VERTICAL-VELOCITY FLUCTURATIONS IN THERMALLY STRATIFIED SHEAR FLOWS

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CER65JEC-HC48

Technical Report

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U. S. Army Research Grant
DA-AMC-28-043-65-G20

and presented at the
International Colloquium on Fine-Scale Structure of the Atmosphere
15-22 June 1965
Moscow, USSR

FLUID DYNAMICS AND DIFFUSION LABORATORY

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by

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Summary

Vertical-velocity fluctuations were measured in a wind-tunnel boundary layer made thermally stable or unstable (corresponding to inversion and lapse conditions) by flow over a horizontal flat plate which was either cooled or heated. Measurements with the crossed hot-wire anemometer yielded vertical distributions of turbulence intensity and the one-dimensional power spectra for the vertical velocity component. The laboratory power spectra were compared with power spectra obtained in the atmospheric surface layer (primarily by Gurvich (1) with an acoustical anemometer). The effect of thermal stability on the turbulence generated in the laboratory is qualitatively in agreement with corresponding effects on atmospheric turbulence. Power spectra of the laboratory data revealed little evidence of an inertial sub-range (-5/3 power behavior) as found by Gurvich for the atmospheric turbulence. This difference is primarily due to Reynolds number being one order of magnitude smaller for the laboratory flow than for the atmosphere -- measurements of power spectra for the longitudinal component of turbulence in the laboratory at the same Reynolds number (distance above the boundary used for a length scale) as encoutered by Pond, Stewart and Burling (2) in their measurements in air over ocean waves show a substantial inertial sub-range. Laboratory spectra for the vertical component in stably stratified flow show a substantial -11/5 power behavior as predicted by Bolgiano (3) for a buoyancy sub-range whereas the atmospheric data presented by Gurvich does not.

Introduction

The effects of thermal stratification on turbulence structure within a turbulent boundary layer are known to be significant, especially on the diffusive characteristics of the flow. Exploratory laboratory studies such as those by Nichol (4), Johnson (5), and Cermak (6), and field studies by Gurvich (1), Perepelkina (7), and Panofsky and McCormick (8) have yielded much information. However, quantitative result on, for example, the change of energy content with Richardson number for the vertical velocity component as a function of disturbance wave number is still not established. In the laboratory, investigators have been limited in their studies by the difficulty of creating thermally stratified boundary layers on a sufficiently large scale to produce flows having turbulence characteristics similar to atmospheric surface-layer flows and by the difficulty of measuring velocity fluctuations in the presence of temperature fluctuations. The first difficulty has been partially overcome in the Fluid Dynamics and Diffusion Laboratory at Colorado State University, by the construction of a special meteorological wind tunnel (9) in which the exploratory results reported at this Colloquium were obtained. On the other hand, hot-wire anemometry techniques have not adequately advanced to enable satisfactory measurement of all desirable turbulence statistics for thermally stratified flows; however, the conventional crossed hot-wire anemometer yields a voltage fluctuation proportional to the vertical-velocity fluctuation which is free from temperature perturbations if the wires are sufficiently similar. Because of the relative simplicity of this measurement, the exploratory study was confined to a study of the vertical component of turbulence.

The intensities of the vertical component of turbulence as a function of Richardson number and the one-dimensional power spectra for different Richardson number are compared with field data obtained by Gurvich (1). The comparisons are made in an effort to determine the similarities and differences of turbulence in thermally stratified laboratory and atmospheric flows. Such comparisons are made in the framework of similarity theory introduced by Monin and Obukhov (10).

Laboratory Measurements

The meteorological wind tunnel (11) was specifically designed and constructed in an effort to obtain flows simulating those in the atmospheric surface layer. The tunnel has a test section of approximately 25 meters long with a cross section of nearly 2 meters by 2 meters. The test-section geometry is shown in Fig. 1. All measurements were made at the section approximately 24 m downstream from the test-section entrance. The thermal and momentum boundary-layer thickness were both approximately equal to 70 cm. A range of Richardson number from 0.5 to -0.5 was achieved by cooling or heating the wind-tunnel floor and heating or cooling, respectively, the ambient air.

Mean-velocity profiles were measured by means of a calibrated pitot-static probe having an outside diameter of about 3 millimeters. The probe was used with a capacitance-type pressure transducer (Trans-sonics Type 120 Equibar Meter) and the dynamic pressure head was plotted automatically as a function of height z. Velocities were calculated using an air density corrected to local temperature conditions.

Mean-temperature profiles were measured with a thermocouple mounted on the actuator. Data were taken point by point in the z-direction so that no time-lag effect occurred in the measurements.

The vertical component of the turbulent velocity was measured with a constant-temperature, X-hot-wire anemometer incorporated with a difference operational amplifier circuit. The RMS value of the fluctuating vertical component of the velocity field was obtained from a true RMS meter (Bruel and Kjaer Type 2409) feeding into an x-y plotter to give the turbulent intensity as a function of height z. The output of the anemometer was also recorded on an FM magnetic tape (Mincom C-100 FM Recorder) at several pre-selected heights in the boundary layer. Fig. 2 shows the block diagram of the measuring equipment. Spectral distributions of turbulent energy were then determined from the magnetic tape recording. The energy-density spectrum in the range from 1 to 16 cycles per second was measured by a wave analyzer (Technical Products Spectrum Analyzer TP 627 with an effective band width of 1.12 cycles per second. A constant-percentage band width spectrum analyzer (Bruel and Kjaer Type 2109) responding in the range from 16 to 10,000 cycles per second was used to measure the energy-density spectra in the frequency range equal to and above 16 cycles per second. The two sets of spectral measurements were matched at a frequency of 16 cycles per second, and the composite spectra were normalized so that the area under the spectral distribution curve for all the frequencies was equal to unity.

Results and Discussion

Mean-velocity profiles in the steady boundary layer on a flat plate were obtained for ambient velocities of 150, 210 and 300 cm/sec. They were taken at a section about 24 meters from the leading edge of the plate corresponding to the position where measurements of turbulence were made. Mean-temperature profiles were also measured at the same section. Typical profiles of the mean-velocity and temperature are shown respectively in Figs. 3 and 4. Both the mean-velocity and the mean-temperature profiles within the height ranging from about 1.3 cm to 10 cm could be expressed by a log plus linear law. However, no attempt was made to fit the data outside of this range on the log plus linear law although the height range might be extended for different velocities under different stability conditions.

Distributions of turbulent intensity of the vertical component for ambient velocities at 150, 210 and 300 cm/sec were inferred from the anemometer data. The turbulent intensity near the wall was always maximum for the unstable thermal stratification and was minimum for the stable stratification at the same ambient velocity. A typical plot of the turbulent-intensity distribution for an ambient velocity at 210 cm/sec is shown in Fig. 5. The turbulent intensity at ambient velocities of 150 and 210 cm/sec under stable condition has a maximum value at mid-layer and decreases, moving either upward or downward as shown in Fig. 6. This is one of the peculiar phenomena observed in the thermally stratified flow of the wind tunnel.

Fig. 6 demonstrates the effect on vertical turbulence of increasing the thermal stratification for stable flow. For sufficiently small Richardson number ($Ri_3 = 0.1$) the distribution is not greatly different than for the neutral flow; however, for $Ri_3 = 0.22$ and 0.3 the intensity of the vertical component is very small near the wall and increases with height. More data are necessary to determine at what Richardson number the turbulence changes structural type--the suggestion has been made that this occurs for $Ri \doteq 0.25$ for atmospheric turbulence.

The dependence of the dimensionless turbulent intensity of the vertical component upon Richardson number was determined from the laboratory measurements and compared with those data obtained by Gurvich (1) in the atmospheric measurements. The results for a velocity of 300 cm/sec and height at 3 cm agree very well with those of Gurvich as shown in Fig. 7. Experimental results for a velocity of 150 cm/sec seem too low. In this case, the Reynolds number $\frac{\bar{U}_o z}{\nu}$ is only approximately 8000 whereas the data reported by Gurvich is estimated to be for a Reynolds number about two orders of magnitude greater. This suggests that the disagreement at 150 cm/sec is a result of relatively larger viscous forces modifying the turbulence. Panofsky (12) claims that the ratio of w'/u_* should be equal to 1.05 under neutral condition. This criterion was not met by the exploratory results of this study.

