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# Heat transfer characteristics of non-Newtonian suspensions

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# HEAT TRANSFER CHARACTERISTICS

# OF

# NON-NEWTONIAN SUSPENSIONS

A THESIS

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## ABSTRACT

A dimensionless equation resembling the Dittus-Boelter equation with modified exponents and additional dimensionless groups has been developed by J. J. Salamone. (12)

$$\frac{hD}{K_f} = Z\left(\frac{DV_B\rho_B}{\mu_B}\right)^{b}\left(\frac{C_f\mu_B}{K_f}\right)^{y}\left(\frac{D}{D_s}\right)^{r}\left(\frac{C_s}{C_f}\right)^{J}\left(\frac{K_s}{K_f}\right)^{n} \quad (1)$$

Salamone investigated the range of Reynolds number between 50,000 and 200,000. The results of the correlated data gave the following exponents for equation: (1)

$$\frac{hD}{K_f} = .131\left(\frac{DV_B\rho_B}{\mu_B}\right)^{.62}\left(\frac{C_s}{C_f}\right)^{.35}\left(\frac{C_f\mu_B}{K_f}\right)^{.72}\left(\frac{D}{D_s}\right)^{.05}\left(\frac{K_s}{K_f}\right)^{.05} \quad (2)$$

Binder and Pollara (19) investigated the lower turbulent region of Reynolds numbers ranging from 10,000 - 70,000 to determine the validity of Salamone's equation in this area. In correlating their data, Binder and Pollara gave the following equation:

$$\frac{hD}{K_f} = .346\left(\frac{DV_B\rho_B}{\mu_B}\right)^{.10}\left(\frac{C_f\mu_B}{K_f}\right)^{.72}\left(\frac{D}{D_s}\right)^{-.152}\left(\frac{C_s}{C_f}\right)^{.35}\left(\frac{K_s}{K_f}\right)^{.08} \quad (3)$$

Using the same equipment constructed by Binder and Pollara and collaborators, an additional amount of data was collected and correlations drawn therefrom by the authors of this thesis. The prime intent of this thesis was to check the magnitude of the constant and exponents of Salamone's equation. It was found from the data obtained in this re-

port, that the magnitude of the constant Z and the exponents gave the following equation:

$$\frac{hD}{K_f} = .0131\left(\frac{DV_B\rho_B}{\mu_B}\right)^{.80}\left(\frac{C_f\mu_B}{K_f}\right)^{.79}\left(\frac{D}{D_s}\right)^{.106}\left(\frac{C_s}{C_f}\right)^{.42}\left(\frac{K_s}{K_f}\right)^{.05} \quad (4)$$

The data for equation (4) was obtained at the values of Reynolds number from 50,000 to 200,000.

# INTRODUCTION

The purpose of this investigation was to collect sufficient data to be incorporated in evaluating the constant Z and the exponents in the equation developed by J. J. Salamone. (12) His investigation was undertaken as a result of a hypothesis formed from fragmentary data on suspensions of finely divided solid particles of high thermal conductivity, using water as a suspending medium. From the data, it was inferred that higher film coefficients could be obtained from water containing particles of high thermal conductivity than from water alone.

Salamone (12) investigated the turbulent range of Reynolds number 50,000 - 200,000 and correlated his data by selecting a few runs of essentially constant viscosity to obtain the exponents of the various groups.

Binder and Pollara (19) investigated the 10,000 - 70,000 Reynolds number range and correlated their data in the same manner as J. J. Salamone.

In the present investigation, Reynolds numbers of 50,000 - 200,000 were investigated. A small part of the data was obtained below 50,000. This method for correlating the data was not the same as that used by J. J. Salamone, and Binder and Pollara.

The method employed is of a statistical nature and average results are obtained. In this manner use was made of all the observed data. It was felt that this method would produce a correlation that is representative of all the data rather than of a few selected values.

