DIRECT CONTACT LIQUID-LIQUID HEAT EXCHANGER: PILOT PLANT RESULTS

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ABSTRACT

Three liquids were tested in a pilot plant scale direct contact liquid-liquid heat exchanger. No temperature stratification was observed in the heat exchanger column. An empirical relationship between the Nusselt and Peclet numbers was observed to be the same for all 3 liquids tested, when the ratio of the viscosities of the continuous and dispersed phase liquids were taken into account.

Analysis showed that the bulk of the resistance to heat transfer lies in the dispersed phase. The minimum continuous phase liquid depth required for complete heat transfer was shown to be a function of the drop size and Prandtl number of the dispersed phase and was less than a meter for all 3 liquids tested.

A full scale direct contact liquid-liquid heat exchanger has been constructed and is presently being tested.

1. DESCRIPTION OF THE DIRECT CONTACT LIQUID-LIQUID HEAT EXCHANGER (DCLLHE)

If one uses an immiscible liquid in the solar collector, then it is possible to eliminate the heat exchanger from the system and have direct heat transfer from the immiscible liquid used in the collector and the water in the storage tank. The main requirement is that the immiscible liquid be substantially different in density from water, and a number of inexpensive immiscible liquids meeting this requirement are available.

An overall view in Figure 1 shows several elements in a DCLLHE. The perforated plate at the top of the unit distributes the incoming hot liquid across the entire horizontal surface of the water. As this liquid streams through small holes in the plate and reaches the water surface, it breaks up into small droplets, affording a large heat transfer surface area per unit volume of water. As the droplets pass down through the column of water, heat is transferred from them to the water phase, and the droplets collect into a liquid pool under the water, which supplies the collector pump.

A conical bottom is used to reduce the volume of immiscible liquid required. This is indicated in Figure 1. Droplets of the immiscible heat transfer liquid pass through the heat storage tank water volume, completely transferring the heat acquired in the solar collector. The liquid droplets coalesce in a conical water-free layer at the bottom of the heat storage tank, from which the solar collector pump draws its supply for recirculation through the solar collector. The load is met by pumping hot water from the storage tank to the air heaters or other units in the building requiring heat and returning the water to the tank in the conventional manner.

Experimental work with this heat exchange system has involved the use of heat transfer liquids heavier than water. Results to date show excellent dispersion of droplets. The drops coalesce readily into a continuous underlying pool from which the collector pump draws the liquid without inclusion of water.

2. ADVANTAGES OF THE DCLLHE

The DCLLHE is a panacea for liquid-heating solar heating and cooling systems for many reasons including the following:

(1) It eliminates freezing problems.
(2) It eliminates corrosion problems in the solar collector loop and consequently permits the use of less expensive metals (such as aluminum) in solar collectors thereby greatly reducing their costs. In addition, the need for elastomers between dissimilar metals in the solar collector loop is eliminated as are filters, getters, etc.
(3) It eliminates boiling problems in the solar collector.
(4) It increases the solar system efficiency to the maximum possible (same as a system with the same liquid in both the solar collector and in the heat storage tank). Use of this system in CSU solar house 1 is expected to increase the useful heat gain of the existing flat plate solar collector about 10%.
(5) By eliminating the heat exchanger and the electrically driven water pump between the solar collector loop and the heat energy...
storage tank, the cost of the solar system is reduced an additional $700 while parasitic power requirements are also reduced.

(6) By reducing the temperature difference between the solar collector loop and the heat energy storage tank, the temperature of the latter could be increased thereby greatly improving the performance of solar energy driven lithium bromide absorption cooling units.

(7) The heat capacity of liquid heating solar collectors will be reduced thereby making them more responsive and less difficult to control. In addition, overnight heat losses will be reduced.

**Figure 1. Direct Contact Liquid-Liquid Heat Exchanger**

3. HEAT TRANSFER IN A DCLLHE

In a heat exchanger the rate of heat transfer, Q, is given by the product of three factors:

\[ Q = U A \Delta T \quad (1) \]

where

- \( Q \) = rate of heat transfer, J/sec=W
- \( U \) = overall area heat transfer coefficient, J/(sec)(cm²)(°C)
- \( A \) = area through which heat transfer occurs, cm²
- \( \Delta T \) = representative temperature difference, °C

In a direct contact liquid-liquid heat exchanger,

\[ \Delta T = T_d - T_c \quad (2) \]