Distributions of the dimensionless one-dimensional spectra $\bar{F} = \frac{\bar{U}}{u_*^2 z} F(\omega, z)$ which was defined by Eq. (7) in reference 1, for ambient velocities at 150, 210, and 300 cm/sec and heights at 1.27, 5.08 and 17.8 cm were calculated and plotted. A typical plot is shown in Fig. 8. The spectra at different heights were of different magnitudes, although the stabilities (Richardson numbers) at the various heights were the same. Hence, the vertical velocity spectra at different heights could not be brought into a coincident curve in the dimensionless frequency space. The spectra were also plotted on Fig. 5 of reference 1 by matching points as shown in Fig. 9a. It is apparent that the spectrum does not have a large frequency range following the -5/3 power law or an extensive inertial sub-range. Although the special wind-tunnel can in fact produce turbulent boundary layers having locally isotropic turbulence at an ambient velocity of about 9 m/sec (13) as shown in Fig. 9b (for the longitudinal component of turbulence in neutral flow), the local isotropy is absent in the present low-speed study. Consequently, it is not surprising that the spectra which are plotted in Fig. 10 do not have a substantial portion of a horizontal straight-line distribution. The wall-distance Reynolds number is approximately 2×10^5 in the former case, and only 1×10^4 in the latter case; thus, the lack of isotropy in the low-speed study can be attributed to an insufficiently large Reynolds number for the flow. For the stable flow, a tendency toward the -11/5 power law advanced by Bolgiano (3) is seen.

Spectral distribution of the turbulent energy of the vertical component was computed for ambient velocities and heights mentioned in the last paragraph. Typical data with the spectra nondimensionalized to show the distribution of energy per octave are shown in Figs. 11 and 12. A systematic shift of the maximum energy per octave to higher dimensionless frequency with increasing height is shown by the data. The results of Gurvich (1) and Panofsky (8), do not show this trend; however, the maximum energy per octave in both laboratory and field data occurs for $0.5 < \frac{fz}{\bar{U}} < 2$. More data, both field and laboratory, are required to quantitatively determine the dimensionless frequency for maximum energy per octave as well as the decrease in energy content at low frequencies with increasing thermal stability.

Conclusions

The exploratory results show that mean velocity and temperature profiles in the thermally stratified flow of a wind tunnel near the wall can be expressed in a log plus linear law which is also representative of the field data. Intensities of vertical-velocity fluctuations in the wall region vary with Richardson number for the wind-tunnel boundary layer and the atmospheric surface layer in a similar manner, if the "wall-distance" Reynolds number exceeds 10^4. In the low-frequency range, the energy content of vertical-velocity fluctuations shows qualitatively the same changes with Richardson number in the laboratory and in the atmosphere. However, laboratory spectra do not show an appreciable range of frequencies following the -5/3 slope as is found for atmospheric spectra--the "wall-distance" Reynolds number should be increased to over 10^5 if a substantial inertial sub-range is to be found for spectra obtained in the laboratory.

Sufficient similarity of the structure of vertical velocity turbulence for thermally stratified flows created in a wind-tunnel boundary layer and that found in atmospheric surface layers was found to warrant an intensive systematic laboratory study of turbulence with the objective being to learn more about turbulence in the atmospheric surface layer. Additional carefully planned and executed field studies are necessary to provide data for objective tests of similarity between atmospheric and laboratory turbulence structure.

Acknowledgments

The authors wish to thank Dr. Y. H. Kuo and staff members of the Fluid Dynamics and Diffusion Laboratory, Colorado State University, for their technical assistance. Financial support provided by the United States Army through Research Grant DA-AMC-28-043-65-G20 for this study and by the National Science Foundation for travel to the Colloquium are gratefully acknowledged.

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List of Symbols

f	frequency, cycle per sec.
F	one-dimensional energy-spectrum function, cm^2/sec^2-cps.
$\bar{F}$	$F\bar{U}/zu_*^2$, dimensionless energy-spectrum function.
g	gravitational acceleration, cm/sec^2.
Re_δ	$\bar{U}_o\delta/\nu$, Reynolds number.
Ri	$g\frac{\partial\bar{T}}{\partial z} / \bar{T}(\frac{\partial\bar{U}}{\partial z})^2$, Richardson number.
$\bar{T}$	mean absolute temperature, ^oK.
u_*	friction velocity, cm/sec.
$\bar{U}$	local mean velocity, cm/sec.
$\bar{U}_o$	mean ambient velocity, cm/sec.
w'	root-mean-square value of turbulence in the vertical direction, cm/sec.
z	Cartesian coordinate in the vertical direction, cm.
δ	boundary-layer thickness, cm.
ν	kinematic viscosity, cm^2/sec.
ω	$2\pi f$, angular frequency, radian per sec.

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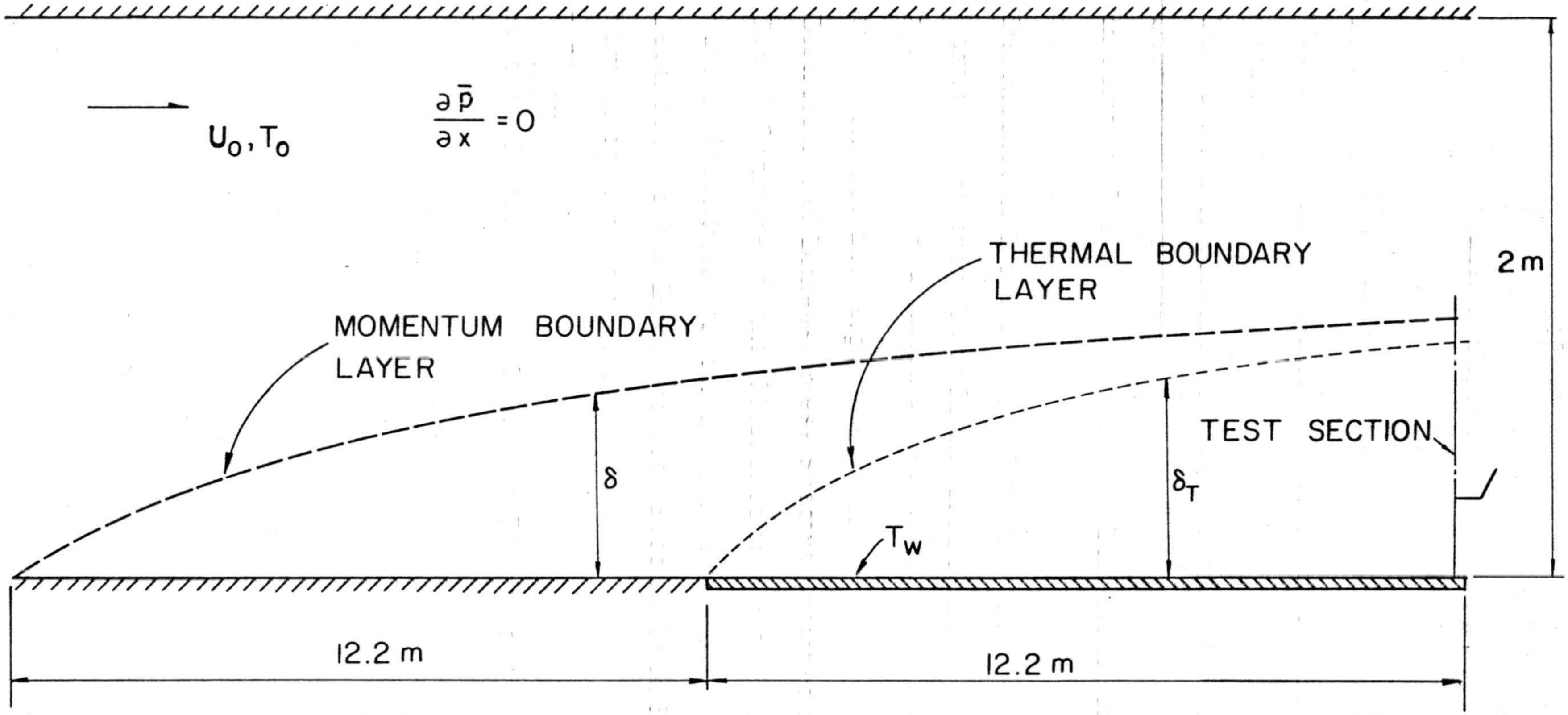


Fig. 1. Test-Section Geometry.

