42 and the maximum skewness is 0.23 as shown in the mesh statistics distribution in Figure 6.6.

### 6.2.2 Headgate

The headgate mesh with the shield leakage gaps to the headgate gob-fringe uses the cut-cell method with a 3.8 cm (0.125 ft) face sizing control on the interface to the gob-fringe. Figure 6.7 shows the location of these controls and the applied edge sizing of 11-divisions in the height and 20-divisions across the entry width. The resulting mesh appears well formed from the cut-cell methods, and Figure 6.8 confirms this with a minimum quality of 0.40 and maximum skewness of 0.72 as shown in the mesh statistics, which meets the excellent standard for meshes. The total number of cells is 30,000.
Figure 6.5: Gob Shaped for Back Return Gob-fringe – Mesh

Figure 6.6: Gob Shaped for Back Return Gob-fringe – Mesh Metrics
Figure 6.7: Headgate – Mesh

Figure 6.8: Headgate – Mesh Metrics
6.2.3 Longwall Face

The longwall face uses the cut-cell method, with the leakage gaps interfacing to the gob, and the same 3.81 cm (0.125 ft) face sizing controls as the headgate, with the maximum size cell set to 0.3 m (1 ft). Figure 6.9 shows the resulting mesh of the face module with a total of 460,000 cells. The minimum quality is 0.40 and the maximum skewness is 0.72. The distribution shown in Figure 6.10 clearly meets the excellent standard for meshes.

![Face Mesh](image)

Figure 6.9: Face – Mesh

6.2.4 Entries – 60-Feet and 220-Feet

Each entry section has similar mesh controls and the resulting mesh. Two are shown for comparison, but a third entry section of 33.5 m (110.0 ft) in length is for the tailgate entry interfacing to the back return gob-fringe. Figure 6.11 shows the 18 m (60.0 ft) entry section that is used as the initial module in the tailgate and headgate bleeder entries series of mesh modules. There are 9-divisions in the height and 15-divisions in the width. A single layer of inflation is shown on the wall with a mapped face mesh control. The resulting mesh has a minimum quality of 0.22 and maximum skewness of 0.84, with a good distribution, as shown in Figure 6.12. The mesh uses tetrahedral cells in the center with wedge shaped cells in the layer of inflation. The total number of cells is 20,849.
Figure 6.10: Face – Mesh Metrics

Figure 6.11: 60-feet Entry – Mesh
Figure 6.13 shows the resulting mesh of a 76 m (220 ft) entry with a total cell count of 76,000 using the same controls as the 18 m (60 ft) entry. The mesh metric distribution is shown in Figure 6.14 with a minimum quality of 0.21 and a maximum skewness of 0.85. This demonstrates that the controls set for both length entries are easily scalable to any length entry. A parameter can be defined for the division number in the length and geometry length and set equal to each other, with an average count of 1,000 cells per meter (or 345 cells per foot). The average quality of the wedge cells is 0.4, and 0.8 for the tetrahedral cells, reaching the good standard for meshes. The wedge cell average skewness is 0.38, and 0.3 for the tetrahedral cells, which meets the good standard for meshes.

6.2.5 Crosscuts

The crosscut mesh uses the same controls as the entries with 9-divisions in height and 15-divisions in width, mapped face controls on the walls and one layer of inflation. Figure 6.15 shows the resulting mesh with these controls. The total number of cells is 8,500 with a minimum quality of 0.20 and a maximum skewness of 0.86. Figure 6.16 shows the mesh.
Figure 6.13: 220-feet Entry – Mesh

Figure 6.14: 220-foot Entry – Mesh Metrics
metrics distributions for the wedge and tetrahedral cells. The average quality for the wedge cells is 0.25 and 0.61 for the tetrahedral cells, which meets the fair standard for meshes. The average skewness is 0.62 and 0.43 for the wedge cells and tetrahedral cells, respectively, which meets the good standard for meshes.

Figure 6.15: 50-feet Crosscut – Mesh

6.2.6 Gob-fringe or Voids

The gob-fringe is meshed as a single 3000 m (10,000.0 ft) module. Figure 6.17 shows the resulting mesh with 4-divisions at the top and bottom and 42-divisions in height. The length in feet is equal to the number of divisions in its length. Using these controls, the face cell size is approximately 1-foot on the interfaces to the crosscuts and gob. Figure 6.18 shows the mesh statistics for quality and skewness. The minimum quality is 0.28 with an average of 0.68, and the maximum skewness is 0.52 with a total number of cells of 1.7 million, at 550 cells per meter (170 cells per foot) of gob-fringe. The skewness distribution clearly meets the good standard.
Figure 6.16: 50-feet Crosscut – Mesh Metrics

Figure 6.17: 10,000-foot Gob-fringe – Mesh
6.2.7 Back Return Gob-fringe

The back return gob-fringe mesh uses a tetrahedral meshing approach. The module interfaces with the 3000 m (10,000.0 ft) gob-fringe module and has matching dimensions. Figure 6.19 shows the resulting mesh employing 28-divisions on the bottom and 11-divisions at the top. The height uses the same 42-divisions as the gob-fringe, and the mesh results show the cell size increasing towards the center. The mesh statistics for quality and skewness are shown in Figure 6.20. The minimum quality is 0.22 with an average of 0.83, and the maximum skewness is 0.79 with an average of 0.24. The total number of cells is 130,000. The skewness and quality distribution meet the excellent standard.

6.3 Mesh Assembly

Once each geometry section is meshed with acceptable mesh quality metrics, the section is assembled into the final representation of the fluid domain. Each module’s surfaces, interior zone, and interfaces are given a unique identifier. Interface definitions are assigned to pairs or sets of faces. The origin point is then translated or rotated in preparation for the input
Figure 6.19: Back Return Gob-fringe – Mesh

![Mesh Image]

Figure 6.20: Back Return Gob-fringe – Mesh Metrics

![Metrics Graphs]

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of the next module into the domain. This process is repeated until the mesh is completely assembled.

A code, developed in Matlab, automates journal file creation for a network of multiple entries and crosscuts for use on the headgate or tailgate sides of the panel (see Appendix C). This is a significant timesaver as the process becomes exceedingly time intensive if it must be completed by hand for the needed 46-entries and crosscuts of the 3,109 m (10,200.0 ft) bleeder model for both the headgate and tailgate sides. Once a network is completed for the headgate side of the panel, the case file is saved and the tailgate side is assembled with a reverse modular build of the parts. These two case files are then added to a case file containing the completed gob modules. Each major interface between the gob-fringes and the gob is assigned and checked visually in Fluent for a properly paired interface.

During this process, ANSYS recommends that Fluent be started in serial mode to avoid a race condition in the parallel processing environment, which may result in a corrupt mesh file. The newly developed Meshing Mode in Fluent Version 15.0 may be stable in a parallel environment, but is untested at the time of this research. Also, Fluent Version 16.0 employing multiple upstream mesh designs will be more common, and the stability of parallel reading and assembly of mesh files will be more stable in the future.

As a part of this research, a custom computer, designated as Azaghal.mines.edu, was built with the most current hardware technology for maximum single threaded performance processing. Running solid-state hard drives and the maximum memory for use on a single CPU, the computer is ideal for mesh creation, mesh assembly, and post-processing results. For large case and data files, it is still preferable to use the Mio compute004 node for mesh assembly or post-processing; it runs with 192 GB of RAM installed.

6.3.1 Bleeder-ventilated Gob Mesh

The bleeder-ventilated gob mesh includes a gob from the longwall face to the startup room, one entry on either side of the gob, and one entry inby from the startup room. Figure 6.21 features the highlighted area represented by the geometry and then assembled
from the mesh modules into the final mesh.

Figure 6.22(a) shows a view of the tailgate side of the panel looking at the back return. The two gob mesh modules are shown with the refined back return module just behind the face followed by the 1520 m (5,000.0 ft) module. Inlets are shown in blue, interfaces in yellow, and wall boundaries in white. Figure 6.22(b) shows a view of the startup end of the panel. The two points on the headgate side are labeled as the headgate regulator (Point 1) and the crosscuts into the startup room (Point 2). The pressure outlet of the model is shown red on the tailgate entry side. Figure 6.22(c) shows a view of the entries, crosscuts, gob-fringe and the gob. Each entry is interfaced to the next and one crosscut. All the crosscuts are interfaced to a single face on the gob-fringe, on each side of the panel.
Figure 6.22: View of Completed Bleeder Mesh
CHAPTER 7
MODEL VALIDATION

This chapter discusses validation of the model. The first section presents a comparison to a tracer gas study that calculates the velocity in the gob. The next section examines ventilation layout changes made possible by the modular mesh approach; and the final section presents the results of mesh refinements through adaptation.

7.1 Gob Air Flow Velocity

Exact values of the velocity in the gob are unknown and must fluctuate greatly between mines due to variance in gas emission rates and gob flow characteristics. However, it is worth examining a comparison between experimental results taken at an Eastern United States mine and the predicted values from the CFD simulation.

The analysis of a tracer gas study results yields the average gas velocity between two points. This is calculated by the differential in release time to the first detected presence of the tracer gas and the shortest estimated distance the gas may travel. The tracer gas study by Diamond et al. (1999), conducted in a coal mine located in the Pittsburgh Coalbed in Greene County, PA injected a tracer gas into an in-taking GVB. Figure 7.1 shows the longwall panel test area of Test 3-1, where the GVB G3 is used as the point of injection. The GVBs are located 76 m (250 ft) from the tailgate side of the panel. The analyses of the results are published by Mucho et al. (2000), and a summary of Test 3-1 is given in Table 7.1. The calculated velocity from G3 to G2 is 0.008 m/s (1.5 ft/min) and from G3 to G1 is 0.004 m/s (0.7 ft/min).

Figure 7.2 shows the CFD simulation results of the velocity magnitude on a log scale. The velocities in the gob range from $3 \times 10^{-4} \text{ m/s}$ and $7 \times 10^{-3} \text{ m/s}$ (0.06 ft/min and 1.4 ft/min) with higher velocities reported near the face. The tracer gas injection point, G3, is located about 380 m (1,250 ft) from the face, corresponding to about 5.7 crosscuts spaced at 67 m
Figure 7.1: Detailed Map of F,G, and H Longwall Panel Area at Time of Borehole Injection Experiment, Test 3-1 (Diamond et al., 1999)

Table 7.1: Tracer Gas Results of Test 3-1

<table>
<thead>
<tr>
<th>Flow Path</th>
<th>Distance, m (ft)</th>
<th>First Arrival Time, min</th>
<th>Velocity, m/s (ft/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G3–G2</td>
<td>762 (2,500)</td>
<td>1,621</td>
<td>$8 \times 10^{-3}$ (1.5)</td>
</tr>
<tr>
<td>G3–G1</td>
<td>2,073 (6,800)</td>
<td>10,436</td>
<td>$4 \times 10^{-3}$ (0.7)</td>
</tr>
<tr>
<td>G3–BF2</td>
<td>NA</td>
<td>30 days</td>
<td>NA</td>
</tr>
</tbody>
</table>
(220 ft). The location of G2 is 1,143 m (3,750 ft) from the face, approximately 17 crosscuts from the face. The average velocity magnitude along this path is $6 \times 10^{-4} \text{m/s}$ (0.12 ft/min). Diamond et al. (1999) also reported that the tracer gas was detected at the second bleeder fan (BF2) 5 days after G2 went offline on day 25 of the test. The distance from the GVB locations, where the tracer gas remained, to the ventilation system is 67 m (250 ft), which equates to a velocity of $2 \times 10^{-4} \text{m/s}$ (0.04 ft/min).

Although not a direct comparison to the mine being modeled, the Eastern United States coal mine measurements in an inactive panel comes within a factor of 2 to 7 of the CFD simulation results. This comparison of velocities indicates that the CFD results are within reason given that the unknown permeability may have a range between one to two orders of magnitude.

### 7.2 Multiple Geometry Meshing Options and Capability

This section illustrates the use of the modular meshing approach used in assembly of different mine ventilation network geometries. The studies include multiple panels, single panels, and partial panels for progressively sealed gobs using U-type ventilation, with and without a back return, and with changes in nitrogen injection locations.

Figure 7.3 shows the ventilation network layout using two adjacent panels, where a single bleeder fan outlet draws air through the ventilation network. The panel headgate supplies 47 m$^3$/s (100,000 cfm) from which 33 m$^3$/s (70,000 cfm) is supplied to the face. At the tailgate, the ventilation system uses an H-type bleeder system, adding additional air at the tailgate at Point E and C of 4.7 m$^3$/s (10,000 cfm) and 7.2 m$^3$/s (15,000 cfm), respectively. The startup room and crosscut are wide-open with a moderate restriction placed at Point G, passing 12 m$^3$/s (25,000 cfm) into the bleeder entries and directs the remaining air flow across the startup room. The gob flow characteristics are that of Mine W with the startup room mirroring the recovery room in the completed panel.

The oxygen concentration of the adjacent bleeder panel model is seen in Figure 7.4. The inactive panel has a significant portion with high oxygen ingress, while the shorter active
Figure 7.2: Velocity – Mine E
Figure 7.3: Multiple Panel Bleeder-ventilated Gob Layout with Air Flow in m$^3$/s
panel has high oxygen ingress up to 500 m (1,640 ft) in by the face. Figure 7.5 shows a single panel H-type bleeder-ventilated gob layout with balanced methane concentrations at the measurement points. The flow across the startup room is restricted at Point 2 to 8 m$^3$/s (17,000 cfm) and Point 1 to 9.4 m$^3$/s (20,000 cfm), with the remainder being forced through crosscuts out by the startup room. The single panel ventilation layout is discussed further in relation to the formation of EGZs in Chapter 8.

Figure 7.4: Oxygen Concentration for Multiple Panel Bleeder-ventilated Gob – Mine W

Figure 7.5: Oxygen Concentration of a Bleeder-ventilated Gob with 9.4 m$^3$/s (20,000 cfm) at Point 1 and 8 m$^3$/s (17,000 cfm) at Point 2 – Mine W

Figure 7.6 shows the modeling of a progressively sealed gob by using a shortened panel and supplying nitrogen at injection points. Figure 7.6(a) shows the oxygen concentration results of a U-Type progressively sealed gob with nitrogen injection. Figure 7.6(b) shows a back
return model with the face air directed one crosscut in by the face. The back return ventilation pattern increases oxygen concentration directly behind the tailgate side as compared to the U-Type ventilation pattern. These results were published by Marts et al. (2014a) and Gilmore et al., 2015c to develop the larger bleeder panel models.

Figure 7.6: Oxygen Concentration of a Progressively Sealed Gob with Nitrogen Injection and Gob Ventilation Boreholes – Mine C (Gilmore et al., 2015c)

Figure 7.7 shows a progressively sealed gob ventilation pattern with increased panel length and multiple possible nitrogen injection points on the headgate side (Marts et al., 2015). The comparison between progressively sealed gobs without nitrogen injection (left) and with nitrogen injection (right) shows that the development of an EGZ can be eliminated with a balanced back return flow and the correct selection of headgate nitrogen injection locations. This forms a “dynamic seal” of low oxygen concentration incapable of forming an explosive mixture before transitioning to a breathable concentration closer to the face.

Figure 7.8 shows another step towards continually refining the modular pieces composing the fluid domain of the longwall simulation. Individual shields spanning the longwall face are created to more effectively model the pressure drop and turbulent nature of the flow.
This creates a series of individual shield modules that interface with the next shield, with the porous media of the gob and open fluid zone of the gob-fringe. Results using GPGPU processing published by Gilmore et al., 2015a revealed that a more complex turbulent model could be used, which models the transitional and turbulent flows to take advantage of GPGPU speed up in Fluent.

The results in this section illustrated the variety and scale of modeling made possible by using a modular meshing approach. Using modules increases the attention to detail of the mesh controls to match the geometry during mesh creation and to better match the flow with the expected simulation solution. Also by using the modular meshing approach, the controls can easily be adjusted to meet the good quality mesh metric, which ensures a more stable solution and faster solution times. Once a complete modular mesh is assembled to represent the fluid domain and an initial first-order solution is obtained, then the process of refinement through mesh adaptation can be used to increase accuracy. The next section discusses the results of mesh adaptation and refinement.
7.3 Mesh Independent Study

A mesh independent study was conducted by using mesh adaptation in two stages. The first stage marked the cells for refinement based on the solution gradients of turbulence, pressure and species. The second stage marked all the cells with a volume greater than 0.24 m$^3$ (8.5 ft$^3$) for refinement. The adaptive mesh refinement is limited by the available memory on the supercomputer node and since the initial mesh contains polyhedral cells not capable of adaptation. The polyhedral cells are found in the gob where the cell size transitions from one size to another within the cut-cell method meshing zones and in the face module near the shield gaps. In addition, mesh refinement is limited by the porous media model assumption that the mesh size must be greater than the particle size, as discussed in Section 2.2. The first stage of the study doubled the cell count from 16 million to 32 million cells and the second stage from 32 million to 39 million cells, at which point computational limitations occurred. The following results used Mine E gob flow characteristics to evaluate solution mesh dependence.

Figure 7.9 shows the results of velocity magnitude using the initial mesh plotted with smooth interpolation between cells. The two insets on the right of the figure magnify a view of the headgate (bottom) and tailgate (top) near the face. These insets show the face air
turning the headgate corner, the air as it passes through each approximated shield gap and
the air turning the corner into the back return on its way to the tailgate center entry. The
sharp edges of velocity in the gob on the startup and recovery ends of the panel are clearly
the result of the body of influence shown in Figure 4.10 and the resulting mesh refinement
in Figure 6.4. The inset on the bottom of the figure shows a detailed view of the cell edge
size transitions from 0.3 m to 4.9 m (1 ft to 16 ft). This also shows the high velocity within
the gob-fringe zone next to the gob and air flow in the headgate center entry. The two insets
on the left of the figure show the startup room on the headgate side (bottom) and tailgate
side (top). The majority of the air flows out of the tailgate center entry to the bleeder fan
with the regulated flow at Point 1.

Figure 7.10 shows the mesh after the first stage of refinement where the resulting velocity
plot was shown in Figure 7.2. The mesh is adapted at the corners where the air changes
direction, in the center of the gob where large species gradients occur, and near the shield
gaps. Also in many places the layer of inflation is refined, which requires the scalable wall
function discussed in Section 5.3.3. The resulting velocity plot is smoother in the gob near
the startup room and recovery ends, and the minimum velocity magnitude in the gob has
changed.

Figure 7.11 shows the mesh after the second adaptation when all the cells having a volume
greater than 0.24 m³ (8.5 ft³), which can change do. This adaptation is then followed by
another refinement using turbulent solution gradients. Figure 7.12 shows the velocity results
using this mesh, but the resulting solution is unconverged in turbulence. This can be seen by
an examination of the velocity results in Figure 7.12 near the face as compared to Figure 7.2.
The stabilization of the recirculation zone as the face air turns the corner at the headgate
is yet unresolved. This is the result of the adaptation being limited by polyhedral cells near
the shield gaps.
Figure 7.9: Initial Mesh Velocity Contours– Mine E
Figure 7.10: Adaptation to Mesh using Solution Gradients
Figure 7.11: Second Adaptation of the Mesh
Figure 7.12: Velocity Contours using the Second Adaptation of the Mesh – Mine E
7.4 Discussion of the Darcy Flow Assumption

This section evaluates the validity of including only the first term in Equation 3.45 to calculate the flow through the porous medium. Using a custom-field-function to calculate a Reynolds number (Ward, 1964) (see Figure 2.3) is given in Equation 7.1

\[
Re_K = \frac{\rho \times |V|}{\sqrt{\text{Resistance}} \times \mu_{\text{laminar}}}
\]  

(7.1)

This Reynolds number is plotted from the solution of a U-type ventilation scheme in Figure 7.13 with and without the application of the inertia resistance term. The maximum value without the inertia resistance term is 10, which is well past the Darcian flow regime and with the inclusion of this term the maximum value drops to 3, which is just outside the bounds of this regime. The effects are located in an area behind the shields where the shield gap assumption has been implemented, and further mesh details would need to be included before arriving any conclusion.

![Image](image_url)

Figure 7.13: Inertia Resistance Effects for U-Type Ventilation

Figure 7.14 shows the results of the Reynolds number from the Mine E bleeder-ventilated gob simulation solution. The maximum value is 700 and quickly drops to 2.5 just behind the shields, after which a value of less than one is maintained throughout the remainder of the gob. This suggests the need to refine the shield gap details and to use the inertia
resistance term in the models. Appendix B presents the UDF code to include this term in future modeling efforts.

### 7.5 Porous Media Assumption

This section evaluates the cell length scale versus the pore scale when considering an ideally packed bed of spherical particles. The packing limit of spheres is 0.64, which is the solid particle volume with porosity of 0.36. The assumed mean particle diameter, \( d_p \), used in this research is 0.2 m (0.7 ft) after the work of Wachel, 2012 taken from the research of Pappas & Mark, 1993a that reported mean particle diameters ranging from 0.1 m to 0.3 m (0.3 ft to 1 ft).

Figure 7.15 shows the comparison of different length scales of spherical particles and REV cells. For example, using a 0.2 m (0.7 ft) particle diameter to evaluate the length scales of the REV cell, \( D_1 \), equal to the particle diameter as shown in Figure 7.15 in blue. In a perfectly packed bed of spheres there are two sizes of interstitial spaces. The largest, \( S_2 \), is at the center of the tetrahedron with points as the center of the four intersecting particles, and the smallest, \( S_1 \), is at the center of each of the faces. Therefore, the REV cell would contain one complete pore channel in each direction. The resulting length scale ratio is calculated in Equation 7.2

\[
\frac{D_1 = 0.2 \, m}{p = 0.029 \, m} = 6.9
\]
where the pore size, \( p \) of the S1 interstitial, is 0.029 m. The porous media assumption requires that this ratio be much greater than one (see Section 2.2). In this research, the smallest model cell size in the gob, \( D_2 \), is 0.3 m as shown in Figure 7.15 in grey, and the ratio increases to 10.5.