## THEORY

In developing the empirical relationship of Nusselt number, Reynolds number, Prandtl number, and the groups relating the physical properties of the individual components of the slurry, it was assumed that the film coefficient was a function of the following:

$D$ = Pipe Diameter

$X$ = Weight Fraction

= Thermal conductivity of the dispersion

$K_f$ = Medium

$D_s$ = Average particle diameter

= Particle Shape

$C_s$ = Specific heat of particle

$C_f$ = Specific heat of dispersion medium

$\rho$ = Density of solid

$\rho$ = Density of dispersion medium

$\mu_B$ = Apparent bulk viscosity of the suspension

$V$ = Velocity, based on bulk density

Weight fraction, density of the solid and dispersion medium may be represented in the form of a bulk density. Then assuming spherical shaped particles, and the equation to be of an exponential type, the following expression may be written:

$$h = Z\left(D^a, V_B^b, \rho_B^e, \mu_B^f, K_f^g, C_f^i, C_s^j, D_s^r, K_s^n\right)$$

And by dimensional analysis, the following equation was derived:

$$\frac{hD}{\mu_B C_f} = Z\left(\frac{DV_B \rho_B}{\mu_B}\right)^b \left(\frac{K_f}{\mu_B C_f}\right)^g \left(\frac{K_s}{\mu_B C_f}\right)^n \left(\frac{D_s}{D}\right)^r \left(\frac{C_s}{C_f}\right)^J$$

The unknown constants were evaluated by experimental data yielding the following equation of J. J. Salamone: (12)

$$\frac{hD}{\mu_B C_f} = .131\left(\frac{DV_B \rho_B}{\mu_B}\right)^{.62} \left(\frac{K_f}{\mu_B C_f}\right)^{.23} \left(\frac{K_s}{\mu_B C_f}\right)^{.05} \left(\frac{D}{D_s}\right)^{.05} \left(\frac{C_s}{C_f}\right)^{.35}$$

Multiplying both sides by $\frac{\mu_B C_f}{K_f}$ and rearranging to give:

$$\frac{hD}{K_f} = .131\left(\frac{DV_B \rho_B}{\mu_B}\right)^{.62} \left(\frac{D}{D_s}\right)^{.05} \left(\frac{C_s}{C_f}\right)^{.35} \left(\frac{C_f \mu_B}{K_f}\right)^{.72} \left(\frac{K_s}{K_f}\right)^{.05}$$

As may be seen from the above equation, the specific heat of the solid and of the fluid, along with the effect of the Reynolds number are of major importance. The group $\left(\frac{D}{D_s}\right)^{.05}$ becomes significant when very small particles are used as the suspended solid.

In observing the Reynolds number and the Prandtl number, the overall effect of bulk viscosity is only to the one tenth power.

The method of determining bulk viscosity of the suspensions at the average temperature of the heat section was the same as adopted by J. J. Salamone.

It has been found that liquids generally are Newtonian or non-Newtonian. For Newtonian fluids, the ratio between shearing stress and rate of shearing strain is the same for all rates of shearing strain.

For a non-Newtonian liquid, the slope is not constant and hence depends on the rate of flow of the fluid.

Since it has been shown by previous investigators that the suspensions used by the authors of this report were of the non-Newtonian and pseudoplastic type, the method adopted to determine viscosity was by way of the pipeline viscometer, where pressure drop across a known length of pipe was noted as a measure of stress on the fluid at known rate of flow. The well-known Fanning friction equation was used to calculate friction factor:

$$\frac{\Delta P}{\rho} = f \frac{L V^2}{D^2 g_c}$$

Water was used to calibrate the pipeline viscometer and a Von Karman plot was made of the friction factor versus Reynolds number, Fig. 4.

$$\frac{1}{\sqrt{f}} = 2 \log Re \sqrt{f} - 0.8$$

If the density, pressure drop, and weight rate of flow of a suspension are known, the apparent viscosity may be estimated from the corresponding Reynolds number. In this investigation, viscosities were found to be essentially constant from a Reynolds number of 75,000 to 200,000 with the exception of iron oxide slurry. The magnitude of the viscosity for the suspension was always greater than the dispersion medium. Appreciable changes in viscosity were noted below 75,000 Reynolds number.

## CRITICAL REVIEW OF PERTINENT WORK

A relatively meager amount of data on heat transfer to suspensions can be found in the literature. Hoopes et al (6) correlated data on the cooling of Filter Cel suspensions with the Dittus-Boelter equation.

At high Reynolds number Mac Laren and Stair (7) correlated their data on heating of Filter Cel (silica), but due to the baked deposit formed on the heated section of the exchanger from the silica suspension, correlation at low Reynolds numbers was not obtained.