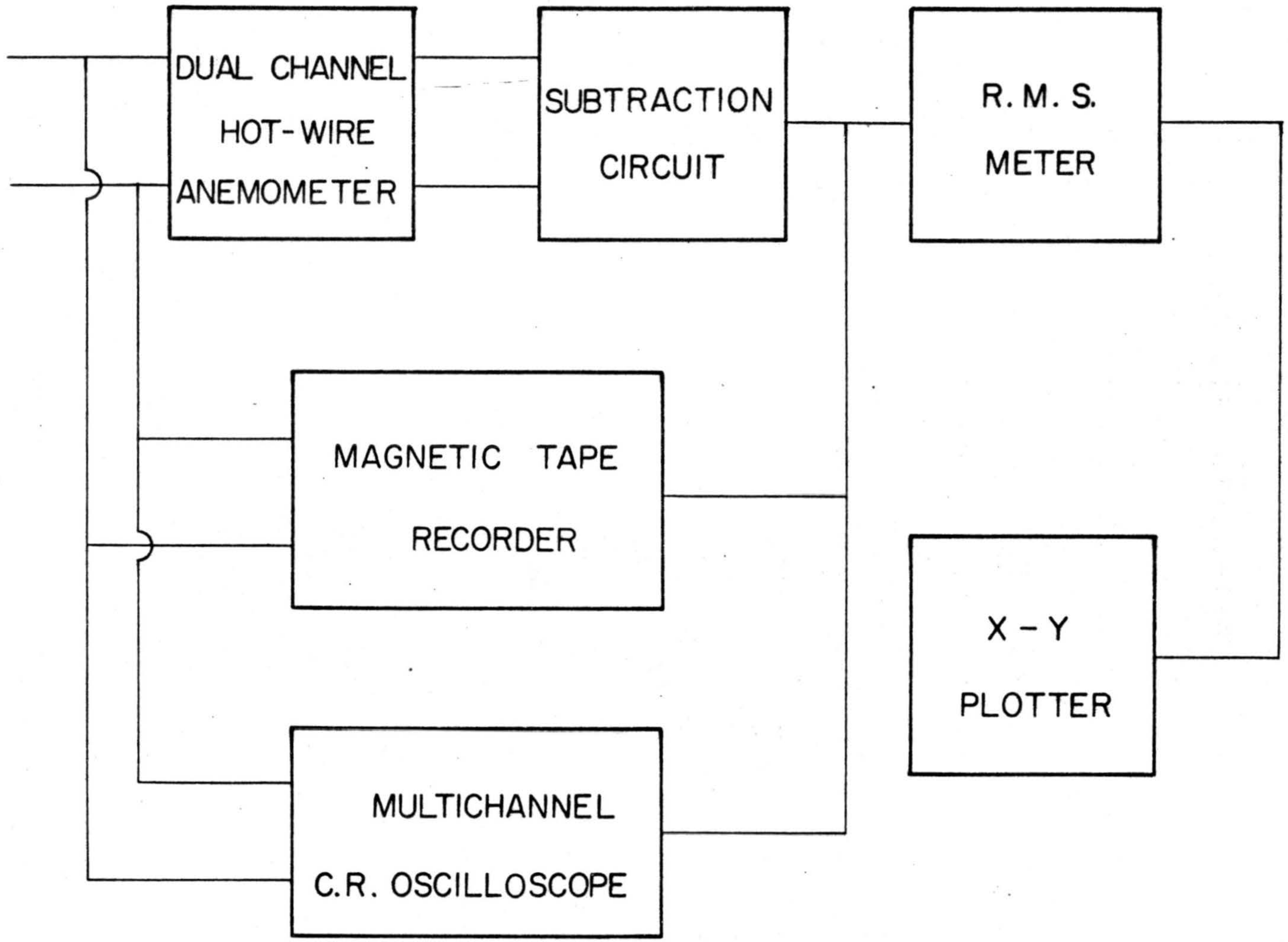


Fig. 2. Block Diagram of Measuring Equipment.

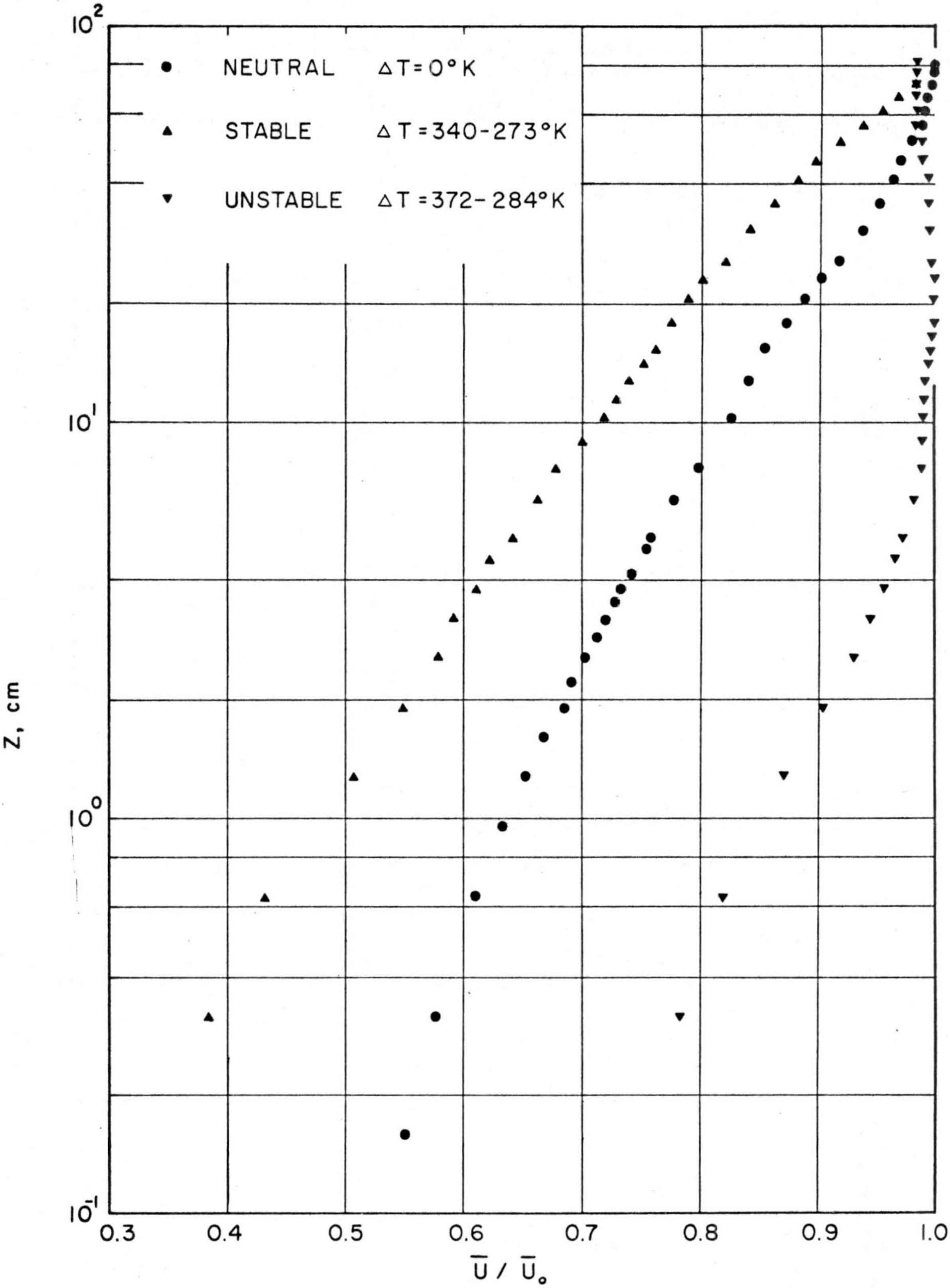


Fig. 3. Velocity Profile for Ambient Velocity at 210 cm/sec.