The calculated porosity behind the shields starts at 50% to 40% depending on the model and rapidly decreases to 30%. The pore size may start out larger than the ideal case, but due to compaction, the pore size decreases to a smaller size. Therefore, the porous media assumption is likely less valid near the face and quickly becomes more valid at an inby location of 30 m to 60 m (100 ft to 200 ft). The effected face area is approximately 1% to 2% of the total model length and would likely have a small effect on the overall development of EGZs that are forming in the gob.
7.6 Validation Conclusions

The CFD simulations run in this research represent coal mines located in the Western United States, which have higher seam heights as compared to coal mines of the Eastern United States discussed in Section 7.1. A velocity difference within an order of magnitude can be considered a reasonable comparison.

The modular meshing approach is shown to be beneficial to the development of the first simulations for many ventilation layouts. Mesh independence using Mine E equation fit is yet to be achieved due to model size and computational limitations. The trends of EGZ development using the assumptions made so far about the geometry of the mine are not likely to change the results with further refinement. Furthermore, it was noted that mesh independence using Mine C equation is observed in the first adaptation with no change in the size or location of the EGZ. This is likely due to lower velocities found in the gob because of greater flow restriction.

Darcian flow in the porous media assumption holds for the majority of the model and breaks down near the face where other geometry assumptions are made. The details of the shield and active face geometry assumptions made in this research have reached the limits of further mesh independence studies and the limits of using the porous media model. Further research is suggested in these areas as discussed in Chapter 10.
CHAPTER 8
EXPLOSIVE GAS ZONES IN BLEEDER-VENTILATED GOBS

This chapter includes discussion of results published by Gilmore et al., 2014, 2015b. These results used the porosity and resistance curve fit used by Worrall (2012), for Mine W (see Section 4.3.5). These results are compared to porosity and resistance curve fits from Mine C and Mine E (see Sections 4.3.2–4.3.3). Also discussed are the importance of the ventilation controls at Point 1 and Point 2, and the bleeder-ventilated gob scheme effectiveness in eliminating the EGZ hazard. The chapter concludes with a discussion on the EGZ hazards that remain in bleeder-ventilated gobs.

8.1 Bleeder-ventilated Gob – Mine W

The following section includes the EGZ results of the CFD simulation of a bleeder-ventilated gob using the Mine W porosity and permeability, and also the development of the ventilation controls necessary to balance the released methane between evaluation points. Furthermore, a simulation of a ventilation reversal on the tailgate entries shows the EGZ approaching the face.

8.1.1 Headgate Side Regulator near the Startup Room at Point 1 – Mine W

Figure 8.1 shows the EGZ results for Cases 1 through 3 that adjust the flow through the regulator at Point 1 with unrestricted flow at Point 2. In Case 1, a stopping is placed at Point 1 as shown in Figure 8.1(a) that directs the flow through the open crosscuts into the startup room and first entry inby (Point 2). This sufficiently dilutes the methane build up in the immediate startup room; however, the fresh air supply is overwhelmed by the time it reaches the tailgate entry, as seen on the left of Figure 8.1(a). In addition, an EGZ is located in the first crosscut outby Point 2 as seen on the right of Figure 8.1(a). Also, by placing a stopping at Point 1, no air is supplied to the bleeder entries outside the model making this
an invalid operating point. Case 2a in Figure 8.1(b) regulates the flow at Point 1 to 9.4 m$^3$/s (20,000 cfm), which is the minimum required flow into two bleeder entries. This operating condition sufficiently sweeps the first entry in by the startup room, but the startup room is filled with an EGZ. In addition, EGZs are observed in the crosscut accessing the startup room and the first crosscut out by. Case 3 in Figure 8.1(c) regulates the flow at Point 1 to 16.5 m$^3$/s (35,000 cfm) increasing the size of the EGZ in the startup room.

![Figure 8.1: Case 1, 2a, and 3: Regulator Controls at Point 1 – Mine W (Gilmore et al., 2015b)](image)

Figure 8.2 shows the resulting normalized EGZ size and methane concentration for controls placed at Point 1 for Cases 1 through 3. Note that the EGZ size is normalized to the size of the EGZ in Case 3. The EGZ size is minimized with the flow of Case 2a when using 9.4 m$^3$/s (20,000 cfm) flowing through Point 1. Also, the methane concentration ranges from 1.9% to 2.1%, which shows a weak correlation response to the change in the size of the EGZ.
This ventilation model is incomplete because the common, though not required, practice is to limit access, and therefore ventilation, into the crosscuts leading at Point 2 in Figure 4.1. Case 2a minimized EGZ size and is selected for further study in the next section.

8.1.2 Headgate Side Flowrates into the Startup Room at Point 2 – Mine W

Figure 8.3 shows Cases 2b and 2c where the flow through Point 1 is fixed at 9.4 m$^3$/s (20,000 cfm) and the flow through Point 2 is regulated. Figure 8.3(a) uses 8 m$^3$/s (17,000 cfm) at Point 2 and Figure 8.3(b) has a stopping. The effect of regulating the flow through Point 2 increases the flow through crosscuts outby the startup room on the headgate side, as shown on the right of the figures. This directs more air into the startup room and eliminates the methane accumulation. In the crosscuts on the tailgate side are filled with EGZs, and the EGZ size has significantly increased.

Figure 8.4 shows the EGZ size and methane concentration at Point 1 in response to the regulated flow through Point 2. As the flow is decreased from 17.5 m$^3$/s (37,000 cfm)
(a) Case 2b: 8 m³/s (17,000 cfm) through Point 2 and 9.4 m³/s (20,000 cfm) through Point 1

(b) Case 2c: Stopping at Point 2 and 9.4 m³/s (20,000 cfm) through Point 1

Figure 8.3: Fixed Flow at Point 1 and Adjusting Flow into Startup Room – Mine W (Gilmore et al., 2015b)
in Case 2a to 0 m³/s (0 cfm) flow in Case 2c the EGZ size increases, and the methane concentration decreases at the Point 1.

This inverse effect of the decreasing methane concentration at Point 1 increasing the EGZ size suggests a negative correlation to safety. But, the EGZ is located further away from the headgate entries possibly making the startup room a safer location.

8.1.3 Mine W Results

Figure 8.5 shows the full panel length view of Case 2b of a bleeder-ventilated gob. The crosscuts on the headgate side are free of EGZs, and methane concentration at Point 1 has been reduced below the regulatory limit. The EGZ is shown to surround the gob and is continuous through the gob-fringes.
8.1.4 Changing Flow Direction on the Tailgate Entries – Points C and D – Mine W

A common problem with maintaining an operational bleeder-ventilated gob system is keeping the tailgate entry open all the way from the face to the startup room. In the United States, a three-development entry system reduces to a single center entry that must carry all the face air in addition to any air supplied to the tailgate side of the panel. First reversing the flow on the tailgate entries and then increasing the flow to the amount of the air supplied to the face simulates the caving of the tailgate entry.

Figure 8.6 shows a series of steady-state CFD simulations with increased flow out of the tailgate gate entries. Figure 8.6(a) shows reversing the flow at Point D to 4.7 m$^3$/s (10,000 cfm) and 7 m$^3$/s (15,000 cfm) at Point C. The EGZ has moved closer to the face and the tailgate entries near the startup room are filled with a fuel-rich mixture. In Figure 8.6(b), the flow is increased at the tailgate entries to 9.4 m$^3$/s (20,000 cfm) at Point D and 16.5 m$^3$/s (35,000 cfm) at Point C. The EGZ continues to move towards the face; the flow out of tailgate entry to the bleeder entries at Point F has reduced and the methane is at a concentration of greater than 2%. Figure 8.6(c) further increases the flow out at Point C to 28.3 m$^3$/s (60,000 cfm) and reduces the flow out of Point D to 0.047 m$^3$/s (100 cfm), which has little effect on the model. In Figure 8.6(d), an increased flow at Point C to 33 m$^3$/s (70,000 cfm) may seem to have little effect on the overall placement of the EGZ, but the startup room and the tailgate entry have filled with a fuel-rich mixture. Also a closer examination of the face as shown in Figure 8.6(e), reveals an EGZ behind the face on the tailgate side.
(a) Tailgate Flow Reversal – 4.7 m³/s (10,000 cfm) at Point D and 7 m³/s (15,000 cfm) at Point C

(b) Tailgate Flow Reversal – 9.4 m³/s (20,000 cfm) at Point D and 17 m³/s (35,000 cfm) at Point C

(c) Tailgate Flow Reversal – 0.047 m³/s (100 cfm) at Point D and 28.3 m³/s (60,000 cfm) at Point C

(d) Tailgate Flow Reversal – 0.047 m³/s (100 cfm) at Point D and 33 m³/s (70,000 cfm) at Point C

(e) Development of EGZ behind the Face with 0.047 m³/s (100 cfm) at Point D and 33 m³/s (70,000 cfm) at Point C

Figure 8.6: Flow Direction Reversal on the Tailgate Entries – Mine W
8.2 Bleeder-ventilated Gob – Mine E

The gob flow characteristics of Mine E (see Section 4.3.3) are used in the results in the next sections. The results of adjusting the headgate side regulator are similar to Cases 1–3, but are studied with an expanded flow range up to 33 m$^3$/s (70,000 cfm) to simulate the effects of a flow reversal in the startup room. Also, the model sensitivity to the maximum gob resistance parameter is examined, followed by results of mesh adaptation and the change in EGZ that occurs. Finally to illustrate the three-dimensional shape of the EGZ in the gob, vertical cross-sections are shown at every crosscut and a three-dimensional rendered surface is presented.

8.2.1 Headgate Side Regulator near the Startup Room at Point 1 – Mine E

Figure 8.7 shows the results of changing the flow from 0.047 m$^3$/s (100 cfm), 14.2 m$^3$/s (30,000 cfm) and 18.9 m$^3$/s (40,000 cfm) with unrestricted flow at Point 2. These results follow the same progression as seen in Cases 1–3 of the startup room filling with an EGZ. However, the EGZ fills a greater number crosscuts on the headgate side. Figure 8.8 shows results of further increasing the flow out at Point 1 causing a reversal of the flow across the startup room at Point 2. The sequence of reversal begins with the EGZ filling both the startup room and first entry inby, then the EGZ becomes a fuel-rich mixture, and finally the fuel-rich mixture is swept with fresh air from the tailgate side. However, the fuel-rich zone dilutes directly into the headgate side regulator at Point 1 and is a violation of the 2% methane concentration regulatory limits.

Figure 8.9 shows the EGZ and methane concentration response to the adjustment of flow through Point 1. The EGZ shows a minimum occurring again at 9.4 m$^3$/s (20,000 cfm) although the methane concentration does not follow the same trends as shown in Figure 8.2. The rapid increase in methane concentration is a result of the flow reversal at Point 2.
Figure 8.7: Adjusting the Regulator at Point 1 – 0.047 $\text{m}^3/\text{s}$ (100 cfm) to 8.3 $\text{m}^3/\text{s}$ (40,000 cfm) – Mine E

Figure 8.8: Adjusting the Regulator at Point 1 – 3.8 $\text{m}^3/\text{s}$ (50,000 cfm) to 33 $\text{m}^3/\text{s}$ (70,000 cfm) – Mine E
8.2.2 Permeability Sensitivity Study – Mine E

The permeability of the gob is the largest source of error and varies greatly between mines to the point that every panel can be different and, indeed vary within itself. The following CFD simulations use 9.4 m$^3$/s (20,000 cfm) of air flowing through Point 1 and the crosscuts at Point 2 remain unrestricted. Figure 8.10 and Figure 8.11 show a series of EGZ results when the base viscous resistance is multiplied by a scalar. The maximum viscous resistance starts at $9.7 \times 10^4$ 1/m$^2$ as shown in the series in Figure 8.10, which is 20% of the initial value of $4.9 \times 10^5$ 1/m$^2$, and increases 500 times to $2.4 \times 10^8$ 1/m$^2$ as shown in the last series in Figure 8.11. The lowest resistance value in this study is above the maximum milli-Darcy values used by other researchers (see Table 2.2), and the highest resistance value is of the same order. A wedge shaped fuel-rich zone exists in many of the results near the startup room with an accompanying EGZ in the startup room, which may be possible to dilute by restricting flow at Point 2. These figures show that there is a persistent EGZ in the gob, and it often fills many crosscuts regardless of the viscous resistance.
Figure 8.10: Resistance Range $9.7 \times 10^4 \text{ } 1/m^2$ to $8.8 \times 10^5 \text{ } 1/m^2$ – Mine E
Figure 8.11: Resistance Range $8.8 \times 10^5 \text{1/m}^2$ to $2.4 \times 10^8 \text{1/m}^2$ – Mine E
Figure 8.12 shows the effects of the maximum viscous resistance on the EGZ size and methane concentration as reported at Point 1. The range of viscous resistance values in the research varies from $10^5$ to $10^7$ resulting in a 20% change in the EGZ size and a variation in methane concentration at Point 1 from 0.8% to 2.9%. The trend seen in the EGZ results has a minimum in the viscous resistance range in this research, and therefore the formation of EGZs persists throughout all ranges of viscous resistance values studied. This further suggests that the error associated with the choice of viscous resistance is ±10% of the EGZ and ±1.85% of the methane concentration at Point 1.

![Graph showing EGZ normalized volume and methane concentration against maximum gob resistance.](image)

Figure 8.12: Resistance effects on EGZ Normalized Volume and Methane Concentration – Mine E

### 8.2.3 Mine E Results

Figure 8.13 shows the EGZ results of the full panel using the Mine E equation fit with 9.4 m$^3$/s (20,000 cfm) of air flowing through Point 1 and unrestricted flow at Point 2. The resulting EGZ near the startup room is similar to the results as shown in Figure 8.1(b), and the procedure of balancing the flow through the startup room would still be required to dilute the EGZ. However, the balancing procedure has very little effect on the EGZ in the
center of the panel, and the EGZ would still remain continuous as it fills the crosscuts on the headgate side.

### 8.2.4 Adapted Mesh – Mine E

Figure 8.14 through Figure 8.17 show the results of the EGZ after the adaptive mesh process described in Section 7.3. The EGZ has changed in size although there are many crosscuts on the headgate side that contain an EGZ. The EGZ is in crosscuts starting at the tenth through the length of the panel. Figure 8.15 and Figure 8.16 show a series of vertical cross-sections at each crosscut. Figure 8.17 shows the connective nature of the EGZ in a three-dimensional view of the startup end of the panel. The EGZ first appears as early as the second crosscut from the face at the top of the gob and becomes continuous across the panel width by the sixth crosscut. The mesh adaptation process limits further resolution of the continuous nature of this EGZ.

Figure 8.14: Full Panel View of EGZ using after Mesh Adaptation – Mine E
Figure 8.15: Vertical Cross-sections of EGZ at Crosscuts 1–32 – Mine E
8.3 Bleeder-ventilated Gob – Mine C

The gob flow characteristics of Mine C (see Section 4.3.2) are used in the following EGZ results. The results of adjustments made to the flow through the headgate side regulator at Point 1 are similar to Cases 1–3, and the results of the full bleeder panel with the same operating conditions are presented.

8.3.1 Headgate Side Regulator near the Startup Room at Point 1 – Mine C

Figure 8.18 shows the results of changing the flow at Point 1 from 0.047 m³/s (100 cfm), 11 m³/s (30,000 cfm) and 5.8 m³/s (40,000 cfm) with unrestricted flow at Point 2. The crosscuts on the headgate side are filled with EGZs or a fuel-rich methane mixture. Also the corner of the gob on the headgate side remains filled with a fuel-rich mixture instead of transitioning to an EGZ as shown previously in Figure 8.7. Increasing the flow out at Point 1 and causing flow reversal across Point 2 still has the same effect of clearing the methane in the startup room, which overwhelms the flow at Point 1 with high concentrations of methane.
Figure 8.17: 3D-Panel View of EGZ at the Startup Room – Mine E
Figure 8.18: Adjusting the Regulator at Point 1 – 0.047 m³/s (100 cfm) to 5.8 m³/s (40,000 cfm) – Mine C

Figure 8.19: Adjusting the Regulator at Point 1 – 23.6 m³/s (50,000 cfm) to 33 m³/s (70,000 cfm) – Mine C
Figure 8.20 shows the EGZ and the methane concentration at Point 1 responding to the flow change at Point 1. The resulting trend in the EGZ is a minima occurring again at 9.4 m$^3$/s (20,000 cfm), but the total range increases to 30% of the maximum. The methane concentration reported at Point 1 follows the same trend as shown in Figure 8.9, but with more values above the 2% limit. The observed peak in methane concentration relates to the flow direction change across Point 2.

![Figure 8.20: EGZ Normalized Volume and Methane Concentration Response to Adjustment of Regulator at Point 1 – Mine C](image)

**8.3.2 Mine C Results**

Figure 8.21 shows the EGZ results of the full bleeder-ventilated gob using Mine C equation fit using 9.4 m$^3$/s (20,000 cfm) of air flowing out at Point 1 and unrestricted flow through Point 2. The results are similar to those shown in Figure 8.11 of the viscous resistance sensitivity study with a similar maximum resistance, but the range is larger in Mine C. The same shape of a fuel-rich zone occurs at the startup end of the panel, and the EGZ in the first quarter of the panel is nearer the face. The EGZ fills almost all the crosscuts on the headgate side and extends across the gob in a wide band. This result emphasizes the point
that although the gob flow characteristics may be the greatest unknown in the system, the EGZ persists.

8.4 Explosive Hazard Discussion of Bleeder-ventilated Gob Operation

In Figure 8.10 and Figure 8.11, the overall shape of the EGZ is shown to change and vary greatly in size depending on the gob flow characteristics. However, the accumulation of methane in the startup room occurs in the models studied. Restricting the flow at Point 2 and forcing more air into crosscuts in by the startup room can mitigate these methane accumulations. It is suggested that there should remain a moderate flow through Point 2 towards the tailgate side to remove methane in the vicinity of these crosscuts.

The EGZ surrounds the gob and has a wide connecting band from the headgate to the tailgate side. This connecting EGZ band is independent of ventilation pattern and gob flow characteristics. The explosive risk posed by this connecting EGZ band is unknown given the flame propagation characteristics inside the gob, and furthermore, the unknown continuous nature of the gob-fringe connecting the headgate to tailgate side across the gob. The ventilation controls near the startup room have very little control on the size of this band, and further simulation beyond the scope of this research is suggested.

The flow reversal at Point C and D suggest the formation of an EGZ directly behind the shield on the longwall face. The formation of this ventilation pattern may be the result of a caving tailgate entry near the face or in the back return crosscut causing an U-Type ventilation pattern. The EGZ risk is similar to results published by Marts et al., 2014a in
the study of U-Type ventilation and back return ventilation.

This research shows that persistent EGZs exist in many of the crosscuts on the headgate side, which are accessible by personnel in the mine. These EGZs are an explosive risk to a safe operation given the existence of potential ignition sources from lightning, sparking rock fall, or spontaneous combustion. The formation of EGZs in the crosscuts or gob-fringes in a properly functioning bleeder-ventilated gob does not follow its intended purpose (Stricklin & Fesak, 2013).
CHAPTER 9
CONCLUSIONS

The CFD model used simulates a bleeder-ventilated gob in this research. Through a study of three gob flow characteristics, each examining regulator controls on the headgate side near the startup room (Section 8.1.1 and 8.1.2, Section 8.2.1 and Section 8.3.1) and a sensitivity study of scaling the porosity relationship to permeability (Section 8.2.2), has demonstrated the existence of a persistent EGZ surrounding the gob. Also, a study of a changing ventilation pattern as the flow reverses at the tailgate demonstrated the efficacy of the CFD model to predict the development of an EGZ directly behind the shields (Section 8.1.4). The modular meshing approach employed in this research, which was used to create the models, has progressively advanced the details of the mesh to better represent the actual mine geometry, and improvements continue with collaboration in the CSM research group (Marts et al., 2014a; Saki et al., 2015).

Modeling results show the presence of a wide EGZ band crossing the gob that connects the tailgate to headgate side, which could propagate an ignition event throughout the mine. Furthermore, an EGZ threat to safe mine operation exists in many crosscuts on both the headgate and tailgate side. The hazards posed by these EGZs are predicted to occur in the studied bleeder-ventilated gob models independent of the gob flow characteristics and scaled permeability.

Ventilation controls near the startup room on the headgate side are essential to eliminate the EGZ hazard in the startup room and nearby crosscuts. The flow direction from headgate to tailgate side must be maintained through the crosscuts at the startup room (Point 2), and if possible in as many crosscuts outby the startup room (Section 8.1.2). However, the EGZ has been shown to increase in size when forcing sufficient air into the open mine entries and crosscuts in an attempt to dilute the methane accumulations. The controls placed near
the startup room on the headgate side (Point 1 and 2) only affect the area surrounding the startup room and do not have sufficient impact to limit the development of EGZs along the panel length.

The sensitivity study of the model to the strata geology, overburden depth and strata in the caving zone forming the gob, which vary significantly between mines, panels or even within the same panel and result in large variation in the values of porosity and permeability, has demonstrated that the EGZ remains, but will vary in size and location. These pockets of explosive gas pose a threat to mine workers and violate the intended purpose of an effective bleeder-ventilated gob system.

Ventilation reversal caused by a roof fall or other unplanned event on the tailgate entries, forming a U-Type ventilation pattern, draws the EGZ closer to the face, causing the formation of EGZs directly behind the shields and near the open crosscut of the back return (Section 8.1.4). The flow out of the tailgate entry to the bleeder fan would no longer be sufficient to dilute the methane concentration, and EGZs fill the tailgate entry across many crosscuts.

This research simulates the ventilation system of a bleeder-ventilated gob, using Fluent. It features a developed meshing approach to model the large scale system of a single bleeder panel, with the gob flow characteristics of three mines. One conclusion finds that ventilation controls near the startup room are insufficient to dilute the accumulated methane in the bleeder-ventilated gob system below the explosive limit required for worker safety. As stated by Stricklin & Fesak, 2013 on bleeder operations, “Accumulations of methane that are explosive, can become explosive when mixed with air, are approaching the explosive range, or are irrespirable, may pose a hazard to the active workings whether they occur in accessible areas or not.” This hazard elimination requirement has clearly not been met in the simulations in this research, but the studies show instead, that the EGZ and high methane concentrations persist across permeabilities studied and through the ventilation control adjustments studied.
SUGGESTIONS FOR FUTURE WORK

The future implications for work and model improvements are detailed in the following chapter, including the areas of geometry and meshing refinements, gob characterization, and solution convergence criteria. Furthermore, it is recommended to repeat many of the studies and sensitivity studies completed previously by Worrall, 2012, which included the study of face ventilation quantity effects on EGZ size and location.