With

\[ \Delta T = \text{temperature difference, °C} \]
\[ T_d = \text{temperature of the dispersed phase liquid, °C} \]
\[ T_c = \text{temperature of the continuous phase liquid (water), °C} \]

Using \( \Delta T_1 \) to represent the initial temperature difference, then

\[ \Delta T = \Delta T_1 / 2 \quad (3) \]

In addition, in a DCLLHE,

\[ L = 1 + \frac{h_c}{h_d} \quad (4) \]

where

- \( h_c \) = continuous phase heat transfer coefficient, J/(sec)(cm²)(°C)
- \( h_d \) = dispersed phase heat transfer coefficient, J/(sec)(cm²)(°C)

The problem of finding \( A \), the interfacial area, can be solved by determining \( A \) indirectly. \( A \) is given by (assuming the drops are spherical in shape)

\[ A = \frac{d^2 \pi n}{6} \quad (5) \]

where:

- \( d \) = drop diameter, cm
- \( n \) = number of drops in the heat exchanger.

If we define the quantity \( H \) (the "holdup") as the fraction of the effective volume (V) of the heat exchanger occupied by the dispersed phase, then

\[ H = \frac{\frac{1}{6} \pi d^3 n}{V} \]

and combining Equations 5 and 6,

\[ A = \frac{6 H V}{d} \]

Because the interfacial area, \( A \), often cannot be determined in liquid-liquid contacting equipment, a volumetric heat transfer coefficient has been defined as the product of the area heat transfer coefficient and \( A \), the interfacial area per unit volume:

\[ a = A/V \]

Consequently, equation 1 becomes

\[ Q = Ua V \Delta T_1 / 2 \]

3.1 Holdup

Holdup is defined as the fraction of the effective volume of the heat exchanger occupied by the dispersed phase. Holdup is dependent on flow rates, liquid system properties (density, viscosity, interfacial tension), operating temperature, and droplet size. The effect of holdup on slip velocity is

\[ V_s = \frac{F/S}{H} (1-H) \]

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where

\[ V_s = \text{slip velocity} = \text{relative velocity between the 2 phases, cm/sec} \]
\[ F = \text{flow rate of the dispersed phase, cm}^3/\text{sec} \]
\[ S = \text{horizontal cross sectional area of the heat exchanger, cm}^2 \]
\[ W = \text{flow rate of the continuous (water) phase, cm}/\text{sec} \]
\[ F/S = \text{superficial velocity of the dispersed phase, cm/sec} \]
\[ W/S = \text{superficial velocity of the continuous (water) phase, cm/sec} \]

3.2 Dimensionless Numbers Used

The dimensionless numbers used in this study include the following:

\[ N_N = \text{Nusselt number} = h_d/k \quad (11) \]
\[ N_R = \text{Reynolds number} = d v / \mu \quad (12) \]
\[ N_P = \text{Prandtl number} = c \mu / k \quad (13) \]
\[ N_{Pe} = \text{Peclet number} = c \mu d / k = N_p N_R \quad (14) \]

where

\[ h = \text{Heat transfer coefficient, J/(sec)(cm}^2)(°C) \]
\[ d = \text{drop diameter, cm} \]
\[ k = \text{thermal conductivity, J/(sec)(cm}(°C) \]
\[ \nu = \text{settling velocity, cm/sec} \]
\[ \rho = \text{mass density, g/cm}^3 \]
\[ \mu = \text{viscosity, g/(cm)(sec) = poise} \]
\[ c = \text{specific heat, J/(g)(°C).} \]

The Prandtl Number is a criterion of the rate of heat transfer from the surface of the dispersed phase liquid drops to the continuous phase liquid. It is dimensionally equivalent to the ratio of the heat absorbed by the continuous phase liquid to the heat transferable through the surface of the dispersed phase liquid drops. The Peclet Number represents the potentiality for heat transfer.

Dimensionally, the Reynolds Number is proportional to the ratio of the inertia forces on an element of liquid to the viscous force acting on the liquid. The length term is any pertinent length. The numerical value of the Reynolds Number may have significance in certain situations. The length term in the Nusselt Number is also any pertinent length.

Handlos and Baron [1] constructed simple mathematical models of heat transfer and analytically determined separate correlations for the inside and the outside of the drop. For the outside of the drop (all parameters are based on the continuous phase)

\[ N_N = 1.13 N_{Pe}^{1/2} \quad (15) \]

For the inside of the drop (all the parameters in the dimensionless numbers are based on the dispersed phase),

\[ N_N = 0.00375 \left( \frac{1}{1 + \nu d / \nu c} N_{Pe} \right) \quad (16) \]

where

\[ \nu c = \text{viscosity of the continuous phase, poise} \]
\[ \nu d = \text{viscosity of the dispersed phase, poise.} \]

In equation 16, the velocity term (in the Peclet number) was \( V_s \), the slip velocity.