Shandling (14) attempted to measure the film coefficients of heat transfer of aluminum-water slurries. No correlation was obtained due to the reaction taken place between aluminum and water. Abnormally high film coefficients could result from such an investigation since aluminum in a finely divided state reacts readily with water. Possibly if the slurry were aged a long period of time a protective oxide layer would form on the particles and enable one to investigate aluminum in water slurries, provided the specific heat and conductivity of the aluminum particle in this state were known. Shandling's results did give an indication that film coefficients of heat transfer with this material would be much higher than for water alone.

Film coefficient heat transfer characteristics of chalk-water slurries were investigated by Bonilla et al (3). The data was obtained for concentrations up to 21%. Correlation with the Dittus-Boelter equation showed a deviation within 10%. Thermal conductivity of slurries, water being the suspending medium was obtained from weighted averages of individual properties of the solid and liquid; the bulk viscosity was computed from the Hastchek (3) relationship:

$$\mu_B = \frac{\mu_W}{(1-\phi^{1/3})}$$

$\mu_W$ = viscosity of water

$\phi$ = volume fraction of solid in suspension

$\mu_B$ = bulk viscosity

A plot of the ratio between Nusselt number and the Prandtl number raised to the one-third power $\left(Nu/Pr^{1/3}\right)$ versus Reynolds number, with percent solids as the parameter, showed that the value of $\left(Nu/Pr^{1/3}\right)$ decreased with increasing solid concentration. The relationship,

$$\left(Nu/Pr^{1/3}\right)_{SLURRY} = \left(Nu/Pr^{1/3}\right) - 555X$$

where x is the weight fraction of the solid, was found to hold approximately up to the slurry concentrations under investigation.

Orr and Dallavalle (10) investigated various suspensions of powdered solids in ethylene glycol. The data correlated fairly well using the Dittus-Boelter equation as modified by Sieder and Tate (13).

$$\left(\frac{hD}{K_B}\right) = .027\left(\frac{DV\rho}{\mu_B}\right)^{.8}\left(\frac{C\mu}{K_B}\right)^{1/3}\left(\frac{\mu_B}{\mu_s}\right)^{.14}$$

where

$$\mu_B = \frac{\mu}{\left(1 - \frac{\phi}{\phi'}\right)^{1.8}}$$

$\mu_B$ = bulk viscosity

$\mu$ = viscosity of liquid

$\phi$ = volume fraction of solid suspension

$\phi'$ = volume fraction of the solid in a sedimented bed

$$K_B = K_F \frac{2K_F + K_s - 2\phi(K_F - K_s)}{2K_F + K_s + \phi(K_F - K_s)}$$

$K_B$ = thermal conductivity of the suspension

$K_F$ = thermal conductivity of the suspending medium

$K_s$ = thermal conductivity of the solid

$\phi$ = the volume fraction of the solid

The equation above is the thermal analogy to electrical conductivity as developed by Maxwell.

Film coefficients of heat transfer for fluids containing no solids but of the non-Newtonian classification were correlated by Chu et al (5) using a viscosity correction factor added to the Nusselt and Prandtl number relation. The assumption in the above correlation is that the pseudoplastic viscosity may be regarded as some measure of its deviation from simple Newtonian behavior. It is a reasonable inference that the degree of pseudoplasticity may also be a measure of the difference between the observed coefficient of heat transfer for the pseudoplastic fluid and the value of the heat transfer coefficient predicted for a simple Newtonian fluid of similar viscosity by the already established relations.

J. J. Salamone (12) investigated a variety of particles suspended in water. A new equation was derived by dimensional analysis and experimental data used to calculate the constant and exponents of the dimensionless ratios representing individual properties of the components of the suspension. Viscosity, velocity, and density were measured as bulk properties at the conditions of heat transfer.

An alternate method for predicting film coefficients of heat transfer was followed which consisted of calculating an effective conductivity to be substituted in the present Dittus-Boelter equation. This effective conductivity was found to be a linear function of the surface area of the suspended particles.

Effective conductivity was calculated from a calibration curve based on $Nu/Pr^{.4}$ versus Reynolds number for water. All data was taken above 50,000 Reynolds number to minimize settling of the particles.

Binder and Pollara (19) constructed similar equipment as used by J. J. Salamone with added improvements. The lower turbulent region of Reynolds number 10,000 to 70,000 was investigated in order to obtain better accuracy in the constant and the exponents of the dimensionless groups. A relationship of effective conductivity with Reynolds number was shown to approach a limiting value above a Reynolds number of 50,000.