10.1 Improvements to the Mine Geometry and Meshing

Improvements to the geometric representation and the resulting modular meshing approach for large and small models would increase the usefulness of CFD as a predictive tool, decrease solution time, increase accuracy and make results reproducible. Some of the areas that this applies to are listed below:

- The mine entry network mesh representation uses two primary straight entry modules that poorly resolve the flow in areas of the corners, tee junctions, and cross junctions. The creation of mesh modules to represent these flow junctions would improve solution times and convergence. This would isolate the inflation layer to the wall boundary, and eliminate the computational errors in the center of the flow at the junction between two modules.

- The use of ANSYS Workbench in Version 16.0 multiple upstream meshing would create a more usable interface for mesh creation. This would utilize the Fluent meshing mode, through the use of a custom journal file, to assemble the modules into the final mesh. Furthermore, user functionality could be increased by creating tools with ANSYS Software Development Kits that would read a mine map file and build the representative mesh.
• The longwall face used in this project is an over-simplification of very complex geometry. Additional modules could be created to represent the shields, armored face conveyor, tailgate and headgate drives, and the crusher obstructing the headgate entry. This would result in better resolution of the velocity and turbulent flows in the face and produce a more realistic pressure drop across the face.

• The wall boundary conditions, simplified face and gob-fringe geometry are insufficient to accurately produce a realistic pressure drop. Therefore, it is suggested to change the entries’ wall boundary conditions to reflect the appropriate roughness, and increase the complexity in the shield model. This would result in a substantial increase in the number of cells in the model and require the use of a complex turbulent flow model (Gilmore et al., 2015a).

10.2 Improvements to the Gob Characterization

The unknown flow characteristics of the gob are the largest source of error in the system, which includes the transport modeling equations and the gob-fringe modeling. The following are some suggested improvements:

• Additional refinements to the applied porosity distribution by including a vertical direction dependence currently vary only on the mining plane. The addition of vertical direction dependence in the model would require varying the compaction of the gob at different heights and need to incorporate the variation in the observed block size. The particle size was assumed constant, but a distribution in the vertical direction would be more appropriate. The UDF coding used in this research that calculates each step to determine the porosity and permeability is functionally ready to program a particle distribution in future work.

• The full transport equation used in the porous media (Section 3.7) includes an additional inertia resistance term, \( C_2 \). The calculation of this value from a relationship to
porosity has been coded into the UDF, but a sensitivity study to examine the effects it will have near the gateroad and behind the face is still required.

- The resulting flow in the gob is heavily dependent on the gob-fringe characteristics such as size, geometry and extent. The gob-fringe connects the fluid zones between crosscuts, may extend the length of the gob, exist above the shields and near the startup room. The VSI distribution when including a vertical direction dependence may be used to better define the shape and extent of the gob-fringe. Assigning a porosity value of one to the gob-fringe and using the relative velocity formulation would create a smooth transition from the fluid zone to the porous media. The roughness and large voids on the surface of the gob material would still require a geometric mesh representation not practical scale of a full mine.

10.3 Solution Convergence Monitor

It is often challenging to determining when a simulation has converged to a solution and to correctly identify an important criterion to monitor. This research has identified the EGZ volume integral, which combines the results of the species concentration of methane and oxygen as the variable of interest. This variable also changes significantly with more iterations and adaptations of the mesh. To improve solution control, this research recommends the use of a user defined scalar equation that calculates the EGZ integral on an iteration bases. This will result in a residual monitor of the scalar equation that can be used by the solver to automate the identification of a converged solution. This is preferred over calculating the EGZ algorithm, EGZ integral, and reporting a value at regular intervals.

10.4 Ignition and Explosive Potential of Explosive Gas Zones

The research funding from NIOSH has been extended to examine the scaling of flame propagation with tube sizes of 0.05 m, 0.13 m, 0.30 m, and 0.76 m (0.16 ft, 0.4 ft, 1 ft, 2.5 ft). The study includes unrestricted laminar flames and flames passing through rock rubble. Also the CFD simulations of a one-step chemistry model will be validated against
these experimental results. This will identify the threat posed by the predicted EGZs in this dissertation.

10.5 Validation of Models with Mine Gas Measurements

The ultimate validation of this research is in the measurement of an existing EGZ in the mine ventilation network at the locations predicted. The identification of an EGZ in an active working mine would result in the immediate shutdown and evacuation of all non-essential personnel to correct the situation. Furthermore, the measurement would be a violation of CFR 30 and result in a fine. Mine operators are thus extremely opposed to further research in this area.

Further validation could be achieved through an examination of explosions that have occurred in the presence of an effectively operating bleeder-ventilated gob. Brune, 2014 discusses a number of these cases and the need for more research in this area in the following statement:

In the United States, a targeted, comprehensive research program would determine whether longwall bleeder ventilation systems can be designed such that they are truly effective in diluting and rendering harmless accumulations of explosive methane-air mixtures, or if alternative longwall gob ventilation systems are needed.
REFERENCES CITED


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The Davies Family Website. 2013. History and Photographs of Mining Coal and Mining.


Uszko, M., Stanecki, I., Dlugosz, J., & Szarafinski, M. 2013. Utilization of Methane Released During Coal Mining Activities. *In: 23rd World Mining Congress*.


The FLAC\textsuperscript{3D} numerical modeling approach follows the initial developed by Esterhuizen & Karacan, 2007, initial implementation for this project by Wachel, 2012, and final refinements by Marts \textit{et al.} (2014b) that resulted in a calibrated model of gob compaction to surface subsidence. The surface subsidence profile in the panel length, as shown in Figure 2.6, matches that of the data of the VSI reported by the numerical model shown in Figure A.1. Mark are the three different zones that break up the data for curve fitting, as discussed in Section 4.3, namely, a startup zone, center zone, and recovery zone. A bounded range for the center zone must be determined in the panel length, and also in the width for super-critical panels, while a sub-critical panel should not have a center zone across the panel width. The startup zone ranges from 0 m (0 ft) to 190 m (620 ft), and the recovery zone ranges from 700 m (2,300 ft) to 1,000 m (3,280 ft) that leaves a expandable center zone from 190 m (620 ft) to 700 m (2,300 ft) for extending the panel length.

![Gob Volumetric Strain](image)

**Figure A.1: Gob Compaction Profile – VSI**
Figure A.2 shows the behavior of the gob compaction and subsidence across the panel width. Again, a center zone can be identified from the data ranging from the center of the panel at 0 m (0 ft) to 500 m (1640 ft), where the data exhibits a less than 1% change from the maximum value. The remaining distance is defined as the width of the gateroad zone. This Figure was used to verify the super-critical behavior of the physics used in the numerical model, and the data used in the two curve fits for Mine C and Mine E used a panel half width of 200 m (655ft). In the actual data curve fit for this project the gateroad width was identified to occur at 60 m (200 ft) from the gateroad, as shown in Figure 4.12.

![Figure A.2: Gob Compaction and Subsidence Profile across Panel Width](image)

**A.1 Data Reading and Parsing**

The output of the FLAC3D data must read into MATLAB where numerical spikes and waviness may be smoothed out. Example output lines for the location data and VSI data are shown in Listing A.1 and Listing A.2. The code to read the location and VSI values into MATLAB, are shown inListing A.3. Upon execution, the user is prompted for the names of the location file and data file.
Listing A.1: Gob Zone Locations Data

Zone Information ...

<table>
<thead>
<tr>
<th>ID</th>
<th>Type</th>
<th>Model</th>
<th>Group</th>
<th>Centroid</th>
</tr>
</thead>
<tbody>
<tr>
<td>145801</td>
<td>Brick</td>
<td>Double-Yield gob</td>
<td>(</td>
<td>5.00e+0, 6.05e+2, 5.00e+0)</td>
</tr>
<tr>
<td>145802</td>
<td>Brick</td>
<td>Double-Yield gob</td>
<td>(</td>
<td>1.50e+1, 6.05e+2, 5.00e+0)</td>
</tr>
<tr>
<td>145803</td>
<td>Brick</td>
<td>Double-Yield gob</td>
<td>(</td>
<td>2.50e+1, 6.05e+2, 5.00e+0)</td>
</tr>
<tr>
<td>145804</td>
<td>Brick</td>
<td>Double-Yield gob</td>
<td>(</td>
<td>3.50e+1, 6.05e+2, 5.00e+0)</td>
</tr>
<tr>
<td>145805</td>
<td>Brick</td>
<td>Double-Yield gob</td>
<td>(</td>
<td>4.50e+1, 6.05e+2, 5.00e+0)</td>
</tr>
<tr>
<td>145806</td>
<td>Brick</td>
<td>Double-Yield gob</td>
<td>(</td>
<td>5.50e+1, 6.05e+2, 5.00e+0)</td>
</tr>
</tbody>
</table>

Listing A.2: Gob Zone Strain Data

Zone Strain Values ...

<table>
<thead>
<tr>
<th>ID</th>
<th>SSR</th>
<th>SSI</th>
<th>VSR</th>
<th>VSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>145801</td>
<td>6.07147e-9</td>
<td>1.13465e-1</td>
<td>-7.81479e-9</td>
<td>-1.96285e-1</td>
</tr>
<tr>
<td>145802</td>
<td>5.05941e-9</td>
<td>1.13066e-1</td>
<td>-7.42470e-9</td>
<td>-1.95815e-1</td>
</tr>
<tr>
<td>145803</td>
<td>6.14612e-9</td>
<td>1.12643e-1</td>
<td>-8.92892e-9</td>
<td>-1.95157e-1</td>
</tr>
<tr>
<td>145804</td>
<td>6.91549e-9</td>
<td>1.12095e-1</td>
<td>-8.74196e-9</td>
<td>-1.94451e-1</td>
</tr>
<tr>
<td>145805</td>
<td>7.38291e-9</td>
<td>1.11327e-1</td>
<td>-9.25488e-9</td>
<td>-1.92870e-1</td>
</tr>
<tr>
<td>145806</td>
<td>7.52705e-9</td>
<td>1.10137e-1</td>
<td>-9.07975e-9</td>
<td>-1.90777e-1</td>
</tr>
</tbody>
</table>

Listing A.3: MATLAB Code to Read FLAC3D Data

% READ FLAC-3D output files for centroid position in the x,y,z
% and read the VSI (Volumetric Strain Index) from the data file
% put into variables for a curve fitting
% Get file names from user (INFO & DATA)
name_info = uigetfile
name_data = uigetfile
% Open INFO file
info = fopen(name_info);
% Read 3 junk lines
for i=1:3; fgetl(info); end
% Read line
line=fgetl(info);
while (~feof(info) || isempty(line) )
% Search array for '(' or ',' char
indstart=find(line == '(',1,'first ');
indcomma=find(line == ',',2,'first ');
% read value of x to next comma
   x(i)=str2num(line(indstart+1:indcomma(1)-1));
% read value of y to next comma
   y(i)=str2num(line(indcomma(1)+1:indcomma(2)-1));
% read value of z to )
   z(i)=str2num(line(indcomma(2)+1:length(line)-1));
   line=fgetl(info);
end
x=x’; y=y’; z=z’;
% Open DATA file
   data=fopen(name_data);
% Read 3 junk line
   for i=1:3; fgetl(data); end
   line=fgetl(data);
   while (~feof(info) || isempty(line))
% Read 5th number to VSI
      indstart=find(line=='.' ,1,'last') ;
      VSI(i)=str2num(line(indstart-2:length(line))) ;
      line=fgetl(data);
   end
VSI=-VSI’;
% close file
fclose(’all’);

The data can now be examined in MATLAB using the cftool toolbox. The data at the panel edges is buffered with zeros and centered. Figure A.3 shows the data plotted along the y-direction at the center of the panel. The startup room is at 0 m (0 ft), and the active face is at 1,000 m (3,280 ft). The highlighted data at 102.5 m (336 ft) with a VSI value of 0.2658 is used as a point of data tracking during the smoothing and data parsing process.

Also, it is possible to identify numerical spikes in the data, which can be found at index 3 and 160 across the panel width. This process is also customized for the panel length in the recovery zone and startup room zone at index 6 and 8 (just to the left of the annotation in Figure A.3) and at y = 40 and 959.95. Each replaced data point uses an interpolated spline function created from the cftool toolbox. The code automates this process once the individual data points have been properly identified with the user’s visual inspection of the data.

Listing A.4: MATLAB Code to Parse Data
Figure A.3: Raw Data – Slice at x = 0

% Resizes x, y, VSI variable and applies smoothing function for visual % inspected data points known to either be numerical instabilities from % modeling efforts or from visual inspected overshoot locations.
% Final Variables are "x1 y1 vsi1"
% Initialize new storage variable x1, y1 for parsed data, and working
    working_vsi1.

x1 = []; y1 = []; working_vsi1 = []; vsi1 = [];
ymin = min(y); % Shift y values
y = y - ymin + 5; % Find length y of data set
i = 1;
while y(i) == y(i + 1); i = i + 1; end
step = i; % Assign y data set length for step size
x = shift and expand x values
xmax = max(x);
roundTO = find(num2str(xmax) == '. ', 1, 'first');
xmaxADD = roundn(xmax, roundTO - 2);
% Begin stepping in the y-direction and repairing VSI data along 2D slices of
% VSI as a function of x (Panel Width).
% Visual inspection of 'l' between 10 < y < 100 is suggested to assign
    indices
% for replacement and smoothing curve fitting parameter functions.
for l=1:length(x)/step

% working slice of x values at constant y
working_x=x((l-1)*step+1:l*step);
working_x=[x_maxADD; working_x;x_maxADD];
x1=[x1; working_x];

% working slice of VSI values at constant y
working_vsi=VSI((l-1)*step+1:l*step);
working_vsi=[0; working_vsi(); 0];

% working slice of y values at constant y
working_y=y((l-1)*step+1:l*step);
working_y=[working_y(1); working_y(1); working_y];
y1=[y1; working_y];

% IMPORTANT customized ctool fit function to replace data
[Fit150X, gof_Fit150X] = Fit150to150Xdirection(working_x, working_vsi);
working_vsi([22:141])=Fit150X(working_x([22:141]));

% IMPORTANT customized ctool fit function to replace data by indices
[Fit2indexX, gof]=XdirectionFitReplace(working_x, working_vsi, [3, 160]);
working_vsi([3, 160])=Fit150X(working_x([3, 160]));
working_vsi1=[working_vsi1; working_vsi];

end

% add VSI=zero all around panel edge
x1=[working_x; working_x; x1];
y1max=max(y1)+.05;
y1=[zeros(step+2,1); y1; y1max*ones(step+2,1)];
working_vsi1=[zeros(step+2,1); working_vsi1; zeros(step+2,1)];

% Begin stepping in the x-direction and repairing VSI data along 2D slices of
% VSI as a function of y (Panel Length).
% Visual inspection of 'l' equal to x > 30 is suggested to assign indices
% for replacement and smoothing curve fitting parameter functions
% Final form and size of vsi
vsi1=working_vsi1;
for l=1:(step+2)
    working_y=y1(1:(step+2):end);
    working_vsi=working_vsi1(1:(step+2):end);

%indy2=find(working_y==15);
[Fit2indexY, gof2]=YdirectionFitReplace(working_y, working_vsi, [6, 8]);
working_vsi([6, 8])=Fit2indexY(working_y([6, 8]));

% working_vsi(indy2)=Fit2indexY(working_y(indy2));
indst=find(working_y==40);
indfin=find(working_y==959.95);
[FitSmoothY, gof_FitSmoothY]=
    FitSmoothYdirection(working_y, working_vsi, [indst, indfin]);
working_vsi(indst:indfin)=FitSmoothY(working_y(indst:indfin));
vsil(1:(step+2):end)=working_vsi;
end

The parse data code uses three cftool created fitting functions that are customized to the data set. Listing A.5 is customized to replace data points by indices along the x and then y direction. Listing A.6 is customized to smooth the data along the x-direction from about 150 m (490 ft) from either end of the data set. The data set is now ready to examine by each section and create an approximate equation fit.

Listing A.5: X or Y-Direction Data Replacement

function [fitresult, gof] = YdirectionFitReplace(stry, strvsi, ind)
% Auto-generated by MATLAB on 06-Jun-2013 21:16:58
%% Fit: 'X or Y-Direction Fit Data and Replace'.
[xData, yData] = prepareCurveData(stry, strvsi);
% Set up fit type and options.
ft = fittype( 'pchipinterp' );
opts = fitoptions( ft );
opts.Normalize = 'on';
ex = excludedata( xData, yData, 'Indices', ind );
opts.Exclude = ex;
% Fit model to data.
[fitresult, gof] = fit( xData, yData, ft, opts );

Listing A.6: Smoothing X-Direction Data

function [fitresult, gof] = Fit150to150Xdirection(strx, strvsi)
% Auto-generated by MATLAB on 10-Sep-2013 22:50:02
%% Fit: 'Fit 150 to 150 X-direction'.
[xData, yData] = prepareCurveData(strx, strvsi);
% Set up fit type and options.
ft = fittype( 'smoothingspline' );
opts = fitoptions( ft );
opts.SmoothingParam = 0.0106447313819827;
% Fit model to data.
[fitresult, gof] = fit( xData, yData, ft, opts );

The results of the data after indices’ replacement and smoothing are shown in Figure A.4, where the Y-axis is zoomed. The highlighted data point has changed 0.0003. The constant value in the center was taken as the final VSI value and a choice was made to cap the
maximum value producing the data shown in Figure A.5. The highlighted data point is now at 0.2637 and is uniformly applied across the length. This procedure was repeated along the panel length for all values of x.

Figure A.4: Data Smoothed and Indices Replacement – VSI Scaled

A.2 Creation the MATLAB Curve Fitting Toolbox Code Sections

The code in Listing A.7 should be executed in sections. Each section is carefully fitted and then output into an auto generated cftool fit function. Each data section is first normalized and oriented with the zeros at the panel edges, and then loaded into the Matlab curve fitting toolbox.

Listing A.7: Preparing the Sections of Data to Curve Fit

% Execute section of code below and custom fit the equation to the % data. Using visual inspection as a guide and removing data % points when necessary. Run command 'cftool' in matlab command % prompt and use the normalized variables for each section.
% FtX, FtY, Z? (1-6) to create the code generated by cftool into
% the functions used to fine tune the coefficients and general
% equation form. For example, the function create_Startup_gateroad
% was modified from the code generated in cftool to customize the
% final form of the curve fit equation for that section of the
% longwall panel.
% Each section is selected by excluding data points
% Data x, y panel sizing
box=[0 100 200 0 190 700 1000]
method='box'; % exclusion type for cftool
% Startup center panel
% Grab data in the area of the startup center
box1=[box(1) box(2)+5 box(4) box(5)+5];
ex1 = excludedata(x1, y1, method, box1);
% create a cfit object from cftool fit functions
[Fit1, gofFit1]=IntCubicFit(x1, y1, vsi1, ex1);
% create grid of x, y values to use for the fit.
[X1, Y1]=meshgrid(box1(1):box1(2), box1(3):box1(4));
% VSI data to fit in the startup center zone
Z1=Fit1(X1, Y1);
% Normalize X,Y and flip scale to best match for curve fitting
FtX=(X1-box1(1))/(box1(2)-box1(1)); FtY=(Y1)/box1(4);
% Creates the fit for this section using FtX, FtY, and Z1 in
% cftool and generate code to simplify setting max, min
% limits, and startup point of coefficients.
[StartupCenter, gof_Stup_center]=
    create_Startup_center(FtX, FtY, Z1, 'startup center ');
% output readable coefficients values and confidence interval
Stup_center_values=coeffvalues(StartupCenter)
Stup_center_95_range=confint(StartupCenter)
% Repeat code execution for each section of the panel
% Startup Gateroad
box2 = [box(2)-5 box(3) box(4) box(5)+5];
ex2 = excludedata(x1, y1, method, box2);
[Fit2, gofFit2]=IntCubicFit(x1, y1, vsi1, ex2);
[X2, Y2]=meshgrid(box2(1):box2(2), box2(3):box2(4));
Z2=Fit2(X2, Y2);
FtX=abs((X2-box2(1))/(box2(2)-box2(1))-1); FtY=(Y2)/box2(4);
% Create the fit
[StartupGateroad, gof_Stup_gateroad]=
    create_corner_FIT_fractional(FtX, FtY, Z2, 'startup gateroad ');
Stup_gateroad_values=coeffvalues(StartupGateroad)
Stup_gateroad_95_range=confint(StartupGateroad)
% Center panel
box3=[box(1) box(2)+5 box(5)-5 box(6)+5]; %[-105 105 185 705];
ex3 = excludedata(x1, y1, method, box3);
[Fit3, gofFit3]=IntCubicFit(x1, y1, vsi1, ex3);
\[ X3, Y3 = \text{meshgrid}(box3(1):5:box3(2), box3(3):25:box3(4)); \]
\[ Z3 = \text{Fit3}(X3, Y3); \]
\[ Ftx = (X3 - box3(1))/(box3(2) - box3(1)); \]
\[ Fty = (Y3 - \min(\min(Y3)))/(\max(\max(Y3)) - \min(\min(Y3))); \]
\[ \text{for } i = 2:\text{size}(Z3, 2) - 1 \]
\[ \% \text{ flatten data again} \]
\[ [Z3, \text{fitresult, gof}Z3] = \text{Center\_Panel\_Ysmoothing}(Y3(:, i), Z3(:, i)); \]
\[ Z3(:, i) = Z3, \text{fitresult}(Y3(:, i)); \text{end} \]
\[ \% \text{ Create the fit} \]
\[ [\text{CenterPanel, gof\_center\_panel}] = \]
\[ \text{create\_Center\_Panel\_linear}(Ftx, Fty, Z3, 'center panel'); \]
\[ \text{Center\_panel\_values} = \text{coeffvalues}(\text{CenterPanel}) \]
\[ \text{Center\_panel\_95\_range} = \text{confint}(\text{CenterPanel}) \]
\[ \% \% \text{ Center Gateroads} \]
\[ \text{box4} = [\text{box}(2)-5 \text{ box}(3) \text{ box}(5)-5 \text{ box}(6)+5]; \]
\[ \text{ex4 = excludedata}(x1, y1, \text{method}, \text{box4}); \]
\[ [\text{Fit4, gofFit4}] = \text{IntCubicFit}(x1, y1, vsi1, ex4); \]
\[ Z4 = \text{Fit4}(X4, Y4); \]
\[ Ftx = \text{abs}((X4 - box4(1))/(box4(2) - box4(1)) - 1); \]
\[ Fty = \text{abs}((Y4 - box(6)+5)/(box(7) - box(6)+5) - 1); \]
\[ \% \text{ Create the fit} \]
\[ [\text{CenterGateroad, gof\_center\_gateroad}] = \]
\[ \text{create\_center\_gateroad}(Ftx, Fty, Z4, 'center gateroad'); \]
\[ \text{center\_gateroad\_values} = \text{coeffvalues}(\text{CenterGateroad}) \]
\[ \text{center\_gateroad\_95\_range} = \text{confint}(\text{CenterGateroad}) \]
\[ \% \% \text{ Recovery Room Center} \]
\[ \text{box5} = [\text{box}(1) \text{ box}(2)+5 \text{ box}(6)-5 \text{ box}(7)]; \]
\[ \text{ex5 = excludedata}(x1, y1, \text{method}, \text{box5}); \]
\[ [\text{Fit5, gofFit5}] = \text{IntCubicFit}(x1, y1, vsi1, ex5); \]
\[ [X5, Y5] = \text{meshgrid}(box5(1):box5(2), box5(3):box5(4)); \]
\[ Z5 = \text{Fit5}(X5, Y5); \]
\[ Ftx = (X5 - box5(1))/(box5(2) - box5(1)); \]
\[ Fty = \text{abs}((Y5 - box(6)+5)/(box(7) - box(6)+5) - 1); \]
\[ \% \text{ Create the fit} \]
\[ [\text{RecoveryCenter, gof\_recovery\_center}] = \]
\[ \text{create\_Recovery\_Center}(Ftx, Fty, Z5, 'recovery center '); \]
\[ \text{Recovery\_center\_values} = \text{coeffvalues}(\text{RecoveryCenter}) \]
\[ \text{Recovery\_center\_95\_range} = \text{confint}(\text{RecoveryCenter}) \]
\[ \% \% \text{ Recovery Gateroad} \]
\[ \text{box6} = [\text{box}(2)-5 \text{ box}(3) \text{ box}(6)-5 \text{ box}(7)]; \]
\[ \text{ex6 = excludedata}(x1, y1, \text{method}, \text{box6}); \]
\[ [\text{Fit6, gofFit6}] = \text{IntCubicFit}(x1, y1, vsi1, ex6); \]
\[ [X6, Y6] = \text{meshgrid}(box6(1):box6(2), box6(3):box6(4)); \]
\[ Z6 = \text{Fit6}(X6, Y6); \]
\[ Ftx = \text{abs}((X6 - box(2)+5)/(box(3) - box(2)+5) - 1); \]
\[ Fty = \text{abs}((Y6 - box(6)+5)/(box(7) - box(6)+5) - 1); \]
\[ \% \text{ Create the fit} \]