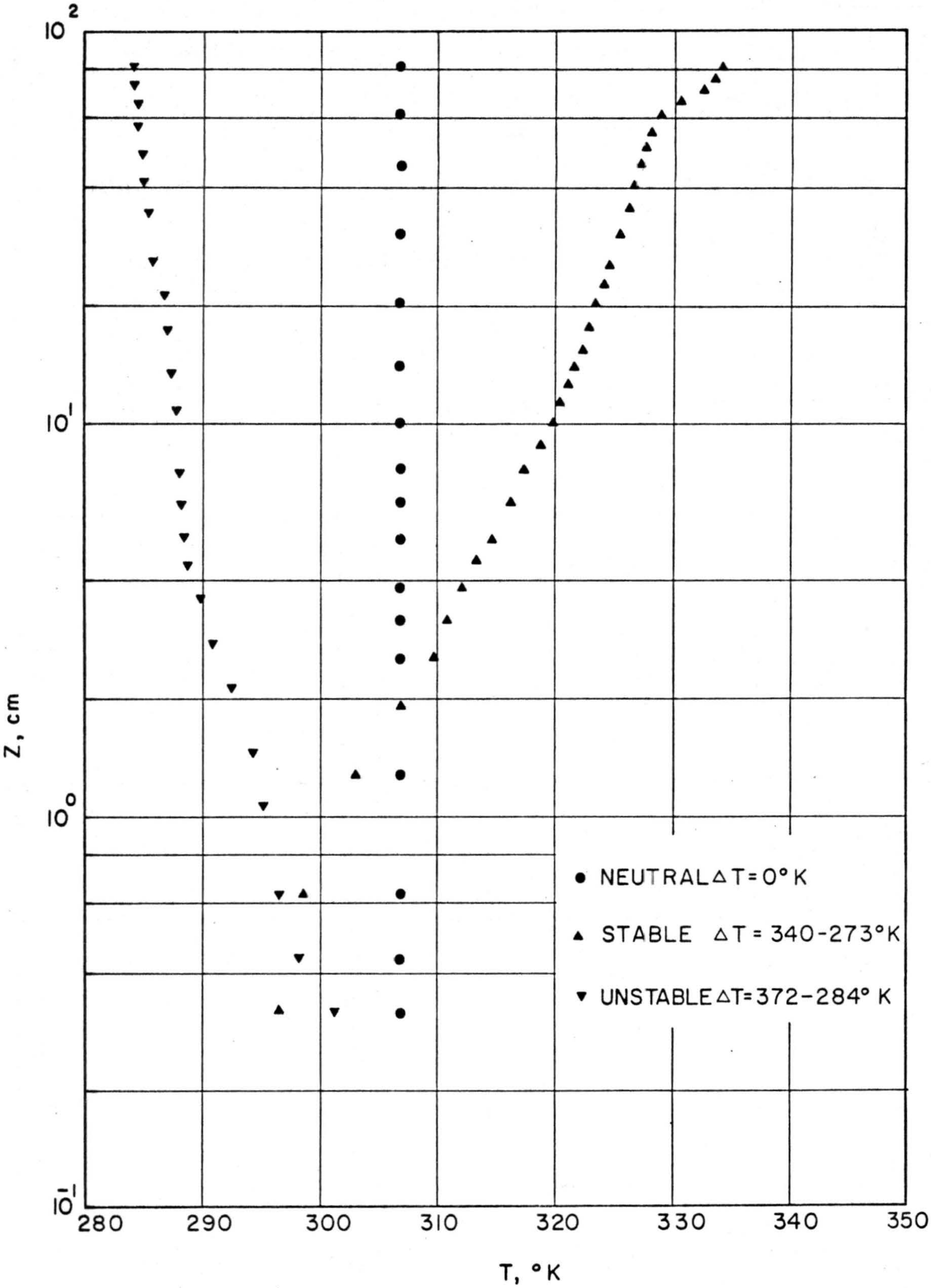
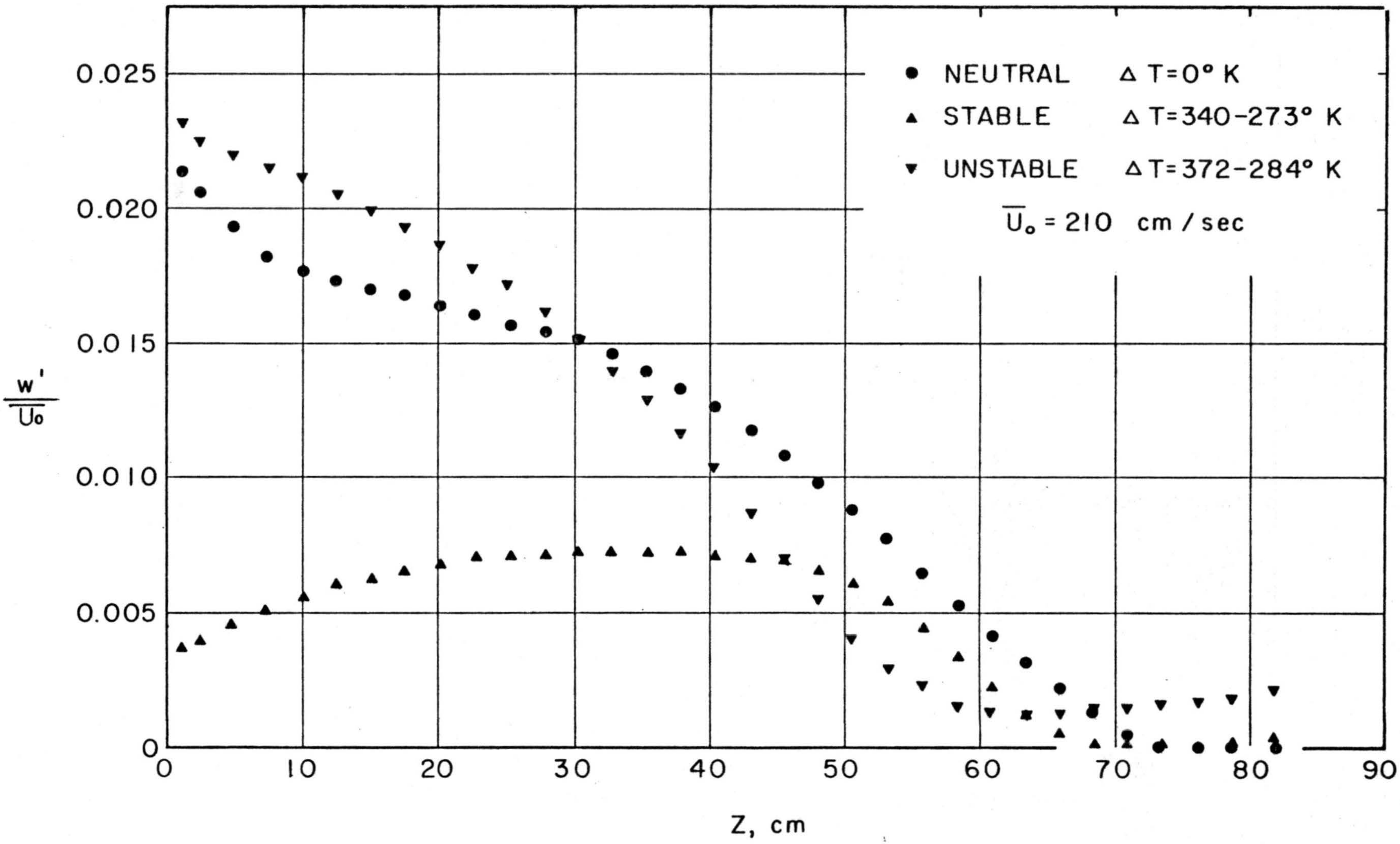


Fig. 4. Temperature Profile for Ambient Velocity at 210 cm/sec.