## DESCRIPTION OF APPARATUS*

"A schematic diagram of the apparatus which is similar to that constructed by Bonilla (3) and Salamone (12) was assembled for the purpose of obtaining the data for this investigation as shown in Figure 1.

"The slurry was prepared and stored in a 55 gallon drum provided with a 'Lightening' motor-driven agitator. An Allis-Chalmers pump of adequate capacity transported the slurry from the storage tank, through a by-pass, which was installed to insure positive rate control and thorough mixing by recycling slurry back into the tank, and then through the system back to the tank.

"The circulatory system consisted of a heat transfer section for transfer measurements, two cooling sections consisting of a concentric pipe heat exchanger located after the heating section which kept the slurry in the viscometer (which came after the cooling exchanger) at the average temperature of the slurry in the heating section; the second section consisted of 100 ft. of close wound ½" copper tubing in the slurry storage tank which maintained the slurry feeding the system at isothermal conditions.

"All lines in contact with the slurry were 85-15 brass, except as noted above.

"The heat transfer section contained a ½" I.P.S. brass pipe inside a 1¼" wrought iron pipe which in turn was surrounded by a 2½" wrought iron pipe. Steam was circulated through both annular spaces, the outer serving as a guard heater. Iron tees and bushings located at the ends of the 2½" and 1¼" pipe provided the inlet and outlet for the steam in both annular sections. Sealing of the outer annulus was accomplished by screwing 2½ x 1½" reducing bushings into the 2½" tees and inserting the 1¼" pipe which was then welded to the bushings. Sealing of the inner annuli was accomplished with the aid of reducing bushings, close nipples, and unions which were turned down inside and packing added to serve as a packing gland at each end. Air vents were provided at each end of the inner annulus.

*Binder-Pollara (19)

"Heating of the slurry was accomplished in the ½" pipe by steam flowing in the inner annulus counter current to experimental solution over a length of 8 ft.. Provision was made for collecting and weighing the condensate obtained from the inner annulus. The 12 ft. length of the inner ½" pipe provided for a calming section of approximately 2 ft. at each end. Each end was connected to a 1" tee containing a thermometer well in which oil was used as a heat transfer medium. The thermometers used to record the inlet and outlet slurry temperatures were graduated in 1/10°C and ranged from -1° to 101°C. Brass flanges with rubber gaskets were installed between the ends of the ½" pipe and the thermometer well tees to minimize end effects due to heat conduction between the heating section and the rest of the apparatus.

"The thermocouples were installed in the ½" brass pipe in the following manner: Three grooves were cut into the pipe wall at either end with the aid of a milling machine. Four of these were made 18"long, two commencing approximately 12" from either end of the ½" brass pipe. The third commencing at the same point as the others on both ends was extended over to the center of the ½" pipe. The grooves were wide enough to accommodate a set of copper-constantan thermocouple wires No.22 gauge. The thermocouple junction was positioned into the groove and the latter filled with molten solder. The solder was smooth and polished with emery cloth until the surface was uniformly circular. The thermocouple wire was snugly positioned along the length of the grooves and some litharge cement with glycerin was used to fill the remaining volume within the grooves. The entire pipe surface was polished smooth with fine emery paper. In all, six copper-constantan thermocouple junctions were attached to the outer surface at the top and bottom near the ends and the center of the inner annulus. A drawing of the thermocouple installation is shown in Figure 1.

"The wires for three of the thermocouples at each end were taped to the ½" inner brass pipe and surrounded with individual strands of plastic translucent tubing for protection. This provision was made for the length of wire extending from the ½" pipe out to a terminal block adjacent to a rotary selector switch. In addition to the use of a strand of plastic tubing for each set of thermocouple wires, a larger size of plastic tubing was used to contain all three of the individual thermocouples at each end.