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The startup room center panel section curve fitting code in Listing A.8 gives the options to start the curve fitting solver. Specification for the maximum and minimum change, upper and lower limits, and a starting point for the coefficients aid the solver in fitting an equation to the data. To obtain a reasonable result, there must be a large enough maximum number of function evaluations and larger enough maximum iterations allowed before exiting. The more accurate the starting point guess values and the more restrictive the upper and lower limits, the faster the solver will present a result. The $x$ independent variable was excluded in the final equation form as the coefficient is relatively small, and a constant flat behavior allows for a variable panel width. The limits and starting points were carefully evaluated for each section. In a similar fashion, the code for the recovery room in the center of the panel and in the center of panel near the gateroad is given in Listing A.9 and Listing A.13.

Listing A.8: Creating Curve Fit Equation for Start-up Room in the Center Panel

```matlab
function [fitresult, gof] = create_Startup_center(FtX, FtY, Z1, Title)
    % Auto-generated by MATLAB on 11-Jun-2013 23:28:05
    % Fit : 'STARTUP CENTER'.
    [xData, yData, zData] = prepareSurfaceData(FtX, FtY, Z1);
    ex = excludedata(xData, yData, 'indices', find((yData > 0.066666 & yData < 0.08717)));
    % Set up fit type and options.
    ft = fittype('a+x^2*(a1)+b*y*exp(-b1*y^2)+c*exp(-c1*y^2)+d*y^2*exp(-d1*y^2)', ...)
    opts = fitoptions(ft);
    opts.DiffMaxChange = 0.1;
    opts.DiffMinChange = 1e-16;
    opts.Lower = [0.1, -0.1, -50, 0.000001, -50, 0.000001, -50, 0.000001];
    opts.Display = 'Off';
    opts.MaxFunEvals = 10000;
    opts.MaxIter = 10000;
    opts.Robust = 'Bisquare';
```

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Listing A.9: Creating Curve Fit Equation for Recovery Room in the Center of the Panel

function [fitresult, gof] = create_Recovery_Center(FtX, FtY, Z1, Title)

% Fit: 'RECOVERY CENTER FIT'.
[xData, yData, zData] = prepareSurfaceData( FtX, FtY, Z1 );
ex = excludedata(xData, yData, 'indices', find((yData>0.066666 & yData<0.08717)));

% Set up fittype and options.
ft = fittype('a+(x)^2*(-0.007156676)+b*y*exp(-b1*y^2)+c*exp(-c1*y^2)+d*y^2*exp(-d1*...'
opts = fitoptions( ft );
opts.DiffMaxChange = 0.1;
opts.DiffMinChange = 1e-16;
opts.Display = 'Off';
opts.MaxFunEvals = 10000;
opts.MaxIter = 10000;
opts.Robust = 'Bisquare';
opts.Lower = [0 0 -1 -1 290 -1 0];
opts.StartPoint = [0.07967 -0.007 0.459 2.445 -0.03708 300 0.2533 0.5165];
opts.Upper = [0.8 -0.5 1 10 1 1e6 1 1e3];
opts.Exclude = ex;

% Fit model to data.
[fitresult, gof] = fit( [xData, yData], zData, ft, opts );

Listing A.10: Creating Curve Fit Equation for Gateroad Center of the Panel

function [fitresult, gof] = create_center_gateroad(FtX, FtY, Z4, Title)

% Auto-generated by MATLAB on 12-Jun-2013 11:22:17
% Fit: 'CENTER GATEROAD FIT'.
[xData, yData, zData] = prepareSurfaceData( FtX, FtY, Z4 );

% Set up fittype and options.
ft = fittype('a+g*x+y*(a1)+b*x*exp(-b1*x)+c*exp(-c1*(x)^2)+d*x*exp(-d1*(x)^2)+e*...'
opts = fitoptions( ft );
opts.DiffMinChange = 1e-16;
opts.Display = 'Off';
opts.MaxFunEvals = 10000;
opts.MaxIter = 10000;
opts.Robust = 'Bisquare';
opts.Lower = [0.1 0 0.1 1 -1 100 -1 1 -5 1 0];
opts.StartPoint = [0.1 0.000604 2.1 4.1 -0.1 1400 -0.47 5.38 -1.47 23.91 0.12];
opts.Upper = [1 0.01 5 20 0 1e5 0 20 0 100 1];
opts.TolFun = 1e-16;
opts.TolX = 1e-16;
% Fit model to data.
[fitresult, gof] = fit( [xData, yData], zData, ft, opts );

The startup room gateroad section curve fitting code in Listing A.11 and recovery room
gateroad corner code in Listing A.9 applies to a fixed width and length. The corner of the
gob intersects in a singularity or zero change in the VSI. This is modeled by multiplying
the whole function with a fractional exponent in x and y. The fixed range from 0.01 to
0.1 seemed to produce repeatable results in the three equations fit during this project. A
process of fixing each coefficient one by one can further improve the quality of the fit, and
then further matching of the curvature of the data by selecting data points to exclude.

Listing A.11: Creating Curve Fit Equation for Start-up Room Gateroad Corner

function [fitresult, gof] = create_corner_FIT_fractional(FtX, FtY, Z2, Title)
% Auto-generated by MATLAB on 12-Jun-2013 16:57:37
% Fit: 'GOB CORNER FITTING'.
[xData, yData, zData] = prepareSurfaceData( FtX, FtY, Z2 );
% Set up fittype and options.
% FIXED EQUATION FRAGMENT:
% + 0.0364*exp(-9.3*x*y) + (0.0350*exp(-66.8104*x^2*y^2)
ft=fittype ( '(x*y)^f*(a+c*exp(-d*y)*x*y+(d11*exp(-b11*x*y)-d10*exp(-b10*x)
-d01*exp(-b01*y)) +g*x^2*exp(-h*x))’, ‘independent’, {’x’, ’y’}, ’
dependent’, ’z’);    
opts = fitoptions( ft );
opts.DiffMinChange = 1e-16;
opts.DiffMaxChange = 0.001;
opts.Display = ’Off’;
% [a b01 b10 b11 c d d01 d10 d11 f h g]
opts.Lower = [0.2 1 1 1 .1 1 0.2 .15 0.01 0.01 0.1 1];
opts.StartPoint = [0.22 49.4 33.3 4.5 .21 3 0.4 0.2 0.03 0.0726 0.3628 2.52];
opts.Upper = [0.265 1e9 100 15 .5 5.5 0.5 .4 0.09 0.1 0.5 10];
Listing A.12: Creating Curve Fit Equation for Recovery Room Gateroad Corner

function [fitresult, gof] = create_Recovery_corner_FIT_fractional(FtX, FtY, Z2, Title)
% Auto-generated by MATLAB on 12-Jun-2013 16:57:37
% Fit: 'RECOVERY ROOM GOB CORNER'.
[xData, yData, zData] = prepareSurfaceData(FtX, FtY, Z2);
% Set up fittype and options.
% EQUATION_FRAGMENT: + 0.0364*exp(-9.3*x*y) + (0.0350*exp(-66.8104*x^2*y^2)
ft = fittype('((x)*(y))^f*(a+c*exp(-d*y)*x*y+d11*exp(-b11*x*y)-d01*exp(-b01
*y)+g*...
   x^2*exp(-h*x^2)+k*y^2*exp(-l*y)+m*x*exp(-n*x)+o*x*exp(-p*x^2)+q*
   exp(-r*...
   x)+s*y*exp(-t*y)+u*y*exp(-v*y^2))', 'independent', {'x', 'y'}, 'dependent', 'z');
optimset = fitoptions(ft);
optimset.DiffMinChange = 1e-16;
optimset.DiffMaxChange = 0.001;
optimset.Display = 'off';
% [ a b01 b10 b11 c d d01 d10 d11 f g h k l m n o p q r s t u v ]
optimset.Lower = [0.001 1 1 -1e3 -1 0 0 1e-4 -1 .1 -5 0 -50 0 -50 -1e5 0 -1 0 0
-1 5];
optimset.StartPoint =
   [0.2 8 20 .001 .1 .3 .03 .01 -.3 20 5 6 -20 55 1 50 35 3e3 1 16
   -.3 7]
optimset.Upper =
   [.6 50 1e3 5 100 .5 .1 .9 -0.01 50 1e4 50 50 1e3 50 1e5 500 1e6 1e4 1e6
   1 100];
optimset.MaxFunEvals = 100000;
optimset.MaxIter = 100000;
optimset.Robust = 'Bisquare';
optimset.TolFun = 1e-16;
optimset.TolX = 1e-16;
The center of the panel section curve fitting code in Listing A.13 used a Y-direction smoothing 1st order polynomial. The variation in the \(x\) and \(y\) direction is extremely small by looking at the coefficients. To simplify the scalability of the panel in length and width a constant value was assumed to be sufficient to model this section.

Listing A.13: Creating Curve Fit Equation for Center of the Panel

```matlab
function [fitresult, gof] = create_center_panel(FtX, FtY, Z3, Title)
% Auto-generated by MATLAB on 12-Jun-2013 13:29:00
%% Fit: 'CENTER PANEL FIT'.
[xData, yData, zData] = prepareSurfaceData( FtX, FtY, Z3 );
% Set up fit type and options.
ft = fittype( 'a + b*x^2+d*x+c*(y-0.5)+e*x*(y-0.5)' , 'independent' , ... 
    opts = fitoptions( ft );
    opts.DiffMinChange = 1e-16;
    opts.Display = 'Off';
    opts.Lower = [0.1 -0.1 -0.01 -0.1 -0.1];
    opts.MaxFunEvals = 10000;
    opts.MaxIter = 10000;
    opts.Robust = 'Bisquare';
    opts.StartPoint = [0.335 -0.00718 0.004 0.008815 0.05];
    opts.TolFun = 1e-16;
    opts.TolX = 1e-16;
    opts.Upper = [0.5 0 0.04 0.01 0.1];
% Fit model to data.
[fitresult, gof] = fit( [xData, yData], zData, ft, opts );
```

Figure A.6 shows all the results of the individual fits. The edges of the gob show an excellent match to the shape of the data for all fits over the previous methods using a polynomial fit, or ignoring the shape all together. Figure A.7 shows the result of a refined final version of the startup gateroad equation fit. The axes are normalized from 0 to 1 and the data match the zeros on all edges with no waviness in the data along the gateroad or startup room edges.
Figure A.6: Curve Fit Results

Figure A.7: Startup Gateroad Fit Result
APPENDIX B - USER-DEFINED-FUNCTION (UDF) CODE

The User-Defined-Function code is contained in Listing B.14 through Listing B.20. The instruction for defining the variable in the scheme Fluent programming environment can be found in the Fluent UDF Manual Section 3.6 Scheme Macros and a brief explanation is included in the comments at the top of Listing B.14. The VSI values are calculated using one of four DEFINE_ON_DEMAND functions that save the values into a user-define-memory location number 4 (udm-4). The viscous resistance values, initial permeability, and porosity functions are used in the DEFINE_PROFILE functions.

Listing B.14: UDF Part 1 – Using the Code and Functions

-- Colorado School of Mines --
Author implementation
Richard C. Gilmore & Dan Worrall Jr. & Jonathan A. Marts
-- Uses with ANSYS FLUENT 15.0 --
Text User Interface Control Commands:
see FLUENT UDF manual Section: 3.6 Scheme Macros
REQUIRED settings:
To set the full panel width and length for the equation to fit
(rp-var-define 'vsi/panel-width 200 'real #f)
(rp-var-define 'vsi/panel-length 3078.48 'real #f)
To set the offset from (x=0, y=0) at the center panel (x-directions) of the recovery room (y-direction) or active face. For example the center of the panel is located at a negative x-direction of 341 meters
(rp-var-define 'vsi/panel-xoffset -341 'real #f)
The recovery room of the panel is located at a positive y-direction of 940 meters.
(rp-var-define 'vsi/panel-yoffset 940 'real #f)
To use multiple panels compile to libudf libraries and set the displacement variables to the correct value before executing. Also,
must assign each panel past the first to a new user-defined-memory location search and replace this code assignment "C_UDMI(c,t,4)" and increment to 5

OPTIONAL settings:
To set a Carman-Kozeny Equation Scalar relationship multiplier:
(rp-var-define 'vsi/resist-scalar 10 'real #f)
To set a Maximum resistance in the gob center that will crop the equation fit to this value:
(rp-set-define 'vsi/maximum-resist 5.0e6 'real #f)
To set a Minimum resistance in the outer edge of the gob that will crop the equation fit to this value:
(rp-set-define 'vsi/minimum-resist 1.45e5 'real #f)
To set the Maximum Porosity in the Gob (0.4 to 0.5):
(rp-var-define 'vsi/maximum-porosity 0.40 'real #f)
To set the Initial Porosity of the Host Rock (Undisturbed rock):
(rp-var-define 'vsi/initial-porosity 0.2577800000000 'real #f)
To set the Maximum Value of VSI change at the center of the panel:
(rp-var-define 'vsi/maximum-vsi 0.40 'real #f)
To display current values of a variable: (%rpgetvar 'vsi/var-name)
To change value: (rpsetvar 'vsi/var-name VALUE)

#include "udf.h"
define domain_ID 2
#include "math.h"

/* PROTOTYPES DECLARED */
/* ----------------------------- Mine E fits -----------------------------*/
double SUPER_CRITICAL_MINE_E_STARTUP_CENTER(double x_loc , double y_loc) ;
double SUPER_CRITICAL_MINE_E_CENTER_PANEL(double x_loc , double y_loc);
double SUPER_CRITICAL_MINE_E_RECOVERY_CENTER(double x_loc , double y_loc );
double SUPER_CRITICAL_MINE_E_RECOVERY_GATERoads(double x_loc , double y_loc ) ;
double SUPER_CRITICAL_MINE_E_STARTUP_GATERoads(double x_loc , double y_loc );
double SUPER_CRITICAL_MINE_E_CENTER_GATERoads(double x_loc , double y_loc );

/* ----------------------------- Mine C fits -----------------------------*/
double SUPER_CRITICAL_MINE_C_STARTUP_CENTER(double x_loc , double y_loc ) ;
double SUPER_CRITICAL_MINE_C_CENTER_PANEL(double x_loc , double y_loc);
double SUPER_CRITICAL_MINE_C_RECOVERY_CENTER(double x_loc , double y_loc );
double SUPER_CRITICAL_MINE_C_RECOVERY_GATERoads(double x_loc , double y_loc ) ;
double SUPER_CRITICAL_MINE_C_STARTUP_GATERoads(double x_loc , double y_loc );

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double SUPER_CRITICAL_MINE_C_CENTER_GATERoads(double x_loc, double y_loc);

/*----------------------- Trona fits -----------------------*/
double SUB_CRITICAL_Trona_RECOVERY_CORNER(double x_loc, double y_loc);
double SUB_CRITICAL_Trona_CENTER_GATERoad(double x_loc);
double SUB_CRITICAL_Trona_STARTUP_CORNER(double x_loc, double y_loc);
double Initial_Perm();
double Cell_Resistance(double cellporo, double initial_perm); void Print_Scheme_Variable_Settings();
int ite = 0;
double Cell_Resistance(double cellporo, double initial_perm) {
    /* The Carman-Kozeny equation for flow through porous media was 
       used to estimate the permeability of the gob (K) as follows: K = K_o / 0.241 *(n^3/(1-n)^2) 
       Where K_o is the base permeability of the broken rock at the maximum 
       porosity, and n is the porosity. The value of K_o was taken as 
       1x10^-6 milliDarcies which places it in the "open jointed rock" range 
       according to Hoek and Bray (1981).* /
    double cellperm;
    cellperm = initial_perm / 0.241 * (cellporo * cellporo * cellporo) / ((1.0 - cellporo) * (1.0 - cellporo));
    return (1.0 / cellperm); }
double Initial_Perm() {
    /* K_o=n^3 / (180 * (1-n)^2) * d^2 where K_o is permeability 
       (milliDarcies), n is porosity (%) and d is the mean particle 
       diameter (meters). The mean particle diameter from Pappas & 
       Mark 1993 = 0.2 meters, Kozeny constant 180. */
    double initial_porosity = 0.25778;
    if (RP_Variable_Exists_P("vsi/initial-porosity")) {
        /* Returns true if the variable exists */
        initial_porosity = (RP_Get_Real("vsi/initial-porosity") );
    }
    return (initial_porosity * initial_porosity * initial_porosity) / (180.0 * (1.0 - initial_porosity) * (1.0 - initial_porosity)) * 0.2 * 0.2;
    } }
DEFINE_ADJUST(demo_calc,d) {
    ite = ite + 1;
    } 

/*Position-Dependent Porous Media USING VSI SUB-CRITICAL*/

DEFINE_ON_DEMAND(VSI_MINE_Trona_Steped) {
    Domain *d; Thread *t; cell_t c; real x[ND,ND];
    /* Fluent location vectors */
    double x_loc_norm, y_loc_norm, x_loc, y_loc;
    double panelwidth = 100; /* specified here as half-width */
    double panellength = 3078.48;
    double panelxoffset = 0.0;
    double panelyoffset = 0.0;
double VSI = 0;
double FUN1, FUN2;
double maximum_vsi = 0.22;
double blendrangey = 25, mix = 0.5;
double box[6] = {0, 100, 0, 300, 600, 1000};
/* default panel sizing */
d = Get_Domain(1);
/* Assign new panel size from scheme variable define with in
FLUENT or use the default sizing above */
/* Returns true if the variable exists */
if ( RP.Variable_Exists_P ("vsi/panel-width") ) {
    panelwidth = ( RP.Get_Real("vsi/panel-width") / 2 );
    /* else default or manual set above is used */
    Message("Panel width is: %g\n", panelwidth*2); }
else{ Message("Panel Width not set. Using default value: %g\n You may
set it with TUI Command:
(rp-var-define 'vsi/panel-width VALUE 'real #f)\n", panelwidth*2); }
box[1] = panelwidth;
if ( RP.Variable_Exists_P ("vsi/panel-length") ){
    panellength = ( RP.Get_Real("vsi/panel-length") ) ;
    Message("Panel length is set to: %g\n reset value using
(rpsetvar 'vsi/panel-length VALUE)\n", panellength); }
else{ Message("Panel Length not set. Using default value: %g\n
You may set it with TUI Command:
(rp-var-define 'vsi/panel-length VALUE 'real #f)\n", panellength); }
box[4] = panellength-400;
box[5] = panellength;
/* Specify a maximum value of VSI for the change porosity
from the scheme variable defined in FLUENT */
if ( RP.Variable_Exists_P ("vsi/maximum-vsi") ){
    maximum_vsi = ( RP.Get_Real("vsi/maximum-vsi") ) ;
    Message("The Maximum change in porosity from the maximum-porosity
behind the face occurs \nat the center of the panel and is set to: %
g\n", maximum_vsi); }
else{ Message("Maximum change in porosity from the maximum-porosity
behind the face occurs \nat the center of the panel and is NOT set.
Using default value: %g\n You may set it with TUI Command:
(rp-var-define 'vsi/maximum-vsi VALUE 'real #f)
\n", maximum_vsi); }
/* Specify the displacement to the center of the old panel
from the scheme variable defined in FLUENT */
if ( RP.Variable_Exists_P ("vsi/panel-xoffset") ){
    panelxoffset = ( RP.Get_Real("vsi/panel-xoffset") ) ;
    Message("The x-direction displacement to the center of the panel
is set to: %g\n", panelxoffset); }
else{ Message("The x-direction displacement to the center of the panel
is to zero. \n You may set it with TUI Command:

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/* Specify the displacement to the recovery room of the old panel from the scheme variable defined in FLUENT */
if (RP_Variable_Exists_P("vsi/panel-yoffset")){
    panelyoffset=( RP_Get_Real("vsi/panel-yoffset") );
    Message ("The y-direction displacement to the recovery room of the panel is set to: %g\n",panelyoffset);
} else{
    Message("The y-direction displacement to the recovery room of the panel is to zero.\n You may set it with TUI Command: (rp-var-define 'vsi/panel-yoffset VALUE 'real #f)\n");
}
thread_loop_c(t,d){
    begin_c_loop(c,t){
        C_CENTROID(x,c,t) /* Get mesh cell location */
        / * Scale each section of the model to the curve fits. */
        MIN=144871.4 1/m² MAX=492170 1/m² /*
        / * UPDATE VALUES */
        x_loc=fabs(x[0]-panelyoffset);
        /* Center of Panel is Zero and Mirrored */
        / * Shift FLUENT MESH to FLAC3D data Zero point at startup room for equations */
        y_loc=(panelength+x[1])-panelyoffset;
        / * limit VSI function to only within panel domain sizing */
        if (x_loc>panelwidth ) { VSI=0; }
    else
        if (y_loc<0) {VSI=0; }
        else if(y_loc < box[3]-blendrangey){
            /* NORMALIZE to equation */
            x_loc_norm=( -(x_loc-box[1])/(box[1]) );
            y_loc_norm=( y_loc /box[5] );
            VSI=SUB_CRITICAL_Troma_STARTUP_CORNER(x_loc_norm , y_loc_norm );
            VSI=SUB_CRITICAL_Troma_CENTER_GATEROAD(x_loc_norm , )
            FUN1=SUB_CRITICAL_Troma_CENTER_GATEROAD(x_loc_norm , );
            FUN2=SUB_CRITICAL_Troma_CENTER_GATEROAD(x_loc_norm , );

        else if((y_loc<(box[3]+blendrangey))&&y_loc>(box[3]-blendrangey))
            mix= -( (y_loc-box[3]-blendrangey)/(2*blendrangey) ) ;
            x_loc_norm=( -(x_loc-box[1])/(box[1] ) );
            y_loc_norm=(y_loc /box[5] );
            FUN1=SUB_CRITICAL_Troma_CENTER_GATEROAD(x_loc_norm , );
            FUN2=SUB_CRITICAL_Troma_CENTER_GATEROAD(x_loc_norm , );
            VSI=SUB_CRITICAL_Troma_CENTER_GATEROAD(x_loc_norm , );
            x_loc_norm=( -(x_loc-box[1])/(box[1] ) );
            FUN1=SUB_CRITICAL_Troma_CENTER_GATEROAD(x_loc_norm , );
            FUN2=SUB_CRITICAL_Troma_CENTER_GATEROAD(x_loc_norm , );
            VSI=SUB_CRITICAL_Troma_CENTER_GATEROAD(x_loc_norm , );
            x_loc_norm=( -(x_loc-box[1])/(box[1] ) );
            FUN1=SUB_CRITICAL_Troma_CENTER_GATEROAD(x_loc_norm , );
            FUN2=SUB_CRITICAL_Troma_CENTER_GATEROAD(x_loc_norm , );
        else if((y_loc<(box[4]-blendrangey-20))&&y_loc>(box[4]-blendrangey+20))
            x_loc_norm=( -(x_loc-box[1])/(box[1] ) );
            FUN1=SUB_CRITICAL_Troma_CENTER_GATEROAD(x_loc_norm , );
            FUN2=SUB_CRITICAL_Troma_CENTER_GATEROAD(x_loc_norm , );
        else if((y_loc<(box[4]-blendrangey+20))&&y_loc>(box[4]-blendrangey-20))
            x_loc_norm=( -(x_loc-box[1])/(box[1] ) );
            FUN1=SUB_CRITICAL_Troma_CENTER_GATEROAD(x_loc_norm , );
            FUN2=SUB_CRITICAL_Troma_CENTER_GATEROAD(x_loc_norm , );
            x_loc_norm=( -(x_loc-box[1])/(box[1] ) );
            FUN1=SUB_CRITICAL_Troma_CENTER_GATEROAD(x_loc_norm , );
            FUN2=SUB_CRITICAL_Troma_CENTER_GATEROAD(x_loc_norm , );
    }
} else{
    x_loc_norm=( -(x_loc-box[1])/(box[1]+40) ) +0.02;
}
\[
y_{\text{loc}}_{\text{norm}} = -(y_{\text{loc}} - \text{box}[5]) / (\text{box}[5] - \text{box}[4]) + .012;
\]

\[
\text{FUN2} = \text{SUB}\_\text{CRITICAL}\_\text{Trona}\_\text{RECOVERY}\_\text{CORNER}(x_{\text{loc}}_{\text{norm}}, y_{\text{loc}}_{\text{norm}});
\]

\[
\text{mix} = -(y_{\text{loc}} - \text{box}[4] - \text{blendrangey} - 20) / (2 \times \text{blendrangey} + 40);
\]

\[
\text{VSI} = \text{SUB}\_\text{CRITICAL}\_\text{Trona}\_\text{RECOVERY}\_\text{CORNER}(x_{\text{loc}}_{\text{norm}}, y_{\text{loc}}_{\text{norm}});
\]

\[
\text{else if}((y_{\text{loc}} < \text{box}[5]) \&\& (y_{\text{loc}} > (\text{box}[4] + \text{blendrangey} + 20))
\]

\[
/* \text{Remained of data points are in the recovery room 600-1000m}*/
\]

\[
x_{\text{loc}}_{\text{norm}} = -(x_{\text{loc}} - \text{box}[1]) / (\text{box}[1] + 40) + 0.02;
\]

\[
y_{\text{loc}}_{\text{norm}} = -(y_{\text{loc}} - \text{box}[5]) / (\text{box}[5] - \text{box}[4]) + .012;
\]

\[
\text{VSI} = \text{SUB}\_\text{CRITICAL}\_\text{Trona}\_\text{RECOVERY}\_\text{CORNER}(x_{\text{loc}}_{\text{norm}}, y_{\text{loc}}_{\text{norm}});
\]

\[
\text{else} \{ \text{VSI} = 0; \}
\]

\[
/* \text{Assign VSI to user-defined-memory location after cropping to maximum change} */
\]

\[
\text{CUDMI}(c,t,4) = (\text{VSI} > \text{maximum_vsi})?\text{maximum_vsi}:\text{VSI};
\]

\end{c_loop}(c,t)

Print_Scheme_Variable_Settings();

}/* MINE C */

DEFINE_ON_DEMAND(VSI_MINE_C_Stepped){

  Domain *d; Thread *t; cell_t c; real x[ND\_ND];
  /* Fluent location vectors */
  double x_{\text{loc}}_{\text{norm}}, y_{\text{loc}}_{\text{norm}}, x_{\text{loc}}, y_{\text{loc}};
  double panelwidth = 151.4856; /* specified here as half-width */
  double panelength = 1000;
  double panelxoffset = 0.0;
  double panelyoffset = 0.0;
  double VSI = 0;
  double FUN1, FUN2;
  double maximum_vsi = 0.2623;
  double blendrange = 15, blendrangey = 25, mix = 0.5;
  double box[7] = {0, 100, 200, 0, 190, 700, 1000};
  d = Get_Domain(1);

  /* Assign new panel size from scheme variable define with in FLUENT or use the default sizing above */
  /* Returns true if the variable exists */
  if (RP_Variable_Exists_P("vsi/panel-width")){
    panelwidth = (RP_Get_Real("vsi/panel-width") / 2);
    /* else default or manual set above is used */
    Message("Panel width is: %g\n", panelwidth*2);
  }
  else { Message("Panel Width not set. Using default value: %g\n"
    You may set it with TUI Command:
    (rp-var-define 'vsi/panel-width VALUE 'real #f)\n    box[1] = panelwidth-100.0;
    box[2] = panelwidth;

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if ( RP_Variable_Exists_P("vsi/panel-length") ){
    panelength=( RP_Get_Real("vsi/panel-length") );
    Message("Panel length is set to: %g\n reset value using
        ( rpsetvar 'vsi/panel-length VALUE)\n",panelength); }
else{ Message("Panel Length not set. Using default value: %g
You may set it with TUI Command:
        (rp-var-define 'vsi/panel-length VALUE real #f)\n", panelength);
    box[5]=panelength-300;
    box[6]=panelength;
/* Specify a maximum value of VSI for the change porosity from the scheme variable defined in FLUENT */
if ( RP_Variable_Exists_P("vsi/maximum-vsi") ){
    maximum_vsi=( RP_Get_Real("vsi/maximum-vsi") );
    Message("The Maximum change in porosity from the maximum-porosity
        behind the face occurs \nat the center of the panel and is set to: %g\n",maximum_vsi);
} else{ Message("Maximum change in porosity from the maximum-porosity
        behind the face occurs at the center of the panel and is NOT
        set.
        Using default value: %g\n You may set it with TUI Command:
        (rp-var-define 'vsi/maximum-vsi VALUE real #f)\n", maximum_vsi );
/* Specify the displacement to the center of the old panel from the scheme variable defined in FLUENT */
if ( RP_Variable_Exists_P("vsi/panel-xoffset") ){
    panelxoffset=( RP_Get_Real("vsi/panel-xoffset") );
    Message("The x-direction displacement to the center of the panel
        is set to: %g\n",panelxoffset);
} else{ Message("The x-direction displacement to the center of the
        panel is to zero. \n You may set it with TUI Command:
        (rp-var-define 'vsi/panel-xoffset VALUE 'real '#f)\n" );
/* Specify the displacement to the recovery room of the old panel from the scheme variable defined in FLUENT */
if ( RP_Variable_Exists_P("vsi/panel-yoffset") ){
    panelyoffset=( RP_Get_Real("vsi/panel-yoffset") );
    Message("The y-direction displacement to the recovery room of the
        panel is set to: %g\n",panelyoffset);
} else{ Message("The y-direction displacement to the recovery room of the
        panel is to zero. \n You may set it with TUI Command:
        (rp-var-define 'vsi/panel-yoffset VALUE 'real '#f)\n" );

thread_loop_c(t,d) {
    begin_c_loop(c,t) {
        C_CENTROID(x,c,t);
        /* Scale each section of the model to the curve fits.
            MIN=144871.4 1/m²  MAX=492170 1/m² */
        x_loc=fabs(x[0]-panelxoffset);
        /* Center of Panel is Zero and Mirrored */
/* Shift FLUENT MESH to FLAC3D data Zero point at startup */
y_loc=(panelength+x[1])-panelyoffset;

/* limit VSI function to only within panel domain sizing */
if( x_loc>panelwidth ){ VSI=0; }
else{
  if( x_loc < (box[1]-blendrange) ) {
    if ( y_loc <0 ) {VSI=0;}
    else if ( y_loc < box[4]-blendrangey-15){
      /* NORMALIZE to equation */
      x_loc_norm=( (x_loc-box[1])+20 )/( box[1] ) ;
      y_loc_norm=(y_loc/box[4]) ;
      VSI =SUPER_CRITICAL_MINE_C_STARTUP_CENTER(x_loc_norm , y_loc_norm);
      }
      mix= ( y_loc-blendrangey-15)/ (2*blendrangey +30) ;
      /* NORMALIZE to equation */
      x_loc_norm=( (y_loc-blendrangey-15) )/( box[1] ) ;
      y_loc_norm=(y_loc/box[4]) ;
      FUN1 =SUPER_CRITICAL_MINE_C_STARTUP_CENTER(x_loc_norm , y_loc_norm);
      }
    else if ( y_loc>(box[4]-blendrangey-15))&&
      (y_loc<box[4]+blendrangey-15)){
      x_loc_norm=( (y_loc-blendrangey-15) )/( box[1] ) ;
      y_loc_norm=(y_loc/box[4]) ;
      FUN2 = SUPER_CRITICAL_MINE_C_CENTER_PANEL(x_loc_norm , y_loc_norm);
      VSI=(FUN2*(mix)+FUN1*(1-mix)) ;
    } else if ( (y_loc>box[5]-blendrangey-15))&&
      (y_loc<box[5]+blendrangey+15)){
      mix = -((y_loc-box[5]-blendrangey-15)/(2*blendrangey+30));
      x_loc_norm=( (y_loc-box[1]) )/( box[1] ) ;
      y_loc_norm=( (y_loc-box[4])/ (box[5]-box[4])) ;
      FUN1 = SUPER_CRITICAL_MINE_C_CENTER_PANEL(x_loc_norm , y_loc_norm);
      }
    else if ( (y_loc>box[5]-blendrangey-15))&&
      (y_loc>box[5]+blendrangey+15)){
      x_loc_norm=( (y_loc-box[1]) )/( box[1] ) ;
      y_loc_norm=( (y_loc-box[4])/ (box[5]-box[4]) ) ;
      FUN2 = SUPER_CRITICAL_MINE_C_RECOVERY_CENTER(x_loc_norm , y_loc_norm);
      VSI=(FUN1*(mix)+FUN2*(1-mix)) ;
    }
  }
  /*Remained of data points are in the recovery room 600-1000m*/
\[ x_{\text{loc norm}} = \left( \frac{x_{\text{loc}} - \text{box}[1] + \text{blendrange} + 15}{\text{box}[1]} \right); \]
\[ y_{\text{loc norm}} = \left( 1 - \frac{y_{\text{loc}} - \text{box}[5]}{\text{box}[6] - \text{box}[5]} \right); \]
\[ \text{VSI} = \text{SUPER\_CRITICAL\_MINE\_C\_RECOVERY\_CENTER}(x_{\text{loc norm}}, y_{\text{loc norm}}); \]
\text{else}\ {\{\text{VSI}=0;\}}
\}

\text{else if}\ (x_{\text{loc}} \leq (\text{box}[1]+\text{blendrange}))\{\}
\text{mix} = \left( \frac{x_{\text{loc}} - \text{box}[1] + \text{blendrange}}{2 \times \text{blendrange}} \right); \]
\text{if}\ (y_{\text{loc}} < 0)\ {\{\text{VSI}=0;\}}
\text{else if}(y_{\text{loc}} < \text{box}[4])\{\}
\text{/* NORMALIZE to equation */}\]
\[ x_{\text{loc norm}} = \left( -\frac{x_{\text{loc}} - \text{box}[1]}{\text{box}[1]} \right); \]
\[ y_{\text{loc norm}} = \left( \frac{y_{\text{loc}}}{\text{box}[4]} \right); \]
\text{FUN1=SUPER\_CRITICAL\_MINE\_C\_STARTUP\_CENTER}(x_{\text{loc norm}}, y_{\text{loc norm}}); \]
\[ x_{\text{loc norm}} = \left( 1 - \frac{(x_{\text{loc}} - \text{box}[1])}{(\text{box}[2] - \text{box}[1])} \right); \]
\[ y_{\text{loc norm}} = \left( \frac{y_{\text{loc}}}{\text{box}[4]} \right); \]
\text{VSI} = (\text{FUN2} \times \text{mix}) + (\text{FUN1} \times (1 - \text{mix})); \}
\text{else if}(y_{\text{loc}} \leq \text{box}[5])\{\}
\text{FUN1=SUPER\_CRITICAL\_MINE\_C\_CENTER\_PANEL}(x_{\text{loc norm}}, y_{\text{loc norm}}); \]
\[ x_{\text{loc norm}} = \left( 1 - \frac{(x_{\text{loc}} - \text{box}[1])}{(\text{box}[2] - \text{box}[1])} \right); \]
\[ y_{\text{loc norm}} = \left( \frac{y_{\text{loc}}}{\text{box}[4]} \right); \]
\text{FUN2=SUPER\_CRITICAL\_MINE\_C\_CENTER\_GATEROADS}(x_{\text{loc norm}}, y_{\text{loc norm}}); \]
\text{VSI} = (\text{FUN2} \times \text{mix}) + (\text{FUN1} \times (1 - \text{mix})); \}
\text{else if}(y_{\text{loc}} < \text{box}[6])\{\}
\text{FUN1=SUPER\_CRITICAL\_MINE\_C\_RECOVERY\_CENTER}(x_{\text{loc norm}}, y_{\text{loc norm}}); \]
\[ x_{\text{loc norm}} = \left( 1 - \frac{(x_{\text{loc}} - \text{box}[1])}{(\text{box}[2] - \text{box}[1])} \right); \]
\[ y_{\text{loc norm}} = \left( \frac{y_{\text{loc}}}{\text{box}[4]} \right); \]
\text{FUN2=SUPER\_CRITICAL\_MINE\_C\_RECOVERY\_GATEROADS}(x_{\text{loc norm}}, y_{\text{loc norm}}); \]
\text{VSI} = (\text{FUN2} \times \text{mix}) + (\text{FUN1} \times (1 - \text{mix})); \}
\text{else}\ {\{\text{VSI}=0;\}}
\}
\text{else}\{\}
\text{if}(y_{\text{loc}} < 0)\ {\{\text{VSI}=0;\}}
\text{else if}(y_{\text{loc}} < \text{box}[4]-\text{blendrange})\{\}
\text{x}_{\text{loc norm}} = \left( 1 - \frac{(x_{\text{loc}} - \text{box}[1])}{(\text{box}[2] - \text{box}[1])} \right); \]
\[ y_{\text{loc norm}} = \left( \frac{y_{\text{loc}}}{\text{box}[4]} \right); \]
\text{VSI} = \text{SUPER\_CRITICAL\_MINE\_C\_STARTUP\_GATEROADS}(x_{\text{loc norm}}, y_{\text{loc norm}}); \}
\text{else}\ {\{\text{VSI}=0;\}}
else if ((y_loc>(box[4]-blendrangey))&&(y_loc<box[4]+blendrangey)) {
    mix = ((y_loc-box[4]+blendrangey)/(2*blendrangey));
    x_loc_norm = ( 1-(x_loc-box[1])/( box[2]-box[1] ) ) ;
    y_loc_norm = (y_loc/box[4]) ;
    FUN1=SUPER_CRITICAL_MINE_C_STARTUP_GATERoads(x_loc_norm , y_loc_norm) ;
    x_loc_norm = ( 1-(x_loc-box[1])/( box[2]-box[1] ) ) ;
    y_loc_norm = ( (y_loc-box[4])/( box[5]-box[4] ) ) ;
    VSI=SUPER_CRITICAL_MINE_C_CENTER_GATERoads(x_loc_norm , y_loc_norm) ;
}
else if ((y_loc<(box[5]-blendrangey-20))&&(y_loc>(box[4]+blendrangey))) {
    x_loc_norm = ( 1-(x_loc-box[1])/( box[2]-box[1] ) ) ;
    y_loc_norm = ( (y_loc-box[4])/( box[5]-box[4] ) ) ;
    VSI=SUPER_CRITICAL_MINE_C_CENTER_GATERoads(x_loc_norm , y_loc_norm) ;
}
else if ((y_loc>(box[5]-blendrangey-20))&&(y_loc<box[5]+blendrangey+20)) {
    mix = ((y_loc-box[5]+blendrangey)/(2*blendrangey)) ;
    x_loc_norm = ( 1-(x_loc-box[1])/( box[2]-box[1] ) ) ;
    y_loc_norm = ( (y_loc-box[4])/( box[5]-box[4] ) ) ;
    FUN1=SUPER_CRITICAL_MINE_C_CENTER_GATERoads(x_loc_norm , y_loc_norm) ;
    x_loc_norm = ( 1-(x_loc-box[1])/( box[2]-box[1] ) ) ;
    y_loc_norm = (1-(y_loc-box[5])/( box[6]-box[5] )) ;
    FUN2=SUPER_CRITICAL_MINE_C_RECOVERY_GATERoads(x_loc_norm , y_loc_norm) ;
    VSI= (FUN2*(mix)+FUN1*(1-mix)) ;
}
else if (y_loc<panelength) {
    x_loc_norm = ( 1-(x_loc-box[1])/( box[2]-box[1] ) ) ;
    y_loc_norm = (1-(y_loc-box[5])/( box[6]-box[5] )) ;
    VSI=SUPER_CRITICAL_MINE_C_RECOVERY_GATERoads(x_loc_norm , y_loc_norm) ;
}
else { VSI=0;}
}
VSI=(VSI<0.0) ? 0 : VSI ;
VSI=(VSI>maximum_vsi)?maximum_vsi:VSI ;
C_UDMI(c , t , 4) = VSI ;
}
end_c_loop(c , t )
Print_Scheme_Variable_Settings() ;
/* MINE E */
DEFINE_ON_DEMAND(VSI_MINE_E_Stepped){
    Domain *d; Thread *t; cell_t c; real x[ND,ND];
    /* Fluent location vectors */
    double x_loc, y_loc, x_loc_norm, y_loc_norm, x_loc, y_loc;
    double panelwidth=151.4856;
    /* specified here as half-width */
    double panellength=1000;
    double panelxoffset=0.0;
    double panelyoffset=0.0;
    double VSI=0;
    double FUN1, FUN2;
    double maximum_vsi=0.179;
    double blendrange=20, blendrangey=20, mix=0.5;
    double box[7]=
        {0, 100, 200, 0, 190, 700, 1000};
    d = Get_Domain(1);
    /* Assign new panel size from scheme variable defined with in
    FLUENT or use the default sizing above */
    /* Returns true if the variable exists */
    if (RP_Variable_Exists_P("vsi/panel-width")) {
        panelwidth=(RP_Get_Real("vsi/panel-width") / 2);
        /* else default or manual set above is used */
        Message("Panel width is: %g\n", panelwidth*2);
    } else {
        Message("Panel Width not set. Using default value: %g\n You may
        set it with TUI Command:
        (rp-var-define 'vsi/panel-width VALUE 'real #f)\n" , panelwidth *2);
    }
    box[1]=panelwidth-100.0;
    box[2]=panelwidth;
    if (RP_Variable_Exists_P("vsi/panel-length")) {
        panellength=(RP_Get_Real("vsi/panel-length") );
        Message("Panel length is set to: %g\n reset value using
        (rpsetvar 'vsi/panel-length VALUE)\n" , panellength); } else {
        Message("Panel Length not set. Using default value: %g\n You
        may set it with TUI Command:
        (rp-var-define 'vsi/panel-length VALUE' real #f)\n" , panellength);
    }
    box[5]=panellength-300;
    box[6]=panellength;
    /* Specify a maximum value of VSI for the change porosity from the
    scheme variable defined in FLUENT */
    if (RP_Variable_Exists_P("vsi/maximum-vsi")) {
        maximum_vsi=( RP_Get_Real("vsi/maximum-vsi") );
        Message("The Maximum change in porosity from the maximum-porosity
        behind the face occurs \n at the center of the panel and is
        set to: %g\n", maximum_vsi); }
    else { Message("Maximum change in porosity from the maximum-porosity