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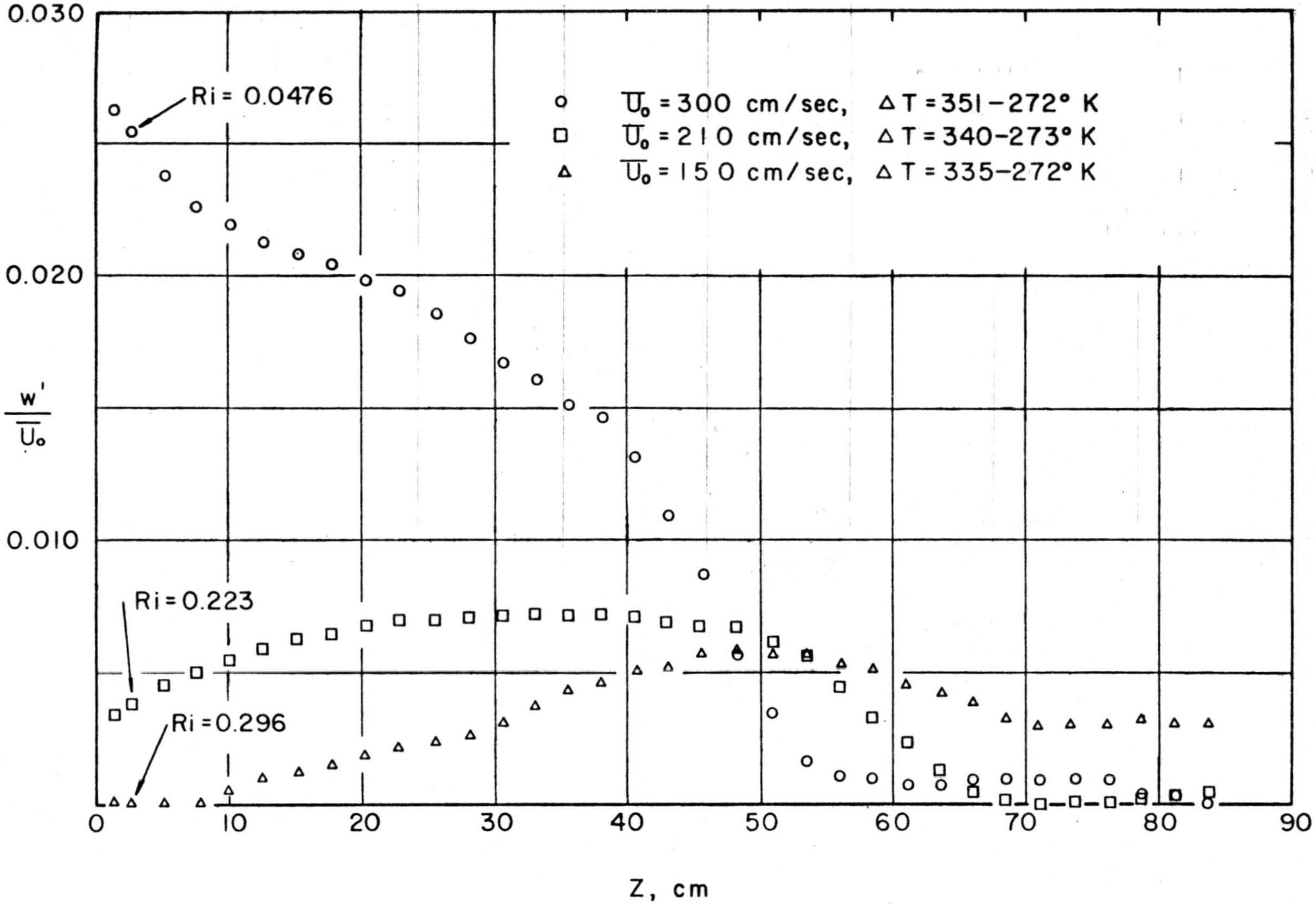
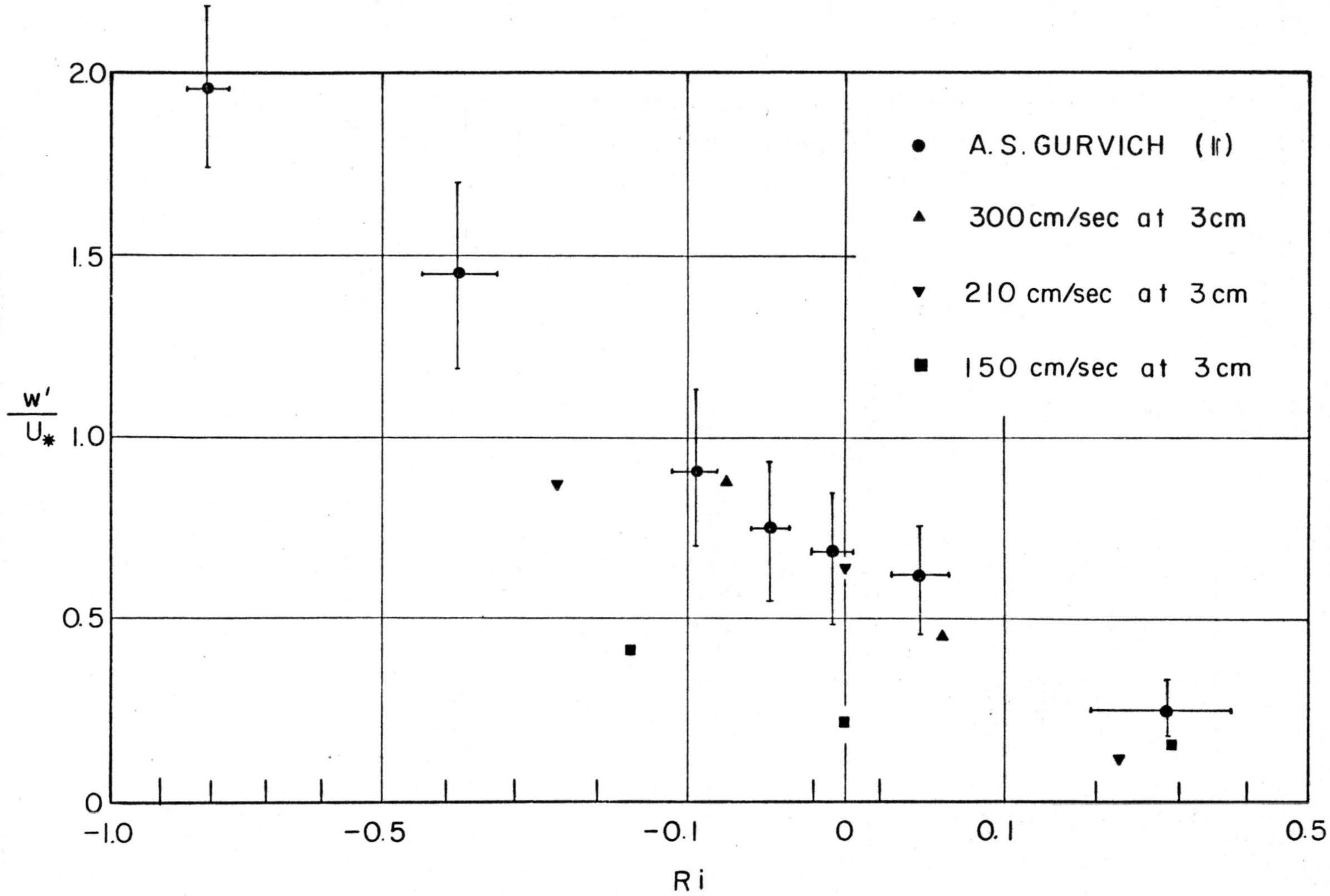


Fig. 6. Intensity of Vertical Component of Turbulence for Stable Stratification.