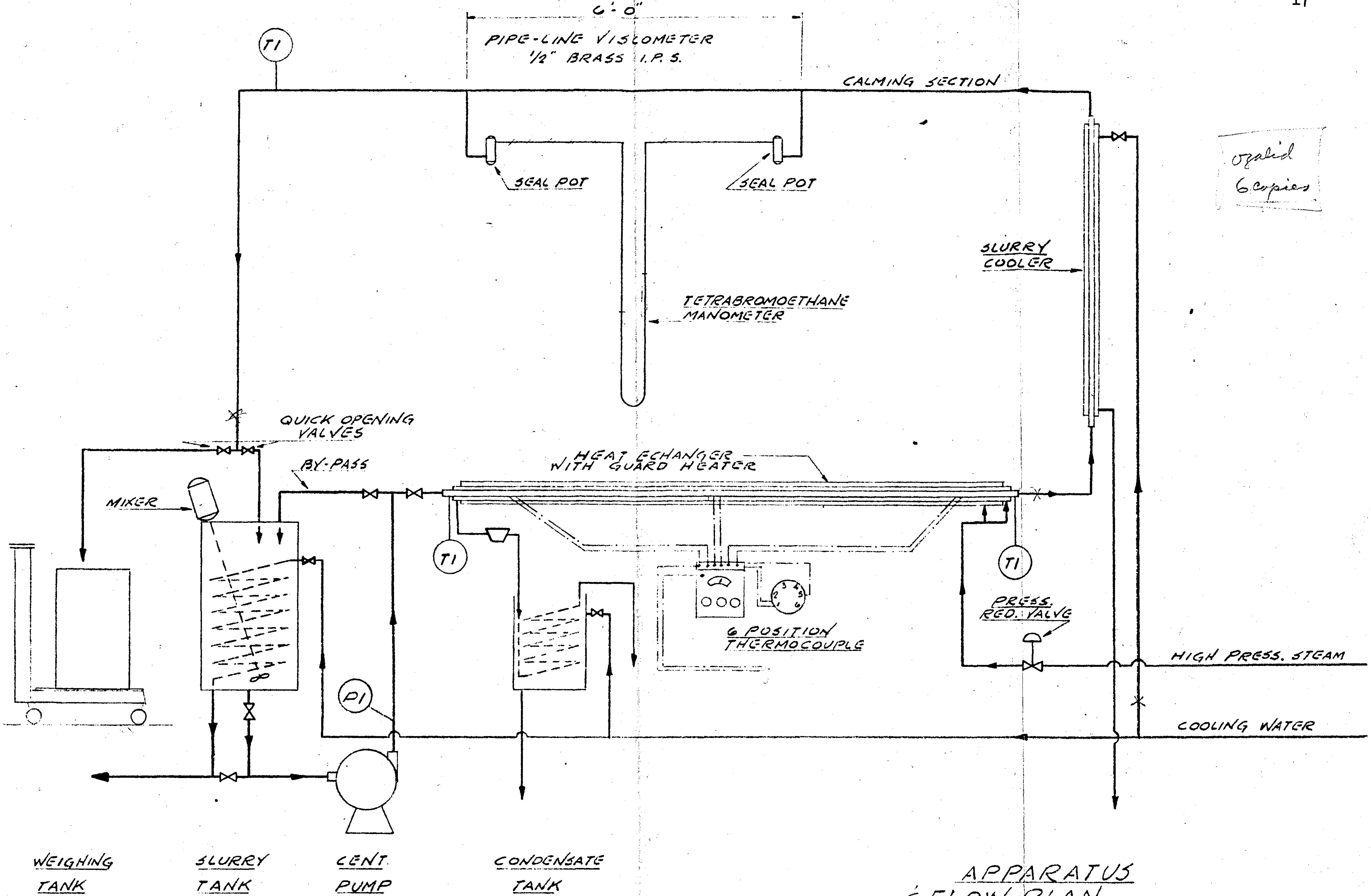
"The thermocouple wires, contained within the plastic tubing, were connected to a terminal block and from this point connected through a rotary switch to a Leeds Northrup portable precision potentiometer. An ice bath was used as a reference junction.

"The heating section was completely insulated with 85% magnesia pipe insulation and aluminum foil. The cooler was a double pipe type heat exchanger consisting of 1" brass I.P.S. pipe inside a 2" standard iron pipe. Cold water was circulated counter-currently to the slurry through the annular space.

"The viscometer consisted of an insulated ½" I.P.S. brass pipe with pressure taps spaced 6 ft. apart. A 2 ft. long calming section preceded the pressure drop section. Approximately 30 in. beyond the pressure drop section provision was made for a tee containing a thermometer well. A tetrabromoethane manometer was used to determine pressure drop data. Traps were installed just after the pressure traps to prevent slurry particles from reaching the manometer lines. Lines to and from the traps were made of transparent Excelon plastic tubing. This provision enabled viewing air or solid material which occasionally found its way into the manometer lines. The manometer was so built that the traps and transparent lines could be conveniently flushed with water. This was done before all readings to remove sediment and air from the lines and traps.