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behind the face occurs at the center of the panel and is NOT set. Using default value: %g
You may set it with TUI Command:
(rp-var-define 'vsi/maximum-vsi VALUE 'real #f)\n', maximum_vsi
}
/* Specify the displacement to the center of the old panel from the scheme variable defined in FLUENT */
if (RP_Variable_Exists_P("vsi/panel-xoffset")){
pannelxoffset=( RP_Get_Real("vsi/panel-xoffset") );
Message ("The x-direction displacement to the center of the panel is set to: %g\n", panelxoffset); } else{ Message("The x-direction displacement to the center of the panel is to zero. \nYou may set it with TUI Command:
(rp-var-define 'vsi/panel-xoffset VALUE 'real #f)\n") ; }
/* Specify the displacement to the recovery room of the old panel from the scheme variable defined in FLUENT */
if (RP_Variable_Exists_P("vsi/panel-yoffset")){
panelyoffset=( RP_Get_Real("vsi/panel-yoffset") );
Message ("The y-direction displacement to the recovery room of the panel is set to: %g\n", panelyoffset); } else{ Message("The y-direction displacement to the recovery room of the panel is to zero. \nYou may set it with TUI Command:
(rp-var-define 'vsi/panel-yoffset VALUE 'real #f)\n") ; }
thread_loop_c(t,d) { begin_c_loop(c,t) {
C_CENTROID(x,c,t);
/* Scale each section of the model to the curve fits.
MIN=144871.4 1/m² MAX=492170 1/m² */
x_loc=fabs ( x[0] - panelxoffset ) ;
/* Center of Panel is Zero and Mirrored */
/* Shift FLUENT MESH to FLAC3D data Zero point at startup room for equations */
y_loc=(panelength+x[1])-panelyoffset;
/* limit VSI function to only within panel domain sizing */
if( x_loc>panelwidth ){ VSI=0; }
else{
 if( x_loc < (box[1]-blendrange) ) {
 if ( y_loc <0) {VSI=0;}
 else if ( y_loc < box[4]-blendrangey-15){
 /* NORMALIZE to equation */
x_loc_norm=( (x_loc-box[1]+20 )/( box[1] ) );
y_loc_norm=( y_loc /box[4] );
VSI=SUPER_CRITICAL_MINETYPE_STARTUP_CENTER(x_loc_norm , y_loc_norm );
 mix=( (y_loc-(box[4]+blendrangey-15))/(2*blendrangey) ) ;
/* NORMALIZE to equation */
}
x_loc_norm=-(x_loc-box[1]+20)/(box[1]);
y_loc_norm=(y_loc/box[4]);

FUN1=SUPER_CRITICAL_MINE_E_STARTUP_CENTER(x_loc_norm,y_loc_norm);
x_loc_norm=-(x_loc-box[1]+10)/(box[1]);
y_loc_norm=(y_loc-box[4]/(box[5]-box[4]));

FUN2=SUPER_CRITICAL_MINE_E_CENTER_PANEL(x_loc_norm,y_loc_norm);
VSI=(FUN2*(mix)+FUN1*(1-mix));

#else if ((y_loc<(box[5]-blendrangey-15))&&(y_loc>(box[4]+blendrangey-15))){
x_loc_norm=-(x_loc-box[1]+10)/(box[1]);
y_loc_norm=(y_loc-box[4]/(box[5]-box[4]));

FUN1=SUPER_CRITICAL_MINE_E_CENTER_PANEL(x_loc_norm,y_loc_norm);

#else if ((y_loc>(box[5]-blendrangey-15))&&
(y_loc>(box[4]+blendrangey-15))}{
  mix = -(((y_loc-(box[5]+blendrangey))/2*blendrangey);
x_loc_norm=-(x_loc-box[1])/(box[1]);
y_loc_norm=(y_loc-box[4]/(box[5]-box[4]));

FUN1=SUPER_CRITICAL_MINE_E_CENTER_PANEL(x_loc_norm,y_loc_norm);
 x_loc_norm=(x_loc-box[1]+blendrange+15)/(box[1]);
y_loc_norm=(1-(y_loc-box[5])/(box[6]-box[5]));

FUN2=SUPER_CRITICAL_MINE_E_RECOVERY_CENTER(x_loc_norm,y_loc_norm);
VSI=(FUN1*(mix)+FUN2*(1-mix));
}
/*Remained of data points are in the recovery room 600-1000m*/
else if (((y_loc<box[6])&&(y_loc>(box[5]+blendrangey-15)))
}{
x_loc_norm=(x_loc-box[1]+blendrange+15)/(box[1]);
y_loc_norm=(1-(y_loc-box[5])/(box[6]-box[5]));

VSI=SUPER_CRITICAL_MINE_E_RECOVERY_CENTER(x_loc_norm,y_loc_norm);
else {VSI=0;}
}else if (x_loc<=(box[1]+blendrange)){
mix = (x_loc-box[1]+blendrange)/(2*blendrange);
if (y_loc<0) {VSI=0;}
else if (y_loc<box[4]){
  /* NORMALIZE to equation */
  x_loc_norm=-(x_loc-box[1])/(box[1]);
y_loc_norm=(y_loc/box[4]);

FUN1=SUPER_CRITICAL_MINE_E_STARTUP_CENTER(x_loc_norm,y_loc_norm);
 x_loc_norm=1-(x_loc-box[1])/(box[2]-box[1]);
y_loc_norm=(y_loc/box[4]);

FUN2=SUPER_CRITICAL_MINE_E_STARTUP_GATERoads(x_loc_norm,y_loc_norm);
VSI=(FUN2*(mix)+FUN1*(1-mix));
else if (y_loc<=box[5]){
FUN1 = SUPER_CRITICAL_MINE_E_CENTER_PANEL( x_loc_norm, y_loc_norm );
x_loc_norm = ( 1-(x_loc-box[1])/(box[2]-box[1]) );
y_loc_norm = ( y_loc-box[4])/(box[5]-box[4]) ;

FUN2 = SUPER_CRITICAL_MINE_E_CENTER_GATERoads( x_loc_norm, y_loc_norm );
VSI = (FUN2*(mix)+FUN1*(1-mix));

else if ( y_loc < box[6]){
    x_loc_norm = ( x_loc-box[1])/(box[1]) ;
y_loc_norm = (1-(y_loc-box[5])/(box[6]-box[5]) );
}

FUN1 = SUPER_CRITICAL_MINE_E_RECOVERY_CENTER( x_loc_norm, y_loc_norm );
x_loc_norm = (1-(x_loc-box[1])/(box[2]-box[1]) );
y_loc_norm = (1-(y_loc-box[5])/(box[6]-box[5]) );

FUN2 = SUPER_CRITICAL_MINE_E_RECOVERY_GATERoads( x_loc_norm, y_loc_norm );
VSI = (FUN2*(mix)+FUn1*(1-mix));
}

else {VSI=0;}
else{
    if ( y_loc <0) {VSI=0;}
    else if ( y_loc < box[4]-blendrangey){
        x_loc_norm = ( 1-(x_loc-box[1])/(box[2]-box[1]) );
y_loc_norm = (y_loc/box[4]) ;
    }

    else if ((y_loc>(box[4]-blendrangey))&&(y_loc<(box[4]+blendrangey))){
        mix = ((y_loc-box[4]+blendrangey)/2*blendrangey);
        x_loc_norm = (1-(x_loc-box[1])/(box[2]-box[1]) );
y_loc_norm = (y_loc/box[4]) ;
    }

    FUN1 = SUPER_CRITICAL_MINE_E_STARTUP_GATERoads( x_loc_norm, y_loc_norm );
x_loc_norm = (1-(x_loc-box[1])/(box[2]-box[1]) );
y_loc_norm = (y_loc-box[4])/(box[5]-box[4]) ;

    FUN2 = SUPER_CRITICAL_MINE_E_CENTER_GATERoads( x_loc_norm, y_loc_norm );
VSI = (FUN2*(mix)+FUN1*(1-mix));
}

else if ((y_loc<(box[5]-blendrangey-20))&&(y_loc>(box[4]+blendrangey))){
    x_loc_norm = (1-(x_loc-box[1])/(box[2]-box[1]) );
y_loc_norm = (y_loc-box[4])/(box[5]-box[4]) ;
}

else if (((y_loc>(box[5]-blendrangey-20))&&(y_loc<box[5]+blendrangey+20))){
mix = ((y_loc-box[5]+blendrangey)/(2*blendrangey));
x_loc_norm=( 1-(x_loc-box[1])/( box[2]-box[1] )) ;
y_loc_norm=( (y_loc-box[4])/( box[5]-box[4] ) );
FUN1=SUPER_CRITICAL_MINE_E_CENTER_GATEROAD(x_loc_norm , y_loc_norm);
x_loc_norm=( 1-(x_loc-box[1])/( box[2]-box[1] ) );
y_loc_norm=(1-(y_loc-box[5])/(box[6]-box[5]) );
FUN2=SUPER_CRITICAL_MINE_E_RECOVERY_GATERoads(x_loc_norm , y_loc_norm);
VSI= (FUN2*(mix)+FUN1*(1-mix));  
  else if (y_loc<panelength){
x_loc_norm=( 1-(x_loc-box[1])/( box[2]-box[1] ) );
y_loc_norm=(1-(y_loc-box[5])/(box[6]-box[5]) );
VSI=SUPER_CRITICAL_MINE_E_RECOVERY_GATERoads(x_loc_norm , y_loc_norm);}
  else {VSI=0;}
}
VSI=(VSI<0.0)?0:VSI;
VSI=(VSI>maximum_vsi)?maximum_vsi:VSI;
C_UDMI(c,t,4) = VSI;
}
end_c_loop(c,t) }
Print_Scheme_Variable_Settings();
} 

/!* !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!!! POROSITY CALCULATION profiles !!!!!!!!!!!!
!!! FROM VSI or Wachel (2012) Fit !!!!!
!!! STORES in (user-define-memory 4) !!!!!
!!! udm-4 !!!!!
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
*/
DEFINE_ON_DEMAND(VSI_MINE_Worrall_C) {
  Domain *d; Thread *t; cell_t c; real x[ND,ND];
  real cellpor; real x_loc; real y_loc;
  double panelwidth=157.255;
  /* 151.4856; specified here as half-width */
  double panellength=2941.3024;
  double panelxoffset=0.0;
  double panelyoffset=0.0;
  double maximum_vsi=0.5;
  /* Returns true if the variable exists */
  if (RP_Variable_Exists_P("vsi/panel-width"){
panelwidth=( RP_Get_Real( "vsi/panel-width" ) / 2 )

// else default or manual set above is used */
Message ("Panel width is: %g\n", panelwidth*2); } else{ Message("Panel Width not set. Using default value: %g\n
You may set it with TUI Command:
(rp-var-define 'vsi/panel-width VALUE 'real #f)\n", panelwidth *2);

if (RP_Variable_Exists_P("vsi/panel-length"){
    panellength=( RP_Get_Real("vsi/panel-length") )
    Message ("Panel length is set to: %g\n reset value using
(rpsetvar 'vsi/panel-length VALUE)\n", panellength); }
else{ Message("Panel Length not set. Using default value: %g\n
You may set it with TUI Command:
(rp-var-define 'vsi/panel-length VALUE' real #f)\n", panellength) 
};

/* Specify a maximum value of VSI for the change porosity from the
scheme variable defined in FLUENT */
if (RP_Variable_Exists_P("vsi/maximum-vsi"){  
    maximum_vsi=( RP_Get_Real("vsi/maximum-vsi") );
    Message ("The Maximum change in porosity from the maximum-porosity
behind the face occurs \nat the center of the panel and is set
to:
%g\n", maximum_vsi);}
else{ Message("Maximum change in porosity from the maximum-porosity
behind the face occurs at the center of the panel and is NOT
set.
Using default value: %g\n You may set it with TUI Command:
(rp-var-define 'vsi/maximum-vsi VALUE 'real #f)\n", maximum_vsi
);}

/* Specify the displacement to the center of the old panel from the
scheme variable defined in FLUENT */
if (RP_Variable_Exists_P("vsi/panel-xoffset")){
    panelxoffset=( RP_Get_Real("vsi/panel-xoffset") );
    Message ("The x-direction displacement to the center of the panel is set
to: %g\n", panelxoffset); }
else{ Message("The x-direction displacement to the center of the panel
is to zero. \n You may set it with TUI Command:
(rp-var-define 'vsi/panel-xoffset VALUE 'real #f)\n");}

/* Specify the displacement to the recovery room of the old panel
from the scheme variable defined in FLUENT */
if (RP_Variable_Exists_P("vsi/panel-yoffset")){
    paneyoffset=( RP_Get_Real("vsi/panel-yoffset") );
    Message ("The y-direction displacement to the recovery room of the
panel is set to: %g\n", paneyoffset); }
else{ Message("The y-direction displacement to the recovery room of
the panel is to zero. \n You may set it with TUI Command:
(rp-var-define 'vsi/panel-yoffset VALUE 'real #f)\n");}
d = Get_Domain(1);

thread_loop_c(t,d) {
begin_c_loop(c,t) {
    C_CENTROID(x,c,t);
    /* headgate 147.63, tailgate at 166.88 */
    x_loc=(fabs(x[0]-panelxoffset)/panelwidth*166.88)-9.625;
    /* recovery 1474.3, startup at -1457 */
    y_loc=((x[1]-panelyoffset)/(panel_length/2)*1474.3)+1465.65;
    if( (fabs(x[0]-panelxoffset) < panelwidth) && (fabs(y_loc) < 1474.3) ){
        /*WORRALL: Scales correctly */
        cellpor = pow(x_loc,1)*pow(y_loc,9)*(-4.11E-36)+pow(x_loc,0)*...
        ...
        /* 2 PAGES OF EQUATIONS -- SEE WORRALL, 2012 */
        C_UDMI(c,t,4) = ((0.5 - cellpor)<0)?0:(0.5 - cellpor);
        else {C_UDMI(c,t,4) = 0;}
        if (C_UDMI(c,t,4) > maximum_vsi) {C_UDMI(c,t,4)=maximum_vsi;}
    }
    end_c_loop(c,t) }
}


void Print_Scheme_Variable_Settings() {
    /* Returns true if the variable exists */
    if (RP_Variable_Exists_P("vsi/porosity-scalar"){)
    /* else default or manual set above is used */
        Message("Porosity scalar: %g\n", RP_Get_Real("vsi/porosity-scalar"); }
    else{ Message("Porosity scalar at default value: 1\n You may define it with TUI Command:
(rp-var-define 'vsi/porosity-scalar VALUE 'real #f)\n"); }
    /* Returns true if the variable exists */
    if (RP_Variable_Exists_P("vsi/maximum-porosity"){)
        Message("The starting maximum porosity behind shields starts at: %g\n", RP_Get_Real("vsi/maximum-porosity"); }
    /* else default or manual set above is used */
    else{ Message("The starting maximum porosity is not set.
 Using default value: 0.40\n You may set it with TUI Command:
(rp-var-define 'vsi/maximum-porosity VALUE 'real #f)\n"); }
    if (RP_Variable_Exists_P("vsi/initial-porosity"){)
        Message("Initial Porosity of host rock is set to: %g\n", RP_Get_Real("vsi/initial-porosity"); }
    else{ Message("Initial Porosity of host rock is set to default value: 0.257780\n You may set it with TUI Command:
(rp-var-define 'vsi/initial-porosity VALUE 'real #f)\n"); }
    if (RP_Variable_Exists_P("vsi/resist-scalar"){}
Message ("Resistance scalar of Carman-Kozeny relationship is set to: %g\n", RP_Get_Real("vsi/resist-scalar")); } else{ Message("Resistance scalar of Carman-Kozeny relationship is set to default value: 1\n You may set it with TUI Command: (rp-var-define 'vsi/resist-scalar VALUE 'real #f)\n"); }
if (RP_Variable_Exists_P("vsi/maximum-resist")){
  Message ("Maximum cropped resistance (before scalar) in the gob center is set to: %g\n", RP_Get_Real("vsi/maximum-resist")); }
else{ Message("Maximum cropped resistance (before scalar) in the gob center is set to default value: 5.00000E6\n You may set it with TUI Command: (rp-var-define 'vsi/maximum-resist VALUE 'real #f)\n"); }
if (RP_Variable_Exists_P("vsi/minimum-resist")){
  Message ("Minimum cropped resistance (before scalar) in the edges of the gob is set to: %g\n", RP_Get_Real("vsi/minimum-resist")) ; }
else{ Message("Minimum cropped resistance (before scalar) in the edges of the gob is set to default value: 1.45000E6\n You may set it with TUI Command: (rp-var-define 'vsi/minimum-resist VALUE 'real #f)\n"); }
}

The porosity of each porous zone must have its own uniquely named DEFINE PROFILE with the code in Listing B.15. The default initial porosity value is 40% and a scalar value for porosity is 1, unless define by the user with scheme variable. The calculation of the one-to-one reduction of porosity to VSI is stored in user-define-memory location number 1 (udm-1).

Listing B.15: UDF Porosity Function

s/* Porosity Zone Function -- One for each zone */
DEFINE_PROFILE(set_poro.VSI ,t ,nv)
{
  /* n = (V_v - VSI) /V_t 
  where n is porosity (%), V_v is volume of voids (cubic meters), 
  vsi is volumetric strain (%), and V_t is total volume (cubic meters).
  */
  real x[ND_ND]; /* position vector x[0]=x, x[1]=y, x[2]=z */
  /* double V_t=10.0000 * 10.0000 * 10.0000; 10 meter cubed grid cell 
     in FLAC3D */
  cell_t c; real cellpor;

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double V_v = 0.40000000;
real a=1; /* for a scalar */
if (RP_Variable_Exists_P("vsi/porosity-scalar")) { /* Returns true if the variable exists */
a=( RP_Get_Real("vsi/porosity-scalar")); }
if (RP_Variable_Exists_P("vsi/maximum-porosity")){
V_v=( RP_Get_Real("vsi/maximum-porosity"));}
beginc_loop(c,t) {
C_CENTROID(x,c,t);
if(ite<=1){
cellpor = ( (V_v - C_UDMI(c,t,4))*a ); /* Initial Maximum gob porosity minus the change in porosity (VSI). */
C_PROFILE(c,t,nv) = (cellpor<0)?0:cellpor; /* 'a' scalar for later use */
C_UDMI(c,t,1) = (cellpor<0)?0:cellpor; }
if(ite>1){ C_PROFILE(c,t,nv) = C_UDMI(c,t,1); }
} endc_loop(c,t) }

The cell resistance consists of three DEFINE_PROFILE functions uniquely named for each direction and zone.