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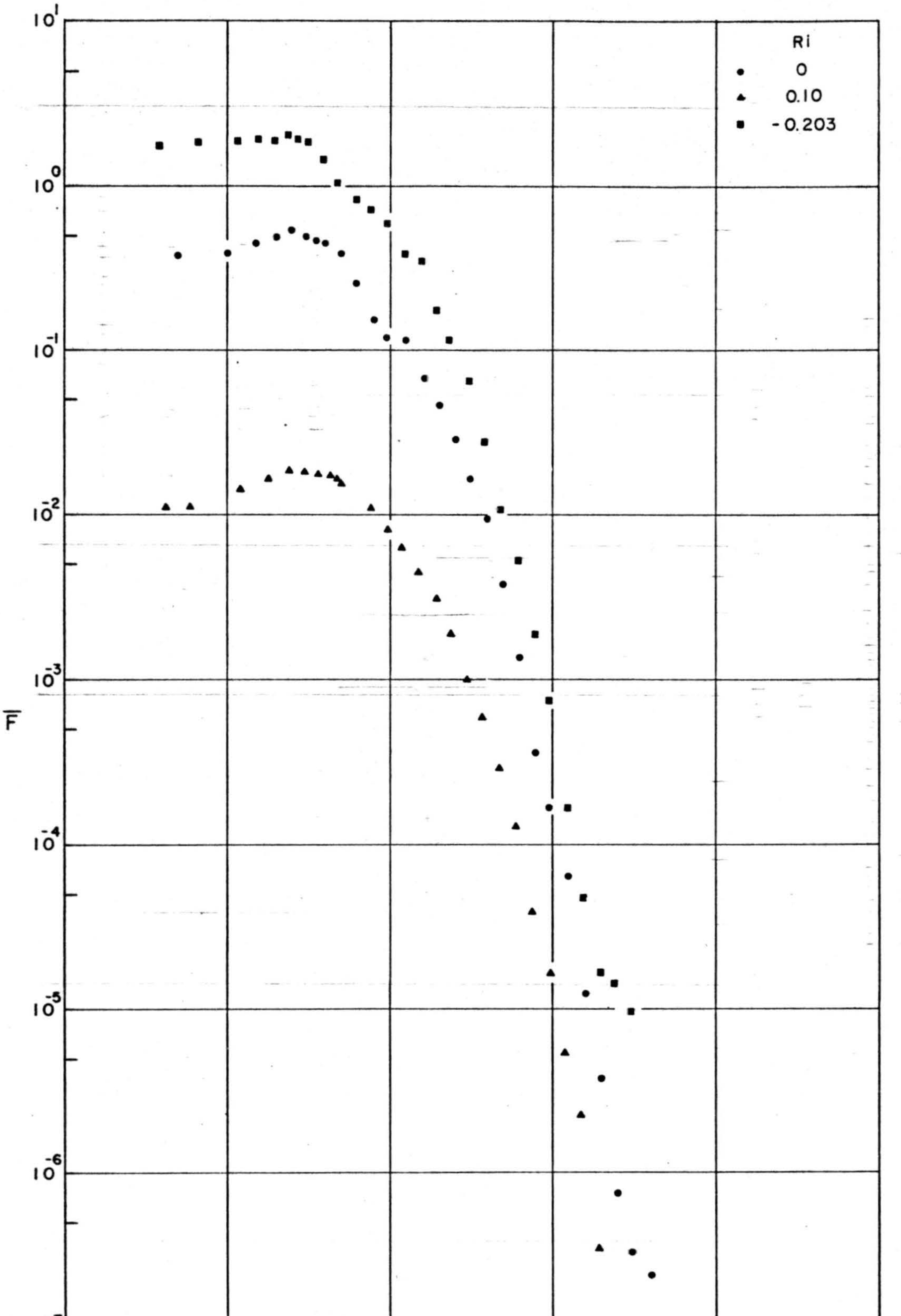

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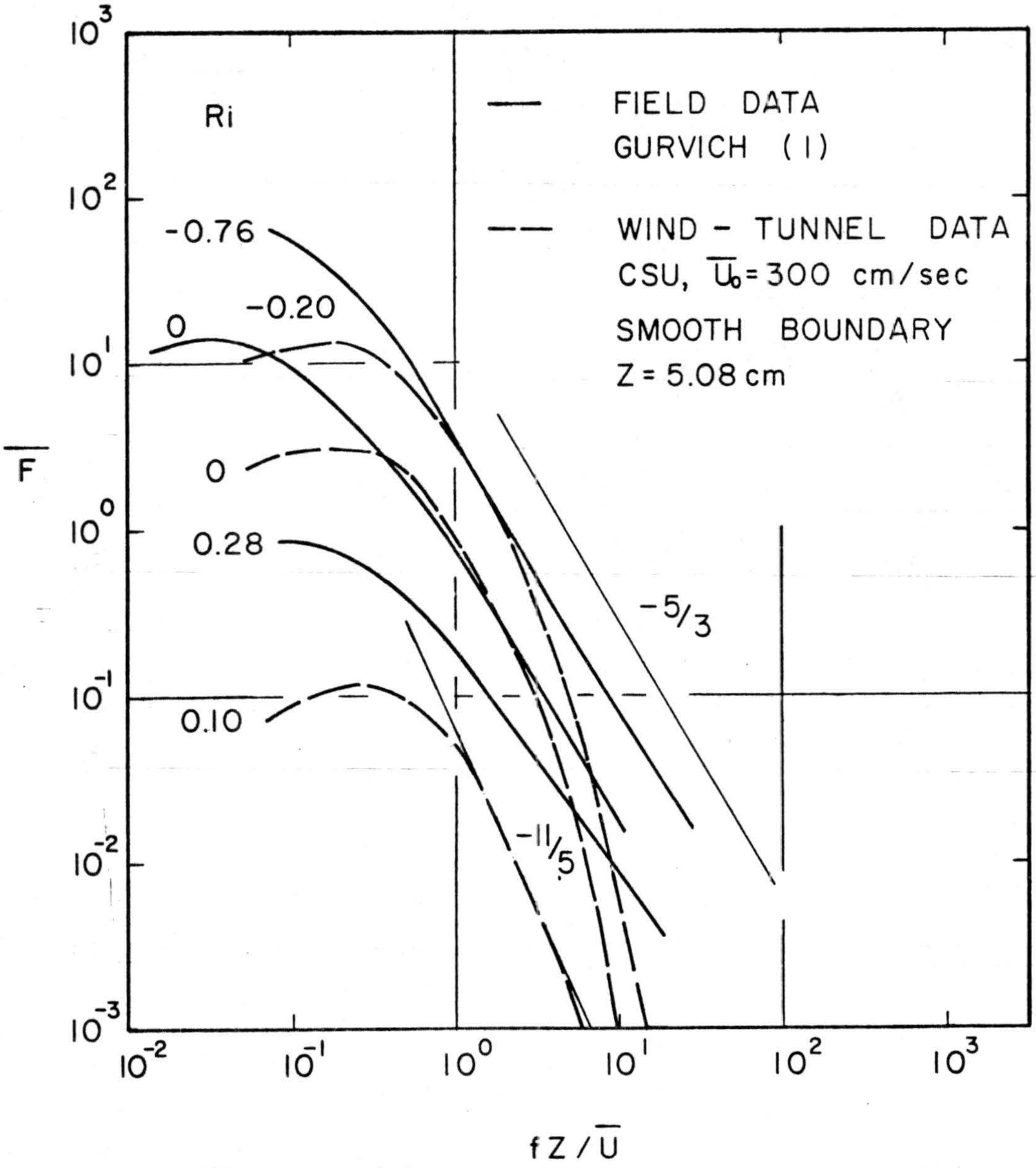