4. LIQUIDS TESTED IN THE DCLLHE

Three liquids were used in the pilot plant scale DCLLHE: diethyl phthalate, dimethyl phthalate, and butyl benzyl phthalate. Some of the properties of these three phthalates as well as four other heat transfer liquids are given in Table 1.

5. DROP SIZE AND SIZE DISTRIBUTION

If the drops are assumed to be spheres, then [2]

\[ d = 0.0067 g \left( \frac{M}{A g} \right) \frac{0.5 \ln \sigma g}{g} \quad (17) \]

where

\[ A = \text{contact area between the dispersed and continuous phases, cm}^2 \]
\[ V_d = \text{volume of the dispersed phase in the continuous phase portion of the column, cm}^3 \]
\[ d_e = \text{diameter of an equivalent sphere, cm} \]
\[ \sigma g = \text{geometric standard deviation of the drop size distribution, dimensionless} \]
\[ M_g = \text{geometric mean drop size, cm} \]

The drop size distribution is a geometrically normal frequency distribution.

The drop size calculated from equation 17 was found to vary linearly with the superficial velocity:

\[ d = \text{intercept} + (\text{slope})(F/S) \quad (18) \]

The numerical values of the coefficients of equation 18 are given in Table 2.

More approximately, it was found that

\[ d = 0.908 F/S + d_n (1 - 4.11 F/S) + (661 - 2,720 F/S) \exp (-85.31 \rho) \quad (19) \]

where

\[ d_n = \text{diameter of the holes in the perforated plate, cm} \]
\[ \rho = \text{the density of the dispersed phase liquid minus the density of water g/cm}^3 \]

6. HOLDUP AND SUPERFICIAL VELOCITY

Holdup was found to be related to superficial velocity as follows:

\[ H = 1 + C_1 (F/S) + C_2 (F/S)^2 \quad (20) \]

where

\[ C_1 = \text{intercept, dimensionless} \]
\[ C_2 = \text{coefficient, sec/cm} \]
The numerical values of the coefficients in equation 20 are given in Table 3.

<table>
<thead>
<tr>
<th>Name</th>
<th>Physical Properties at 93.3 °C</th>
<th>°C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mass Density, g/cm³</td>
<td>Viscosity, cP</td>
</tr>
<tr>
<td>Water</td>
<td>0.963</td>
<td>0.003</td>
</tr>
<tr>
<td>50% Ethylene Glycol</td>
<td>1.016</td>
<td>0.007</td>
</tr>
<tr>
<td>Diethyl Phthalate</td>
<td>1.052</td>
<td>0.021</td>
</tr>
<tr>
<td>Dimethyl Phthalate</td>
<td>1.121</td>
<td>0.020</td>
</tr>
<tr>
<td>Butyl Benzyl Phthalate</td>
<td>1.064</td>
<td>0.043</td>
</tr>
<tr>
<td>Therminol 55</td>
<td>0.839</td>
<td>0.042</td>
</tr>
<tr>
<td>Dowtherm J</td>
<td>0.807</td>
<td>0.004</td>
</tr>
</tbody>
</table>

* Dimethyl phthalate contracts on freezing.

Table 1. Some Properties of the 3 Phthalates and 4 other Heat Transfer Liquids

<table>
<thead>
<tr>
<th>Phthalate</th>
<th>Equation 18</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Intercept, cm</td>
<td>Slope, sec</td>
</tr>
<tr>
<td>Dimethyl</td>
<td>0.101</td>
<td>0.632</td>
</tr>
<tr>
<td>Butyl</td>
<td>0.18</td>
<td>0</td>
</tr>
<tr>
<td>Diethyl</td>
<td>0.568</td>
<td>-1.4</td>
</tr>
</tbody>
</table>

Table 2. Numerical Values of the Coefficients in Equation 18

<table>
<thead>
<tr>
<th>Phthalate</th>
<th>C₁, sec/cm</th>
<th>C₂, (sec/cm)^2</th>
<th>Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimethyl</td>
<td>-0.00643</td>
<td>0.151</td>
<td>0</td>
</tr>
<tr>
<td>Butyl</td>
<td>0</td>
<td>0.0472</td>
<td>-0.131</td>
</tr>
<tr>
<td>Diethyl</td>
<td>0</td>
<td>0.1</td>
<td>0.237</td>
</tr>
</tbody>
</table>