Listing B.16: Viscous Resistance Function

3/* Viscous Resistance (1/Permeability) use a function for each direction in the a Zone */
DEFINE_PROFILE(set_perm_1_VSI,t,nv)
{
/* FLUENT allows for an inertial resistance parameter to account for turbulent and transitional flow. Inertial resistance can be found using the following equation ANSYS (2010):
C2 = 3.5 / d * (1-n)/ n^3
where d is the mean particle diameter (meters) and n is the porosity (%) of the medium.
This equation is valid for use in the momentum conservation equation used by Ansys, Inc. in FLUENT. */
real x[ND,ND]; /* position vector x[0]=x, x[1]=y, x[2]=z */
cell_t c; double cellpor; double initial_permeability; double cellresist;
double V_v=0.40000000; double a=1; double resist_scalar=1; double maximum_resist=5.000000E6; double minimum_resist=1.450000E5; /* equals 6.91e-6 1/m2 permeability */
if (RP_Variable_Exists_P("vsi/maximum-porosity")) { /* Get scheme variable and assign it if it exists */
\begin{verbatim}
V_v = ( RP_Get_Real("vsi\_maximum\_porosity") );
if ( RP_Variable_Exists_P("vsi\_porosity\_scalar") ){
a = ( RP_Get_Real("vsi\_porosity\_scalar") );
}
if ( RP_Variable_Exists_P("vsi\_resist\_scalar") ){
    resist\_scalar = ( RP_Get_Real("vsi\_resist\_scalar") );
}
if ( RP_Variable_Exists_P("vsi\_maximum\_resist") ){
    maximum\_resist = ( RP_Get_Real("vsi\_maximum\_resist") );
}
if ( RP_Variable_Exists_P("vsi\_minimum\_resist") ){
    minimum\_resist = ( RP_Get_Real("vsi\_minimum\_resist") );
}
initial\_permeability = Initial\_Perm();
begin_c_loop(c,t) {
    C\_CENTROID(x,c,t);
    if (ite <= 1) {
        cell\_poro = ( (V_v - C\_UMI(c,t,4)) *a < 0 ) ? 0 : (V_v - C\_UMI(c,t,4)) *a;  */ Limit lowest value of porosity to zero */
        cell\_resist = Cell\_Resistance(cell\_poro,
            initial\_permeability);  */ Carmen-Kozeny Relationship */
        }  /* Limit MAX and MIN resistance */
        if (cell\_resist < maximum\_resist) {
            if (cell\_resist < minimum\_resist) { cell\_resist = minimum\_resist; }
        }
    else {
        cell\_resist = maximum\_resist;  }
    C\_PROFILE(c,t,lv) = cell\_resist
        * resist\_scalar;  */ scalar applied to cell resistance */
    C\_UMI(c,t,0) = cell\_resist
        * resist\_scalar;
    }
    if (ite > 1) {
        C\_PROFILE(c,t,lv) = C\_UMI(c,t,0);  }
} end_c_loop(c,t)
\end{verbatim}

Listing B.17: Explosive Gas Zone Algorithm

/* Explosive Gas Zone Algorithm (EGZ) */
DEFINE_ON_DEMAND(calc\_explosive\_mix\_NEWER) {
    Domain *d; Thread *t; cell\_t c;
    real px; real py; real u; real v;
    real u1; real v1; real w;

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real Y_CH4, Y_O2, Y_N2, MW_CH4, MW_O2, MW_N2, MW_Mix, X_CH4, X_O2;
real explode;
d = Get_Domain(1);
thread_loop_c(t,d) {
begin_c_loop(c,t) {
    /* Y_X = Mass Fraction of Species X || X_X = Mole Fraction of Species X */
    Y_CH4=C_YI(c,t,0);
    Y_O2=C_YI(c,t,1);
    Y_N2=1.0-Y_CH4-Y_O2;
    MW_CH4= 16.043;
    MW_O2= 31.9988;
    MW_N2= 28.0134;
    MW_Mix= 1/(Y_CH4/MW_CH4+Y_O2/MW_O2+Y_N2/MW_N2);
    X_CH4=(Y_CH4*MW_Mix)/MW_CH4; /* X = Mole Fraction of X */
    X_O2=(Y_O2*MW_Mix)/MW_O2;
    px= X_CH4;
    py=X_O2;
    u = 0.8529*px+0.0606; /* Near Explosive to Explosive Slope */
    v=-0.21*px+0.21; /* Upper Explosive Limit */
    u1=0.8864*px+0.0445; /* Near Explosive to Requires Air Slope */
    v1=-1.3929*px+0.195;
    w=v1;
    /*v1=1.2647*px+0.1771; Cyan to Yellow Slope Transition */
    /*w=1.8545*px+0.2095; Continuation of Slope Oxygen Rich to Oxygen Poor */
    /* Explosive Zone - RED */
    if (py>u && px>0.055 && py<v) {
        explode=1.0E0;
        C_UDMI(c,t,2) = explode;
    }
    /* Near Explosive Zone - ORANGE */
    else if (py>u1 && px>0.04 && py<v) {
        explode=0.81E0;
        C_UDMI(c,t,2) = explode;
    }
    /* Fuel Rich Inert - YELLOW */
    else if (py<v1 && py>v1 && px>0.055) {
        explode=0.66E0;
        C_UDMI(c,t,2) = explode;
    }
    /* Oxygen Lean Inert - Green */
    else if (py<v1 && px>0.04) {
explode = 0.48E0;
C_UDMI(c,t,2) = explode;

} /* Oxygen Lean Inert - DARK GREEN */
else if (py<0.08 && px<0.04) {
explode = 0.0E0;
C_UDMI(c,t,2) = explode;
}
/* Oxygen Lean Inert - Green B */
else if (py<w && px<0.04) {
explode = 0.48E0;
C_UDMI(c,t,2) = explode;
}
/* Oxygen Rich Inert - CYAN */
else if (py>w) {
explode = 0.27E0;
C_UDMI(c,t,2) = explode;
}
/* Explosive Zone - DARK BLUE */
else{
explode = 2.66E0;
C_UDMI(c,t,2) = explode;
}
} end_c_loop(c,t)

DEFINE_ON_DEMAND(calc_explosive_integral_gob)
/* For use in the gob - currently porosity in strata is user-defined-
variable and this will return a value of zero in the strata
because the value of the porosity stored in C_UDMI(c,t,1) is zero. This
could be changed by patching a value into C_UDMI for the strata.
For strata use: calc_explosive_integral*/
{
Domain *d; Thread *t; cell_t c;
d = Get_Domain(1);
thread_loop_c(t,d) {
begin_c_loop(c,t) {
if (C_UDMI(c,t,2)>0.99e0 && C_UDMI(c,t,2)<1.01){
/* Assign marker value for cell volume that is
explosive */
C_UDMI(c,t,3)=1.00E0*C_UDMI(c,t,1); } /* Report
Volume-Volume-Integral udm-3 */
/* Cell_Volume*Cell_Porosity*1.000e0 = The
explosive volume reported */

} end_c_loop(c,t) }
} DEFINE_ON_DEMAND(calc_explosive_integral)
/* For use in the strata - requires manual manipulation of user defined
 strata porosity */
{
    Domain *d; Thread *t; cell_t c;
d = Get_Domain(1);
thread_loop_c(t,d){
    begin_c_loop(c,t) {
        if (C_UDMI(c,t,2)>0.99e0 && C_UDMI(c,t,2)<1.01) {
            /* Assign marker value for cell volume that is
               explosive */
            C_UDMI(c,t,3)=1.00e0; } /* Report Volume-Volume-
               Integral udm-3 */
            /* Cell_Volume*1.000e0= The explosive volume
               reported */
    } end_c_loop(c,t) }
}
DEFINE_ON_DEMAND(reset_explosive_integral)
{
    /* Required to execute on transient runs - otherwise
    explosive volume is additive */
    Domain *d; Thread *t; cell_t c;
d = Get_Domain(1);
thread_loop_c(t,d) {
    begin_c_loop(c,t) {
        C_UDMI(c,t,3)=0.00E0;
    } end_c_loop(c,t) }
}

Listing B.18: Sub-Critical Panel

/*
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!!!!!!!!!!!! SUB CRITICAL PANEL ---- TRONA FIT !!!!!!!!!!!!!
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
*/
double SUB_CRITICAL_Trona_RECOVERY_CORNER(double x_loc, double y_loc)
{
    double FUN=0.0;
    FUN = pow((x_loc*y_loc),0.107302089705487)*( 0.1477 -
          0.812278751377339*exp(-9.96978304250904*y_loc)*y_loc*x_loc +
          0.103507270969929*exp(-688.057090793680*y_loc)*x_loc +
          0.1738*exp(-6.368*x_loc) + 0.1971*x_loc*x_loc*exp(-1.38*x_loc*
          x_loc) + 13.6*y_loc*y_loc*exp(-2890*y_loc) - 14.56*x_loc*exp
          (-47.01*x_loc) + 11.19*x_loc*exp(-7883*x_loc*x_loc) +
          0.07992*exp(-2.155*y_loc) - 6.274*y_loc*exp(-99.58*y_loc) +
          0.03141*y_loc*exp(-8.748*y_loc*y_loc));

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/* SUB-CRITICAL(Trona) RECOVERY CORNER */

\[ f(x, y) = (x \cdot y) \cdot \left( 0.1477 + c \cdot \exp(-d \cdot y) \cdot x \cdot y + d11 \cdot \exp(-b11 \cdot x \cdot y) - 0.1738 \cdot \exp(-6.368 \cdot y) + 0.1971 \cdot x \cdot y \cdot \exp(-1.38 \cdot x \cdot y) + 13.6 \cdot y \cdot \exp(-2890 \cdot y) + 14.56 \cdot x \cdot \exp(-47.01 \cdot x) + -11.19 \cdot x \cdot \exp(-7883 \cdot x) + 0.07992 \cdot \exp(-2.155 \cdot x) + -6.274 \cdot y \cdot \exp(-99.58 \cdot y) + 0.03141 \cdot y \cdot \exp(-8.748 \cdot y) \right) \]

688.057090793680 -0.812278751377339 9.96978304250904
0.103507270969929 0.107302089705487

ans = 'b11' 'c' 'd' 'd11'

double SUB_CRITICAL_Trona_STARTUP_CORNER(double x_loc, double y_loc)
{
    double FUN=0.0;
    FUN = pow((x_loc*y_loc), 0.1007)*(0.1796 + 0.2762*\exp(-4.552*y_loc)*x_loc + 0.04375*\exp(-5.354*x_loc*y_loc) - 0.3093*\exp(-60.54*x_loc) - 0.2702*\exp(-50.36*y_loc) + 0.437*x_loc*y_loc*\exp(-2.728*x_loc));
}

/* SUB-CRITICAL(Trona) STARTUP CORNER */

General model:

\[ f(x, y) = (x \cdot y) \cdot \left( 0.1227 \cdot \left( \frac{1}{2} \cdot y \cdot \exp(-d \cdot y) \cdot x \cdot y + \left( 0.4769 \cdot \exp(-b11 \cdot x \cdot y) - 0.2057 \cdot \exp(-31.53 \cdot x) - 0.2646 \cdot \exp(-40.73 \cdot y) \right) + g \cdot x \cdot \exp(-h \cdot x) \right) \]

Coefficients (with 95% confidence bounds):

b11 = 4.045 (4.037, 4.053)
d = 3.858 (3.853, 3.864)
g = 5.089 (5.08, 5.099)
h = 2.844 (2.841, 2.846)
Mine TRONA Startup Gateroad */
FUN = (FUN<0)?0:FUN;
return FUN; /* Limit the change to only positive*/

Listing B.19: Mine-E VSI Equation Fits

double SUPER_CRITICAL_MINE_E_STARTUP_CENTER(doub double x_loc, double y_loc)
{
    double FUN=0.0;
    FUN = 0.155394214+x_loc*x_loc*(-0.004966014) +0.142894504*y_loc*exp(-1.11507158*y_loc*y_loc) -0.154156852*exp(-994.6190264*y_loc*y_loc) -0.165429282*y_loc*y_loc*exp(-2.119029131*y_loc*y_loc);
    /* Mine E CHECK Startup Center */
    /* a+x^2*(a1)+b*y*exp(-b1*y^2)+c*exp(-c1*y^2)+d*y^2*exp(-d1*y^2)*/
    /* a a1 b b1 c c1 d d1 */
    /* 0.155394214 -0.004966014 0.142894504 1.11507158 -0.154156852 994.6190264 -0.165429282 2.119029131 0.23446547 -0.007274502 0.21112871 1.254341353 -0.232563013 0.182881808 0.000219076 -0.001701901 -0.003415753 0.182881808 0.000219076 -0.001701901 -0.003415753 */
    FUN = (FUN<0)?0:FUN;
    return FUN; /* Limit the change to only positive*/
}

double SUPER_CRITICAL_MINE_E_CENTER_PANEL(doub double x_loc, double y_loc)
{
    double FUN=0.0;
    FUN = 0.182881808+0.000219076*y_loc-0.001701901*x_loc*x_loc+0.003415753*x_loc*x_loc*x_loc;
    /* Mine E CHECK Center Panel */
    /* p00+p01*y+p20*x^2+p30*x^3 */
    /* 0.182881808 0.000219076 -0.001701901 -0.003415753 0.182881808 0.000219076 -0.001701901 -0.003415753 */
    /* 0.26928324 0.000607666 -0.001387445 */
    FUN = (FUN<0)?0:FUN;
    return FUN; /* Limit the change to only positive*/
}

double SUPER_CRITICAL_MINE_E_RECOVERY_CENTER(double x_loc, double y_loc)
{
    double FUN=0.0;
    FUN = 0.034705045+x_loc*x_loc*(-0.007156676) +0.392853454*y_loc*exp(-2.690847002*y_loc*y_loc)-0.016570035*exp(-290*y_loc*y_loc) +0.20691545*y_loc*y_loc*exp(-0.513740978*y_loc*y_loc);
double SUPER_CRITICAL_MINE_E_STARTUP_GATERoads(double x_loc, double y_loc) {
    double FUN = 0.0;
    FUN = pow((x_loc * y_loc), 0.070680995) * (0.162003881 + 0.114056257 * exp(-2.060750448 * y_loc) * y_loc * x_loc + 0.027309527 * exp(-2.32002878 * x_loc * y_loc) - 0.134633756 * exp(-8.323851432 * x_loc) - 0.263467643 * exp(-50.0208638 * y_loc) + 51.01309648 * x_loc * x_loc * exp(-24.66420708 * x_loc));
    / \ Mine E CHECK Startup Gateroads */
    return FUN; /* Limit the change to only positive */
}

double SUPER_CRITICAL_MINE_E_CENTER_GATERoads(double x_loc, double y_loc) {
    double FUN = 0.0;
    FUN = 0.10083973 + 0.05329973 * x_loc + 0.000111875 * y_loc + 0.715710581 * x_loc * exp(-3.193027724 * x_loc) - 0.100070375 * exp(-1200.384929 * x_loc * x_loc) - 0.15163961 * x_loc * exp(-3.716593738 * x_loc * x_loc) - 0.378856069 * x_loc * x_loc * exp(-16.20732696 * x_loc * x_loc);
    / \ Mine E CHECK Center Gateroads */
    return FUN; /* Limit the change to only positive */
}
FUN = (FUN<0)?0:FUN;
return FUN; /* Limit the change to only positive*/

double SUPER_CRITICAL_MINE_E_RECOVERY_GATERoads(double x_loc, double y_loc)
{
    double FUN=0.0;
    FUN = pow ( (x_loc*y_loc),0.251307505)*
    ( 0.197539477 -0.258183405*exp(-2.06215525*y_loc)*y_loc*x_loc +0.02301539*exp(-21.41498958*y_loc)*x_loc*
        (17.13983263*x_loc*x_loc)+4.68818221*y_loc*y_loc*x_loc*(-5.633256844*y_loc)*x_loc*exp(-65.9273908*x_loc)*
        +0.772026679*x_loc*exp(-68.9978585*x_loc*x_loc)+34.5*exp(-3200.000001*x_loc)+0.263621861*y_loc*exp(-27.16257242*y_loc)*
        -0.255066042*y_loc*exp(-9.010678902*y_loc*y_loc)/;
    /* Mine E CHECK Recovery Gateroads */
    /* ((x)(y))^f(a+c*exp(-d*y)*x*y+d11*exp(-b11*x*y)-d01*exp(-b01*y)+g*x^2*exp(-h*x^2)+k*y^2*exp(-l*y)-m*x*exp(-n*x)+o*x*exp(-p*x^2)+q*exp(-r*
        x)+s*y*exp(-t*y)+u*y*exp(-v*y^2)) */
    /* a b01 b11 c d d01 d11 f g h k l m n o p q r s t u v */
    /* 0.197539477 10.01527015 21.41498958 -0.258183405 2.06215525 0.15928258 0.02301539 0.251307505 0.445654501 17.13983263 4.68818221 5.633256844 -13.90840849 65.9273908 0.772026679 68.9978585 34.5 3200.000001 0.263621861 9.010678902 0.183702387 9.632781899 372.4030661 -0.176739562 2.683826404 0.169037785 0.054614777 0.167106788 -1 44.61606272 3.35898269 5.785522066 -17.23680573 69.20628701 0.339264617 39.86386103 34.5 3199.999994 1.65966029 38.95936604 -0.258196679 9.982806144 */
    /* 0.262664370836130 8.8902752481122 228.389753817175 -0.253166473007042 3.2033582824672 0.243491669292467 0.0654918256966825 0.162024334530162 -0.10000000000000426 47.2974300364826 5.00798339750128 5.70033048005178 -27.1058247819212 73.6049605283396 0.315580700722219 51.8957956767753 38.986613917604 3169.2552087171 2.08942405255152 30.0098038288443 -0.303675246839708 7.38256233004023 */
    FUN = (FUN<0)?0:FUN;
return FUN; /* Limit the change to only positive*/

Listing B.20: Mine-C VSI Equation Fits

/+ ++++++++ ++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ ++++++++ +AAAAAA

+++++++ MINE C Equation fit ++++

+++++++ 6 regions ++++

+++++++ Data fit of FLAC3D ++++
```c
double SUPER_CRITICAL_MINE_C_STARTUP_CENTER(double x_loc, double y_loc)
{
    double FUN=0.0;
    FUN = 0.23446547 + x_loc * x_loc * (-0.007274502) + 0.21112871 * y_loc * exp(-1.254343135 * y_loc * y_loc) - 0.232563013 * exp(-986.7723584 * y_loc * y_loc) - 0.288213205 * y_loc * y_loc * exp(-2.41029839 * y_loc * y_loc) - 0.232563013 * exp(-986.7723584 * y_loc * y_loc) - 0.288213205 * y_loc * y_loc * exp(-2.41029839 * y_loc * y_loc);
    FUN = (FUN < 0) ? 0 : FUN;
    return FUN; /* Limit the change to only positive */
}

double SUPER_CRITICAL_MINE_C_CENTER_PANEL(double x_loc, double y_loc)
{
    double FUN=0.0;
    FUN = 0.26928324 + 0.000607666 * y_loc - 0.001387445 * x_loc * x_loc - 0.005923021406 * x_loc * x_loc * x_loc;
    FUN = (FUN < 0) ? 0 : FUN;
    return FUN; /* Limit the change to only positive */
}

double SUPER_CRITICAL_MINE_C_RECOVERY_CENTER(double x_loc, double y_loc)
{
    double FUN=0.0;
    FUN = 0.054623275 + x_loc * x_loc * (-0.007156676) + 0.537305093 * y_loc * exp(-3.725760322 * y_loc * y_loc) - 0.028010127 * exp(-290 * y_loc * y_loc) + 0.501978887 * y_loc * y_loc * exp(-0.911642577 * y_loc * y_loc);
    FUN = (FUN < 0) ? 0 : FUN;
    return FUN; /* Limit the change to only positive */
}

double SUPER_CRITICAL_MINE_C_RECOVERY_GATERoads(double x_loc, double y_loc)
{
    double FUN=0.0;
    FUN = pow((x_loc * y_loc), 0.162024335) * (0.262664371 - 0.537305093 * y_loc * exp(-3.725760322 * y_loc * y_loc) - 0.028010127 * exp(-290 * y_loc * y_loc) + 0.501978887 * y_loc * y_loc * exp(-0.911642577 * y_loc * y_loc));
    FUN = (FUN < 0) ? 0 : FUN;
    return FUN; /* Limit the change to only positive */
}
```
**SUPER CRITICAL MINE CENTER GATERoads**

```c
double SUPER CRITICAL MINE CENTER GATERoads(double x_loc, double y_loc) {
    double FUN=0.0;
    FUN = pow((x_loc*y_loc),0.072583782)*(0.222803703+0.217897624
               *x_loc+0.035000529*exp(-4.519932999*x_loc*
               y_loc)-0.213737696*exp(-33.3990023*x_loc)*0.399728137
               *exp(-49.33761923*y_loc)+0.36279155*x_loc*x_loc*
               exp(-2.519206805*x_loc));
    return FUN; /* Limit the change to only positive*/
}
```

**SUPER CRITICAL MINE STARTUP GATERoads**

```c
double SUPER CRITICAL MINE STARTUP GATERoads(double x_loc, double y_loc) {
    double FUN=0.0;
    FUN = pow((x_loc*y_loc),0.072583782)*(0.222803703+0.217897624
               *x_loc+0.035000529*exp(-4.519932999*x_loc*
               y_loc)-0.213737696*exp(-33.3990023*x_loc)*0.399728137
               *exp(-49.33761923*y_loc)+0.36279155*x_loc*x_loc*
               exp(-2.519206805*x_loc));
    return FUN; /* Limit the change to only positive*/
}
```

**SUPER CRITICAL MINE STARTUP CENTER GATERoads**

```c
double SUPER CRITICAL MINE STARTUP CENTER GATERoads(double x_loc, double y_loc) {
    double FUN=0.0;
    FUN = pow((x_loc*y_loc),0.072583782)*(0.222803703+0.217897624
               *x_loc+0.035000529*exp(-4.519932999*x_loc*
               y_loc)-0.213737696*exp(-33.3990023*x_loc)*0.399728137
               *exp(-49.33761923*y_loc)+0.36279155*x_loc*x_loc*
               exp(-2.519206805*x_loc));
    return FUN; /* Limit the change to only positive*/
}
```
The inertia resistance from the 2nd term of the Ergun equation can be added to the CFD simulation with the addition of the following code:

Listing B.21: Inertia Resistance from VSI Equation Fits

double Cell_Inertia_Resistance(double cellporo, double initial_inertia_resistance){
    /* The Blake-Kozeny equation for flow through porous media was used to estimate the inertia resistance or C2 value in FLUENT of the gob as follows:
    C2 = 3.5/Dp * (1-n)/n^3
    where the initial inertia resistance is base on the initial porosity of the rock, and the change is calculated as:
    C2 = C2_initial * (1-n)/n^3
    */
    return (initial_inertia_resistance*(1.000000-cellporo)/(cellporo*cellporo*cellporo));
}

double Initial_Inertia_Resistance(){
    /* C2_initial=3.5/Dp * (1-n)/n^3
    Dp is the mean particle diameter, and n is porosity (%)
    mean particle diameter from Pappas & Mark 1993 = 0.2 meters, Kozeny constant 180. */
    double initial_porosity=0.2577800000000;
    if (RP_Variable_Exists_P("vsi/initial-porosity") ){ /* Returns true if the variable exists */
        initial_porosity=( RP_Get Real("vsi/initial-porosity") );
    return (3.5/0.2000000 *(1.0000000000000-initial_porosity) / (initial_porosity*initial_porosity*initial_porosity) );
    }
}

DEFINE_PROFILE(set_inertia_1_VSI,t,nv){
    /* FLUENT allows for an inertial resistance parameter to account for turbulent and transitional flow. Inertial resistance can be found using the following equation ANSYS (2010):
    C2 = 3.5 / d * (1-n)/ n^3
    */
where \( d \) is the mean particle diameter (meters) and \( n \) is the porosity (\%) of the medium.