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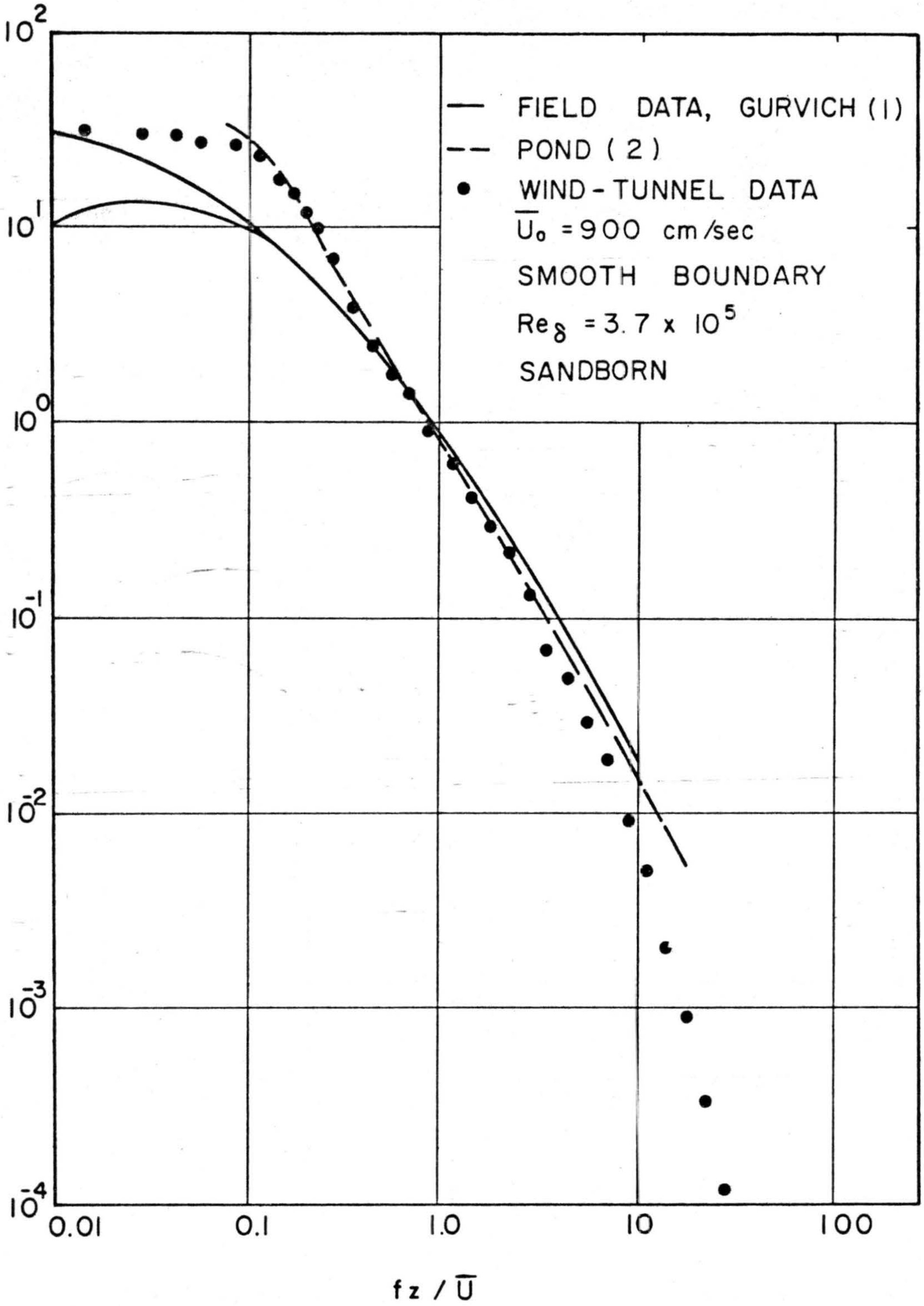

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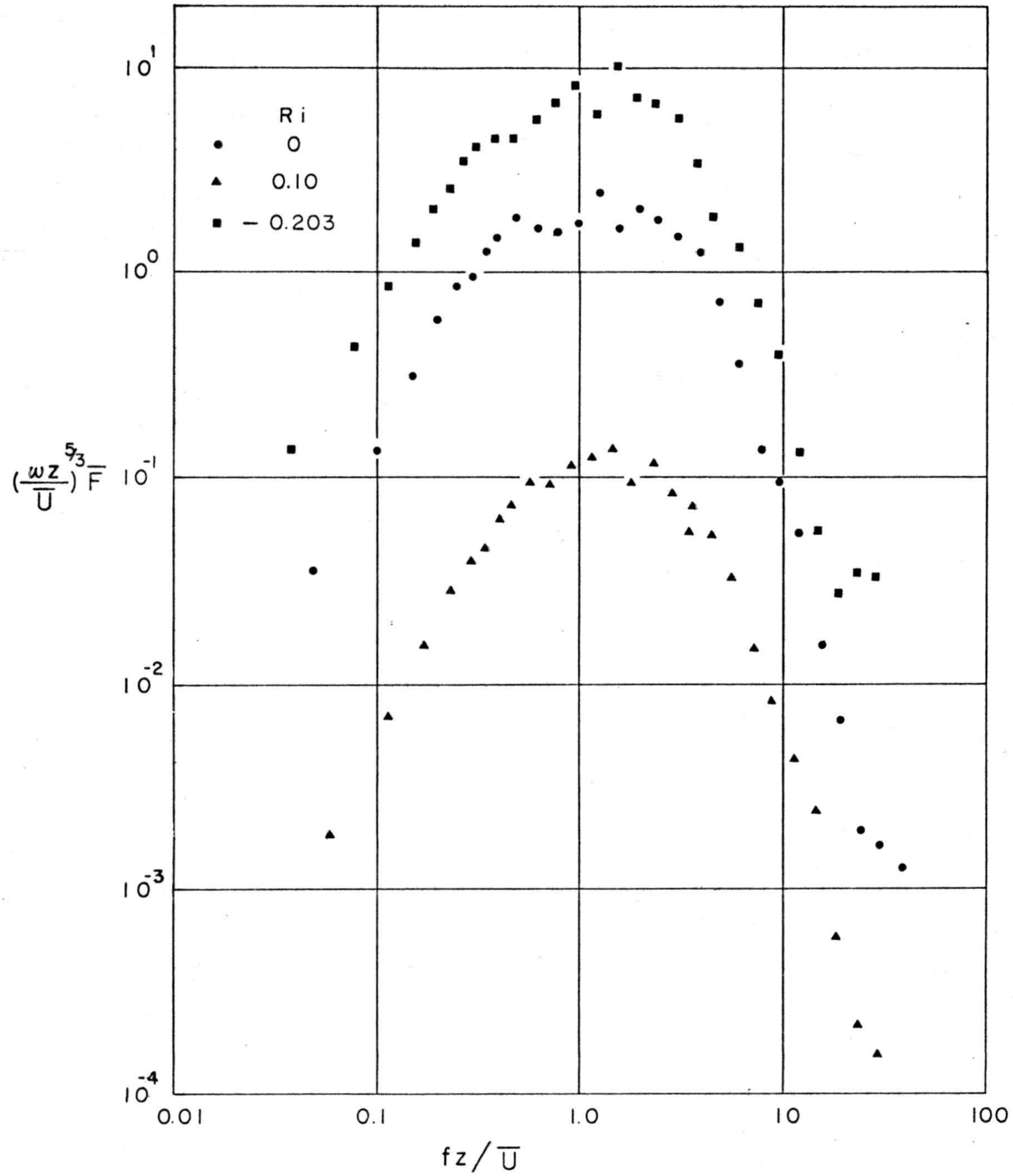