Table 3. Numerical Values of the Coefficients in Equation 20

Combining equations 7 and 8, one obtains

\[ a = 6H/d \]  

(21)

The following equation has a correlation coefficient of 0.954:

\[ a = 0.059 \left( \frac{\rho_d}{\mu_d} \right)^{0.975} \]  

(22)

where \( \rho_d \) = the mass density of the dispersed phase liquid, g/cm³

It was found that equation 22 can be approximated as

\[ a = 0.0561 \left( \frac{\rho_d}{\mu_d} \right) F/S \]  

(23)

7. HEAT TRANSFER RESULTS

It has been shown [3] that \( h_c >> h_d \), so that equation 4 can be approximated as

\[ U = h_d \]  

(24)

and consequently equation 11 can be written

\[ N = Ud/k_d \]  

(25)
where 
\[ k_d = \text{thermal conductivity of the dispersed phase liquid, J/(sec)(cm)(°C)} \]

Also equation 12 becomes
\[ N_R = \frac{d v_s p_d}{\mu_d} \]  
(26)

and equation 13 becomes
\[ N_p = \frac{c_d p_d}{k_d} \]  
(27)

where \( c_d = \text{specific heat of the dispersed phase liquid, J/(g)(°C)} \)

7.1 Heat Transfer Correlations

For \( \frac{v_d}{\mu_c} \gg 1 \), equation 16 can be approximated as
\[ N_N = 0.00375 \frac{\mu_c}{\mu_d} N_p \]  
(28)

The experimental data obtained during the course of this project for the 3 phthalates was found to be correlated by the following equation (correlation coefficient = 0.986):
\[ N_N = -2.63 + 0.0101 \frac{\mu_c}{\mu_d} N_p \]  
(29)

7.2 Minimum Continuous Phase Depth for Complete Heat Transfer

Using equation 23, it has been shown [3] that the minimum continuous phase depth required for complete heat transfer is
\[ L_{min} = 5.43 \frac{c_d p_d}{k_d} = 5.43 d N_p \]  
(30)

Taking values of \( N_p \) at 93.3°C from column 6 of Table 1 and the maximum observed values of \( d \) during the course of this project, the maximum calculated values of \( L_{min} \) for the 3 phthalates are as follows:

<table>
<thead>
<tr>
<th>Phthalate</th>
<th>( N_p ) at 93.3°C</th>
<th>Maximum Observed d, cm</th>
<th>Complete heat transfer depth ( L_{min}, \text{cm} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diethyl</td>
<td>26</td>
<td>0.496</td>
<td>70</td>
</tr>
<tr>
<td>Dimethyl</td>
<td>23.3</td>
<td>0.257</td>
<td>33</td>
</tr>
<tr>
<td>Butyl Benzyl</td>
<td>53.7</td>
<td>0.18</td>
<td>53</td>
</tr>
</tbody>
</table>

An additional examination of Equation 10 is worthwhile in view of the results of this project. In all the experiments conducted 0.00209 < \( H \) < 0.0309. From Table 1, it is clear that if heat is being removed from storage as fast as it is being added, and if the temperature differences are the same, \( W = 0.41 \) because the heat capacity of the phthalates is only about 41% that of water (see column 7 of Table 1), and consequently \( W/S \approx 0.41F/S \).

Therefore, Equation 10 can be approximated as (for \( H \ll 1 \))
\[ \frac{v_s}{F/S} = 0.41 \frac{F/S}{H} \]  
(31)

Consequently the pilot plant correlations are not necessarily limited by the fact that \( W/S \) was zero.

The superficial velocities of the phthalates used varied from 37% to 259% of what would be required if one or more of the phthalates had been used in CSU Solar House I. CSU Solar House I [4] was designed to accommodate a solar collector efficiency of about 40%, so the phthalate flow rates used correspond to solar collector efficiencies of from about 15% to over 100%.

Examination of Tables 2 and 3 shows that the behavior of these 3 somewhat similar liquids with respect to drop size and holdup is quite different (of the 2, holdup is easier to determine experimentally). Drop diameters varied from 1.5 to 5 times nozzle diameter (1.5 to 5mm) and holdup varied from 0.16% to 3.1%.