This equation is valid for use in the momentum conservation equation used by Ansys, Inc. in FLUENT.

```plaintext
real x[ND,ND]; /* position vector x[0]=x, x[1]=y, x[2]=z */
cell_t c; double cellporo; double initial_inertia_resist;
double cellinertiaresist;
double V_v=0.40000000; double a=1; double resist_scaler=1; double
maximum_inertia_resist=1.3E5; double minimum_inertia_resist=0.000;
if (RP_Variable_Exists_P("vsi/maximum-porosity")){ /* Get
scheme variable and assign it if it exists */
    V_v=( RP_Get_Real("vsi/maximum-porosity") );
} if (RP_Variable_Exists_P("vsi/porosity-scaler")){
    a=( RP_Get_Real("vsi/porosity-scaler") );
} if (RP_Variable_Exists_P("vsi/resist-inertia-scaler") ){
    resist_scaler=( RP_Get_Real("vsi/resist-inertia-scaler") );
} if (RP_Variable_Exists_P("vsi/maximum-inertia-resist") ){
    maximum_inertia_resist=( RP_Get_Real("vsi/maximum-inertia-
resist") );
} if (RP_Variable_Exists_P("vsi/minimum-inertia-resist") ){
    minimum_inertia_resist=( RP_Get_Real("vsi/minimum-inertia-
resist") );
}
initial_inertia_resistance = Initial_Inertia_Resistance();
begin_c_loop(c,t) {
    C_CENTROID(x,c,t);
    if(ite<=1){
        cellporo =((V_v - C_UDMI(c,t,4 ))*a<0 )?0:(V_v - C_UDMI
(c,t,4 ))*a; /* Limit lowest value of porosity to
zero */
        cellinertiaresist = Cell_Inertia_Resistance(cellporo ,
        initial_inertia_resistance); /* Blake-Kozeny
Relationship */
        /* Limit MAX and MIN resistance */
        if(cellinertiaresist < maximum_inertia_resist){
            if(cellinertiaresist < minimum_inertia_resist){
                cellinertiaresist=minimum_inertia_resist;
            }
        }
    else{
        cellinertiaresist =
        maximum_inertia_resist;
    }
    C_PROFILE(c,t,nv) =
        cellinertiaresist *
        resist_scaler; /* Scaler
applied to cell resistance */
    C_UDMI(c,t,5) =
        cellinertiaresist *
        resist_scaler; }
```
if (ite > 1) {
    C_PROFILE(c, t, nv) = C_UDMI(c, t, 5); }
} end_c_loop(c, t)
APPENDIX C - MESH ASSEMBLY JOURNAL FILE CREATION CODE

The follow appendix contains the Matlab code for assembling the meshes of the entry and crosscut ventilation system. The headgate side code is in the executable Listing C.22, and the tailgate side in Listing C.30. The number entry and crosscuts is 45, however, the headgate numbering starts at the face with crosscut 1, while on the tailgate side the numbering start at 0 at the startup room and ending with 44 near the face. The tailgate section must be rotate 180 degree about the z-axis once assembly is complete. An additional 200-foot section of mesh modules was later added to represent the open tailgate entry to the center tailgate entry with a back return ventilation pattern. The final mesh assembly used in this project was carefully assembled from these sections of headgate and tailgate entry systems with the gob, face, headgate, tailgate, void, and startup room modules. After assembly it is advised to check graphically the correct alignment of all interfaces to ensure the desired resulting mesh.

Listing C.22: Assembly of Headgate Side Entries

```matlab
% Create Entries and Bleeders for FLUENT journal file assembly of mesh from the
% parts of selected files.
% Such as Void, Crosscuts, entry 60, 220, 40 and bleeder parts.
% Headgate entries begin at 1 and range to 45, building from the face towards
% the start-up room.
% Name of journal file to save the TUI commands into:
fileID=fopen('Create-HG-Entries-and-Void.jou','w');
% Absolute path to mesh file locations:
path='"C:\Mesh-Modules\Bleeder-Mesh-Files"';
num_of_cuts=0;
% Open an initial mesh file for a starting point rename faces/interface and solids.
% Change the number times the loop executes to the number desired Entries
% and Crosscuts along the panel length.
for i=1:45;
```

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Listed C.23: Mesh Assembly adding a Crosscut on the Headgate Side

function [num_plus_one] = crosscut(fileID, path, num)
% Add a headgate side crosscut, returns an incremented value.
% File name of mesh
filename='crosscut_50ft.msh';
if num==0
    fprintf(fileID, '%s%s%s%s
', '/file/read-case/', path, filename, '
');
else
    append(fileID, filename, path);
end
%increment unique number of crosscuts before naming parts
num=num+1;
num_plus_one=num;
it1=['it_cut', num2str(num), '_hgvoid '];
it2=['it_cut', num2str(num), '_to_ent', num2str(num)];
renam(fileID,'interface_crosscut_to_void',it1);
renam(fileID,'interface_crosscut50ft_to_t',it2);
%rename part
renam(fileID,'crosscut',[Crosscut',num2str(num)]);
renam(fileID,'wall-crosscut',[wall-crosscut',num2str(num)]);
renam(fileID,'interior-crosscut',['interior-crosscut',num2str(num)]);

Listing C.24: Mesh Assembly Append to a Case File

function [] = append(fileID,meshfile,path)
    command='/mesh/modify-zones/append-mesh/';
    fprintf(fileID,'%s%s%s\n',command,path,meshfile,'"');
end

Listing C.25: Mesh Assembly Renaming Zone Type Command

function [] = renam(fileID,oldname,newname)
    command='/define/boundary-conditions/modify-zones/zone-name';
    fprintf(fileID,'%s %s %s\n',command,oldname,newname);
end

Listing C.26: Mesh Assembly Display the Mesh

function [] = dis(fileID)
    command='/display/mesh-outline';
    command1='/display/views/auto-scale';
    fprintf(fileID,'%s\n%s\n',command,command1);
end

Listing C.27: Mesh Assembly adding an Entry

function [] = entry(fileID,path,len,num,hg_tg)
% Adds an entry, renames the zone and faces, and creates the interface commands.
% Mesh entry file name have the format of "entry<length>ft.msh" for a 220 ft
% the file name would be entry220ft.msh
% Mesh face zones have names in the format of:
% interface_entry<length>ft_<direction>
% For example: interface_entry220ft_y- is the name of the interface on the
% negative facing y-direction.
len=num2str(len);
% The first entry must initial the case file, while all remaining entries are
% appended to the case file.
if num==0
    fprintf(fileID, '%s%s%s
', '/ file / read-case /', path, ['entry', len , ' ft.msh'], "' ");
else
    append(fileID, ['entry', len, ' ft.msh'], path);
end

% Section for adding Headgate side entries and a Section for Tailgate side entries
if strcmp(hg_tg, 'hg')==1
    if (num==1)
        % incremental make uniquely named interface
        it1=['it_ent', num2str(num), '_to_cut', num2str(num)];
        it2=['it_cut', num2str(num), '_to_ent', num2str(num)];
        % rename the interface with a uniquely named value
        % adding a 'hg' identify could be useful at some point.
        renam(fileID, ['interface_', 'entry', len, 'ft_x-'], it1);
        % make the interface between the crosscut and the entry
        mkit(fileID, ['interface_ent', num2str(num), '_to_cut', num2str(num)], it1 , it2 , 'no');
        it3=['it_ent', num2str(num), '_to_ent', num2str(num-1)];
        it5=['it_ent', num2str(num), '_to_ent', num2str(num+1)];
        renam(fileID, ['interface_', 'entry', len, 'ft_y+'], it3);
        renam(fileID, ['interface_', 'entry', len, 'ft_y-'], it5);
        % rename zone
        renam(fileID, ['entry', len, 'ft'], ['entry', len, 'ft', num2str(num)]);
        renam(fileID, ['wall-entry', len, 'ft'], ['wall-entry', len, 'ft', num2str(num)]);
        renam(fileID, ['interior-entry', len, 'ft'], ['interior-entry', len, 'ft', num2str(num)]);
    else
        it3=['it_ent', num2str(num), '_to_ent', num2str(num-1)];
        it4=['it_ent', num2str(num-1), '_to_ent', num2str(num)];
        it5=['it_ent', num2str(num), '_to_ent', num2str(num+1)];
        it6=['it_ent', num2str(num), '_to_cut', num2str(num)];
        renam(fileID, ['interface_', 'entry', len, 'ft_y+'], it3);
        renam(fileID, ['interface_', 'entry', len, 'ft_y-'], it5);
        renam(fileID, ['interface_entry', len, 'ft_x-'], it6);
        mkit(fileID, ['interface_ent', num2str(num), '_to_ent', num2str(num-1)], it3, it4, 'yes');
        mkit(fileID, ['interface_cut', num2str(num), '_to_ent', num2str(num)], ['it_cut', num2str(num), '_to_ent', num2str(num)], it6, 'no');
        renam(fileID, ['entry', len, 'ft'], ['entry', len, 'ft', num2str(num)]);
        renam(fileID, ['wall-entry', len, 'ft'], ['wall-entry', len, 'ft', num2str(num)]);
        renam(fileID, ['interior-entry', len, 'ft'], ['interior-entry', len, 'ft', num2str(num)]);
    end
end
%
Tailgate section
else
if (num<=1)
    it1=[’it_ent’, num2str(num), ’_to_cut’, num2str(num)];
    it2=[’it_cut’, num2str(num), ’_to_ent’, num2str(num)];
    renam(fileID, [’interface_’, ’entry’, len, ’ft_x-’], it1);
    it3=[’it_ent’, num2str(num), ’_to_ent’, num2str(num-1)];
    it5=[’it_ent’, num2str(num), ’_to_ent’, num2str(num+1)];
    it4=[’it_cut’, num2str(num-1), ’_to_ent’, num2str(num)];
    renam(fileID, [’interface_’, ’entry’, len, ’ft_y+’], it3);
    renam(fileID, [’interface_’, ’entry’, len, ’ft_y-’], it5);
    if (num==1)
        mkit(fileID, [’interface_ent’, num2str(num-1), ’_to_cut’, num2str(num-1)], [’it_ent’, num2str(num-1), ’_to_ent’, num2str(num-1)], [’it_cut’, num2str(num-1)], ’no’);
        mkit(fileID, [’interface_ent’, num2str(num), ’_to_ent’, num2str(num-1)], it3, it4, ’yes’);
    end
end
%
rename zone
renam(fileID, [’entry’, len, ’ft’], [’entry’, len, ’ft’, num2str(num)]);
renam(fileID, [’wall-entry’, len, ’ft’], [’wall-entry’, len, ’ft’, num2str(num)]);
renam(fileID, [’interior-entry’, len, ’ft’], [’interior-entry’, len, ’ft’, num2str(num)]);
else
    it3=[’it_ent’, num2str(num), ’_to_ent’, num2str(num-1)];
    it4=[’it_ent’, num2str(num-1), ’_to_ent’, num2str(num)];
    it5=[’it_ent’, num2str(num), ’_to_cut’, num2str(num+1)];
    it6=[’it_ent’, num2str(num), ’_to_cut’, num2str(num)];
    renam(fileID, [’interface_’, ’entry’, len, ’ft_y-’], it5);
    renam(fileID, [’interface_’, ’entry’, len, ’ft_y+’], it3);
    renam(fileID, [’interface_’, ’entry’, len, ’ft_x-’], it6);
    mkit(fileID, [’interface_ent’, num2str(num), ’_to_ent’, num2str(num-1)], it3, it4, ’yes’);
    mkit(fileID, [’interface_cut’, num2str(num-1), ’_to_ent’, num2str(num-1)], it5, it6, ’no’);
    renam(fileID, [’entry’, len, ’ft’], [’entry’, len, ’ft’, num2str(num)]);
    renam(fileID, [’wall-entry’, len, ’ft’], [’wall-entry’, len, ’ft’, num2str(num)]);
end
end
end
Listing C.28: Mesh Assembly Make Interface

```matlab
function [] = mkit( fileID, name, names1, names2, match)

% EXAMPLE of TUI questions and answers
% NAME 1st empty 1st empty periodic-repeats coupled-wall matching
% /define/mesh-interface/create intface-t1-ent2 it_ent2_t1 () it_t1_ent2 () no no yes

command = '/define/mesh-interface/create';
% For interfacing more than one zone to a single zone there cannot be
% periodic repeats so only two
% questions needed answers.
if ( isempty( find(names1==' ')==1) && isempty( find(names2==' ')==1) )
    % A interface between two zones
    fprintf(fileID,'%s %s %s %s %s %s %s %s
', command, name, names1, '()', names2, '()', 'no', 'no', match);
else
    % Multiple zones interfacing to a single zone
    fprintf(fileID,'%s %s %s %s %s %s %s %s
', command, name, names1, '()', names2, '()', 'no', 'no', match);
end
```

Listing C.29: Mesh Assembly Translate Location

```matlab
function [] = translate( fileID, distance)

command= '/mesh/translate';
fprintf(fileID,'%s %s
', command, distance);
end
```

Listing C.30: Assembly of Tailgate Side Entries

```matlab
function [] = assemble_tg_fns( fileID, distance)

% Create Entries and Bleeders for FLUENT journal file assembly of mesh
% from the parts
% of selected files. Such as Void, Crosscut, entry 60,220,40 and
% bleeder parts.
% Tailgate Entries start at 0 and range to 44, building from the Start-
% up room
% towards the face.
% Name of journal file to save the TUI commands into:
fileID=fopen('Create-TG-Entries-and-Void.jou', 'w');
% Absolute path to mesh file locations:
path='"C:\Mesh-Modules\Bleeder-Mesh-Files"';
num_of_cuts=0;
% Open an initial mesh file for a starting point rename faces/interface
% and solids.
```
% start by adding an entry to create a pattern of entries and crosscuts:
% A crosscut is '==', and entries are three vertical '|',
% with the star '* ' representing two face zones of needing interfacing
% %
% Crosscut0-> ==*|
% %
% Building towards face once case is rotated 180 degrees
entry(fileID,path,220,num_of_cuts,'tg');
% Uncomment to display mesh graphic
% dis(fileID);
translate(fileID,'0 60.96 0'); %24.0792=79 ft
num_of_cuts=crosscut_tg(fileID,path,num_of_cuts);
% dis(fileID);
for i=1:44;
    translate(fileID,'0 6.096 0');
    entry(fileID,path,220,num_of_cuts,'tg');
    translate(fileID,'0 60.96 0');
    num_of_cuts=crosscut_tg(fileID,path,num_of_cuts);
    % dis(fileID);
end
mkit(fileID,['interface_cut',num2str(num_of_cuts-1),'_to_ent',num2str(num_of_cuts-1)],['it_cut',num2str(num_of_cuts-1),'_to_ent',num2str(num_of_cuts-1)],['it_ent',num2str(num_of_cuts-1),'_to_cut',num2str(num_of_cuts-1)],'no');
% Must save case file manual or add command to save the case file.
fclose(fileID);

Listing C.31: Mesh Assembly adding a Crosscut on the Tailgate Side

function [ num_plus_one ] = crosscut_tg( fileID , path , num )
% Add tailgate side crosscut mesh, returns an incremented value
% Mesh file name:
filename='crosscut_50ft.msh';
% Case file is already open from previous entry
append(fileID,filename,path);
it1=['it_cut',num2str(num),'_hgyoid'];
it2=['it_cut',num2str(num),'_to_ent',num2str(num)];
renam(fileID,'interface_crosscut_to_void',it1);
renam(fileID,'interface_crosscut50ft_to_t',it2);
%rename part
renam(fileID,'crosscut',['crosscut',num2str(num)]);
renam(fileID,'wall-crosscut',['wall-crosscut',num2str(num)]);
renam(fileID,'interior-crosscut',['interior-crosscut',num2str(num)])

% increment after naming parts
num=num+1;
num_plus_one = num;
end

Listing C.32: Mesh Assembly Change Zone Type

function [] = typ(fileID, name, type)
command='define/boundary-conditions/modify-zones/zone-type';
fprintf(fileID,'%s %s %s
',command,name,type);
end
APPENDIX D - RUNNING FLUENT ON MIO WITH GOFLUENT

The following syntax is used to execute GoFluent:

gofluent  <number of nodes>x<number of processors> <journal file name.jou> <DAYS-HOURS:MIN>

The parameter, <number of nodes>, is the request number of nodes to run the job on Mio and the parameter, <number of processors>, is the minimum number of processors on each node. The job queries the available number and will run on the total number identified when the job starts. For example, “4x8” will request the use of four nodes with at least eight processors, but the job scheduler may run the job on 12-core, 16-core or 20-core machines using all the available processors. The parameter, <journal file name.jou>, is required as an input and must contain the suffix .jou, which will become the name of the base working directory for the Mio jobs. The parameter, <DAYS-HOURS:MIN>, for example, uses the format, 4-14:02, which means the job will halt un-saved 4 days, 14 hours and 2 minutes from the time it is started. The files for the case, data and C-file are then moved to the Fluent job name directory named after the journal file, and then a unique folder is created to contain the transcript and output files from the job.

To setup a Mio enviroment see Listing D.33, and Listing D.34 for the contents a .bashrc file with the Fluent module loaded for 15.0. In Listing D.35 a simple script to check the available Fluent licence useage, and in Listing D.36 the bash script for GoFluent.

Listing D.33: Directory Creation

#!/bin/sh
mkdir /scratch/$USER
mkdir /scratch/$USER/runs
ln -s /scratch/$USER/runs ~/runs
Listing D.34: Mio Login Environment

```bash
# .bashrc

# Source global definitions
if [ -f /etc/bashrc ]; then
    . /etc/bashrc
fi

#add utility for mio node reservations such as dores, getnodes, etc. see inside.mines.edu/mio/utility.html
export PATH=/opt/utility:$PATH

#add my scripts to the mio path for vim, vmv, and rainbow parens
export PATH=$HOME/bin:$PATH

#add ffmpeg to path for custom movie processing
export PATH=/opt/ansys/inc/v150/CFD Post/tools/ffmpeg 20071211/bin/
    linux amd64:$PATH

#Load Library path
export LD_LIBRARY_PATH=/usr/lib:/usr/lib64:/opt/lib/openmpi/1.4.2/
    intel/lib:/opt/lib/openmpi/1.4.2/intel/share:/opt/intel/lib/intel64
    /opt/intel/lib/ia32:/opt/intel/lib/mic:/opt/ansys_inc/v150/fluent/
    fluent15.0.0/lnamd64/syslib

#setup parallel running environment on mio, and compilers
if [ -f /usr/local/bin/setup/setup ]; then source /usr/local/bin/
    setup/setup intel; fi

#load fluent version 15.0.1 or current version
module load ansys/fluent/15.0

#Load Suggested modules from inside.mines.edu/mio/mio001 list
module load PrgEnv/intel/default >& /dev/null
module load utility >& /dev/null

#load the OpenMPI version of MPI
module load openmpi/intel/1.6.5 >& /dev/null

#load the Intel MPI compiler impi
module load impi/intel/4.1.1 >& /dev/null

# User specific aliases and functions
alias go='˜/bin/gofluent'
alias sq='squeue'
alias lic='˜/bin/license check'
```

Listing D.35: Fluent HPC License Check
lmstat -f aa_r.hpc | awk '/start/ { print $1, " \t", $2; print "\t\t\t", $8, $9, $10, $11, $12; } /Total/'

Listing D.36: GoFluent Script

#!/bin/sh
# gofiluent <Number of Nodes>x<Number of Processors> <JournalFile.jou>
#<DAYS HOURS:MINS>
# run the default time
# gofiluent <Number of Nodes>x<Number of Processors> <JournalFile.jou>
# runs the default number of processors and time
# gofiluent <JournalFile.jou>
case $1 in
  *".jou") echo running on 2 nodes
cpus=default
nodes=2
journalfile=$1
;;
*"x") echo Running on a group of nodes and CPUs
nodes='echo $1 | awk F x '{ print $1 }'

##"


cpus='echo $1 | awk F x '{ print $2 }'
journalfile=$2
;;
*) echo What do you want to run?;;
esac

echo Using $nodes nodes and running on at least: $cpus CPUs
#This better be a .jou file
echo The journal file: $journalfile

#Set time in Days Hours:Minutes for running time
#SET default time to run jobs for 0 08:00:00 = 0days 8 hours 0mins 0secs
if [ $3 ]; then TIME="08:00:00"
else TIME=$3:00; fi
#mins:secs appends seconds to given TIME
echo Running FLUENT for: $TIME

#SET default number of CPUs
if [ $cpus = "default" ]; then cpus=8
else echo Will submit job to nodes that have at least $cpus CPUs
fi

#Setting up working environment for job
export JORFILE=$journalfile
#crops .jou off for job name
export NAME='echo $journalfile | awk F '{ print $1 }'

#Set the working directory in your users scratch folder

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export WORK_DIR=/scratch/$USER/$NAME

# Test for exists of WORK_DIR from previous jobs
if [ -d "$WORK_DIR" ]; then echo directory exists; else
    mkdir $WORK_DIR
fi

# Copies all working files to scratch
cp $JORFILE $WORK_DIR
if [ -f $WORK_DIR/.*.gz ]; then echo case file found; else mv *.gz $WORK_DIR; fi
if [ -f *.c ]; then mv *.c $WORK_DIR; fi

cd $WORK_DIR

echo Submitting job to SLURM

# Below is the script that is submitted to SLURM by the command "sbatch"
# To check on the job run "squeue" or "scancel JOBID" to stop
# The JOBID number is found by running squeue

echo ":!/bin/sh
#SBATCH time=$TIME
#SBATCH nodes=$nodes
#SBATCH n $cpus
#SBATCH export=ALL
## Start the job on a list of nodes only
##SBATCH nodelist=compute000,compute001,compute002,compute004
## p is the partition or group name of the nodes to run on "compute"
## is the common nodes
## p jbrune will cancel non group jobs and start this job
#SBATCH p compute
## You can run overcommit to have the other CPUs on the node available to users
## or you can run exclusive allowing only on job.
#SBATCH exclusive

# See slurm.JOBID.out for results of these commands
echo ":$SLURMJOBID
export SLURM_JOB_NAME=$NAME,$SLURM_JOBID
echo Starting SLURM job $SLURM_JOB_NAME
echo Number of NODES:$SLURM_NNODES
echo Number of Processors:$SLURM_NPROCS

cd $SLURM_SUBMIT_DIR

# makes a unique directory to store output files in
# If re running script comment out these 4 lines and run "sbatch script
 JOBID" to try again
mkdir \$SLURM_JOB_NAME

cd \$SLURM_JOB_NAME

mv \$SLURM_SUBMIT_DIR/\$JORFILE ./\$SLURM_JOB_NAME.jou

cp \$SLURM_SUBMIT_DIR/* . \$SLURM_SUBMIT_DIR/\$SLURM_JOB_NAME/.

# Link case and data files in base directory to unique Slurm directory
ln -s \$WORK_DIR/$NAME.dat.gz ./$NAME.dat.gz

ln -s \$WORK_DIR/$NAME.cas.gz ./$NAME.cas.gz

# Outputs this script to a file

```bash
cat \$0 > script.\$SLURM_JOBID
```

# Counts the number of hosts and calculates the total number of CPUs to use
```
export ncpus="/opt/utility/expands \$SLURM_JOB_NODELIST | wc -l"

echo nodelist found this many CPUs: \$ncpus
```

# Create a list of nodes in the file nodes. First listed is the Fluent host node
```
/opt/utility/expands \$SLURM_JOB_NODELIST > nodes

fluent 3ddp t\$ncpus cnf=nodes slurm gui i \$SLURM_JOB_NAME.jou > \$SLURM_JOB_NAME.trn driver null
```

" > \$JORFILE.runjob

# Submits the above script to the Slurm scheduler
```
sbatch \$JORFILE.runjob
```

rm \$JORFILE.runjob