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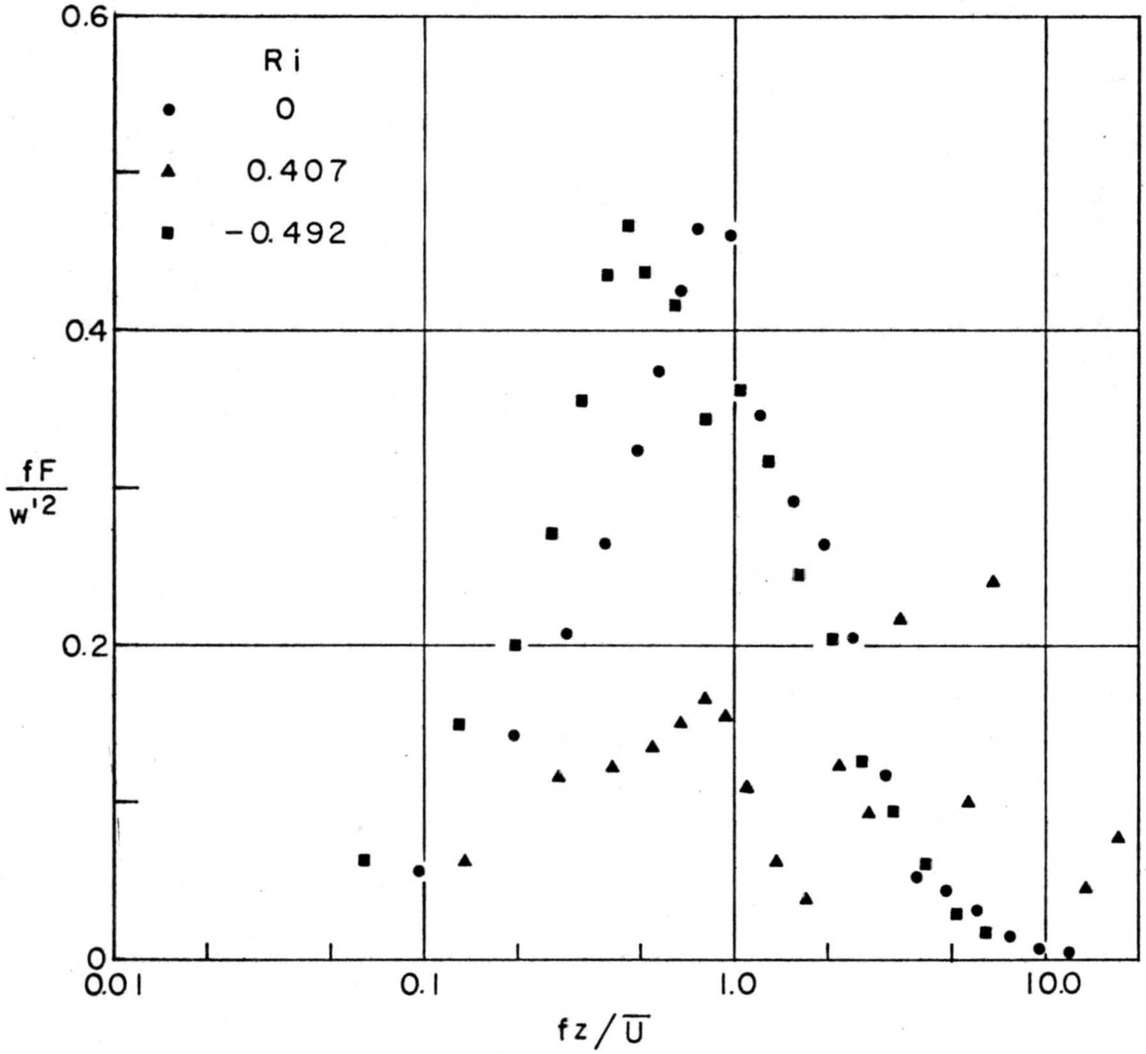
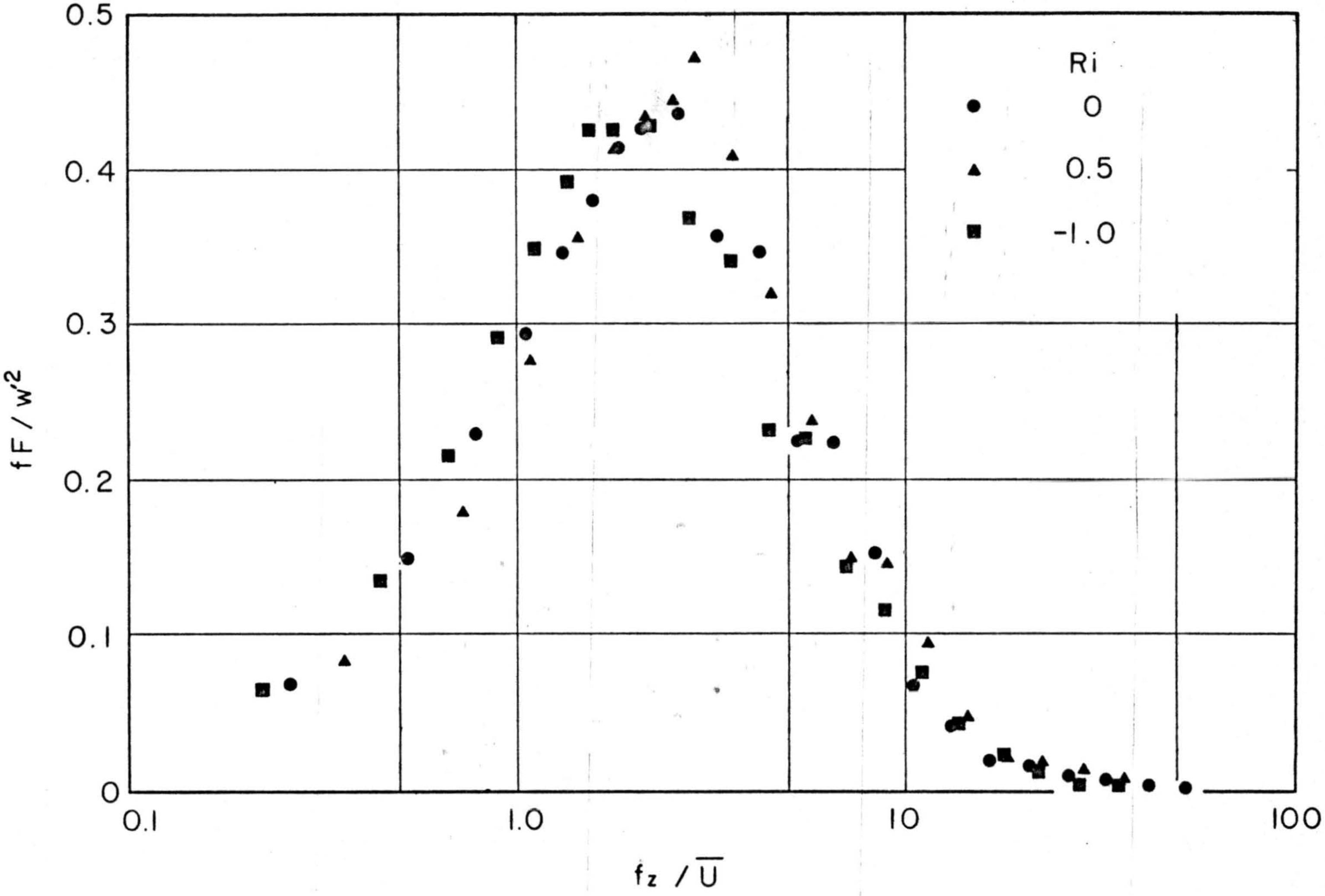


Fig. 11. Spectral Distribution of Turbulent Energy of the Vertical Component for Ambient Velocity at 150 cm/sec and Height at 5.08 cm.



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