Nevertheless an equation (Equation 19) was developed that relates drop diameter to superficial velocity, nozzle diameter, and the density difference between the continuous and dispersed liquids. This equation applies to all 3 liquids.

The holdup can be determined by combining equations 21 and 23 to obtain:
\[ H = 0.00935 \frac{d \mu_d}{p_d} F/S \]  
(32)

It has been shown that [3]
\[ L_{min} = \frac{d}{211} N_p \]  
(33)

The maximum calculated value of \( L_{min} \) for the 3 liquids was only 70 cm, so that the continuous phase liquid depth required for complete heat transfer is quite modest and easily satisfied from a practical standpoint.

The data on which this paper is based covered the following ranges for the pertinent dimensionless numbers (all of which are calculated using the properties of the dispersed phase):
\[ 0.8 \leq N_N \leq 6; \quad 25 \leq N_p \leq 72; \quad 80 \leq N_R \leq 195; \quad \text{and} \quad 2,334 \leq N_{Pe} \leq 8,124. \]
Equation 29 is an empirical relationship between the Nusselt and Peclet (product of the Prandtl and Reynolds numbers) numbers common to all 3 liquids tested and presumably valid for other liquids not tested. It is worth noting that this relationship includes one additional dimensionless ratio, namely \( \frac{\mu_c}{\mu_d} \) (in this work, the range for this ratio was 0.07 \( \leq \frac{\mu_c}{\mu_d} \leq 0.16 \)). From Equations 11 and 14 it is clear that neither the Nusselt nor the Peclet number contain a viscosity term. The properties correlated by Equation 29 are the following: overall area heat transfer coefficient, drop diameter, slip velocity, water viscosity, and the viscosity, specific heat, thermal conductivity, and mass density of the dispersed phase liquid. Equation 29 explains over 97% of the observed variance, leaving less than 3% unexplained by the terms in Equation 29.

The overall area heat transfer coefficient \( U \) is largely determined by the dispersed phase heat transfer coefficient \( h_d \), at least when water is the continuous phase liquid. In other words, the bulk of the resistance to heat transfer is in the dispersed phase. Therefore Equation 24 appears to be justified.

The range of validity of Equation 29 can be estimated as follows. It is impossible for \( N_N \) to have negative values, so this means that Equation 29 is not valid for values of \( (\frac{\mu_c}{\mu_d}) N_Pe \) \( \leq 260 \). The smallest values of \( \frac{\mu_c}{\mu_d} N_Pe \) observed during the course of this project were as follows:

<table>
<thead>
<tr>
<th>Liquid</th>
<th>Minimum ( \frac{\mu_c}{\mu_d} N_Pe ) Value Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phthalate</td>
<td>394</td>
</tr>
<tr>
<td>Diethyl</td>
<td>394</td>
</tr>
<tr>
<td>Dimethyl</td>
<td>394</td>
</tr>
<tr>
<td>Butyl Benzyl</td>
<td>451</td>
</tr>
</tbody>
</table>

It has been shown [3] that Equation 29 may be valid at least for values of \( (\frac{\mu_c}{\mu_d}) N_Pe \) up to 915. Consequently, it appears that the limits of validity of Equation 29 may be as follows: \( 0 \leq N_N \leq 6.6 \) and 260 \( \leq (\frac{\mu_c}{\mu_d}) N_Pe \leq 915 \).

9. ACKNOWLEDGEMENT

The work upon which this paper is based was supported by the Solar Heating and Cooling Branch, Conservation and Solar Applications, U.S. Department of Energy.

10. NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>interfacial area per unit volume, cm(^{-1})</td>
</tr>
<tr>
<td>A</td>
<td>area through which heat transfer occurs, cm(^2)</td>
</tr>
<tr>
<td>c</td>
<td>specific heat, ( J/(g)(^\circ C) )</td>
</tr>
<tr>
<td>( c_d )</td>
<td>specific heat of the dispersed phase liquid, ( J/(g)(^\circ C) )</td>
</tr>
<tr>
<td>( C_2 )</td>
<td>coefficient, (sec/cm)(^2)</td>
</tr>
<tr>
<td>d</td>
<td>drop diameter, cm</td>
</tr>
<tr>
<td>( d_n )</td>
<td>nozzle or hole diameter, cm</td>
</tr>
<tr>
<td>DCLLHE</td>
<td>Direct Contact Liquid-Liquid Heat Exchanger</td>
</tr>
<tr>
<td>F</td>
<td>flowrate of the dispersed phase, cm(^3)/sec</td>
</tr>
<tr>
<td>F/S</td>
<td>superficial velocity of the dispersed phase liquid, cm/sec</td>
</tr>
<tr>
<td>h</td>
<td>heat transfer coefficient, ( J/(sec)(cm)(^2)(^\circ C) )</td>
</tr>
<tr>
<td>( h_C )</td>
<td>continuous phase (water) heat transfer coefficient, ( J/(sec)(cm)(^2)(^\circ C) )</td>
</tr>
<tr>
<td>( h_d )</td>
<td>dispersed phase heat transfer coefficient, ( J/(sec)(cm)(^2)(^\circ C) )</td>
</tr>
<tr>
<td>H</td>
<td>the fraction of the effective volume of the heat exchanger occupied by the dispersed phase (holdup), dimensionless</td>
</tr>
<tr>
<td>I</td>
<td>intercept, dimensionless</td>
</tr>
<tr>
<td>k</td>
<td>thermal conductivity, ( J/(sec)(cm)(^\circ C) )</td>
</tr>
<tr>
<td>( k_d )</td>
<td>thermal conductivity of the dispersed phase liquid, ( J/(sec)(cm)(^\circ C) )</td>
</tr>
<tr>
<td>( L_{min} )</td>
<td>minimum continuous phase depth required for complete heat transfer, cm</td>
</tr>
<tr>
<td>M(_g)</td>
<td>geometric mean drop size, cm</td>
</tr>
<tr>
<td>n</td>
<td>number of drops in the heat exchanger, dimensionless</td>
</tr>
<tr>
<td>( N_N )</td>
<td>Nusselt number = ( h d/k ), dimensionless (equation 11)</td>
</tr>
<tr>
<td>( N_P )</td>
<td>Prandtl number = ( \frac{\mu d}{k} ), dimensionless (equation 13)</td>
</tr>
<tr>
<td>( N_{Pe} )</td>
<td>Peclet number = ( \frac{c \mu d}{k} ) = ( N_P N_R ), dimensionless (equation 14)</td>
</tr>
<tr>
<td>( N_R )</td>
<td>Reynolds number = ( d_v \sqrt{d} ), dimensionless (equation 12)</td>
</tr>
<tr>
<td>Q</td>
<td>rate of heat transfer, J/sec = W</td>
</tr>
<tr>
<td>S</td>
<td>horizontal cross sectional area of the heat exchanger = 390 cm(^2) for the pilot plant</td>
</tr>
<tr>
<td>( T_C )</td>
<td>temperature of the continuous phase liquid (water), ( ^\circ C )</td>
</tr>
<tr>
<td>( T_d )</td>
<td>temperature of the dispersed phase liquid, ( ^\circ C )</td>
</tr>
<tr>
<td>( \Delta T )</td>
<td>temperature difference, ( ^\circ C )</td>
</tr>
<tr>
<td>( \Delta T_R )</td>
<td>representative temperature difference, ( ^\circ C )</td>
</tr>
<tr>
<td>( \Delta T_I )</td>
<td>initial temperature difference, ( ^\circ C )</td>
</tr>
<tr>
<td>U</td>
<td>overall area heat transfer coefficient, ( J/(sec)(cm)(^2)(^\circ C) )</td>
</tr>
<tr>
<td>( U_a )</td>
<td>volumetric heat transfer coefficient, ( J/(sec)(cm)(^3)(^\circ C) )</td>
</tr>
<tr>
<td>v</td>
<td>settling velocity, cm/sec</td>
</tr>
<tr>
<td>( v_s )</td>
<td>slip velocity (relative velocity between the dispersed and continuous phases), cm/sec</td>
</tr>
</tbody>
</table>
V = volume of the continuous phase in the heat exchanger, cm³ (for the pilot plant, 60,000 ≤ V ≤ 70,200 cm³)

Vd = volume of the dispersed phase in the column, cm³

W = flowrate of the continuous phase liquid (water), cm³/sec

μ = viscosity, g/(cm)(sec) = poise

μc = viscosity of the continuous phase liquid (water), poise

μd = viscosity of the dispersed phase liquid, poise

π = 3.14159..., dimensionless

ρ = mass density, g/cm³

ρd = mass density of the dispersed phase, g/cm³

Δρ = the difference in the mass densities of 2 liquids, g/cm³

σg = geometric standard deviation of the drop size distribution, dimensionless

11. REFERENCES