"The pipe returning to the slurry tank was provided with a set of quick opening valves to conveniently allow diverting the slurry into a weighing tank for flow rate measurements. A cooling coil was provided in the slurry tank to maintain isothermal conditions in the tank."

The solids used for the slurries are described in Table I.




APPARATUS
& FLOW PLAN

FIG. NO. 1

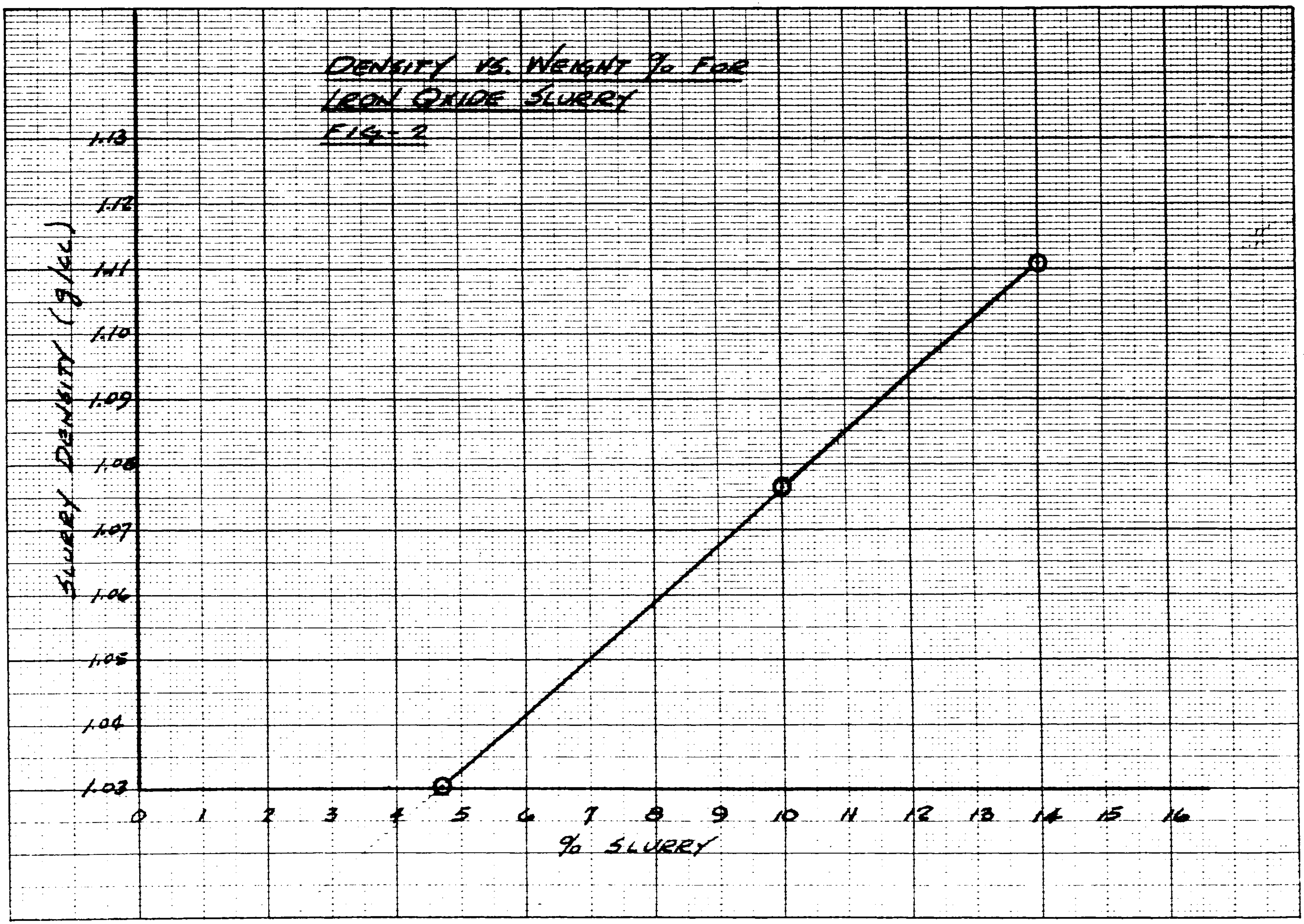
'55 - FRANKS - RINALDI

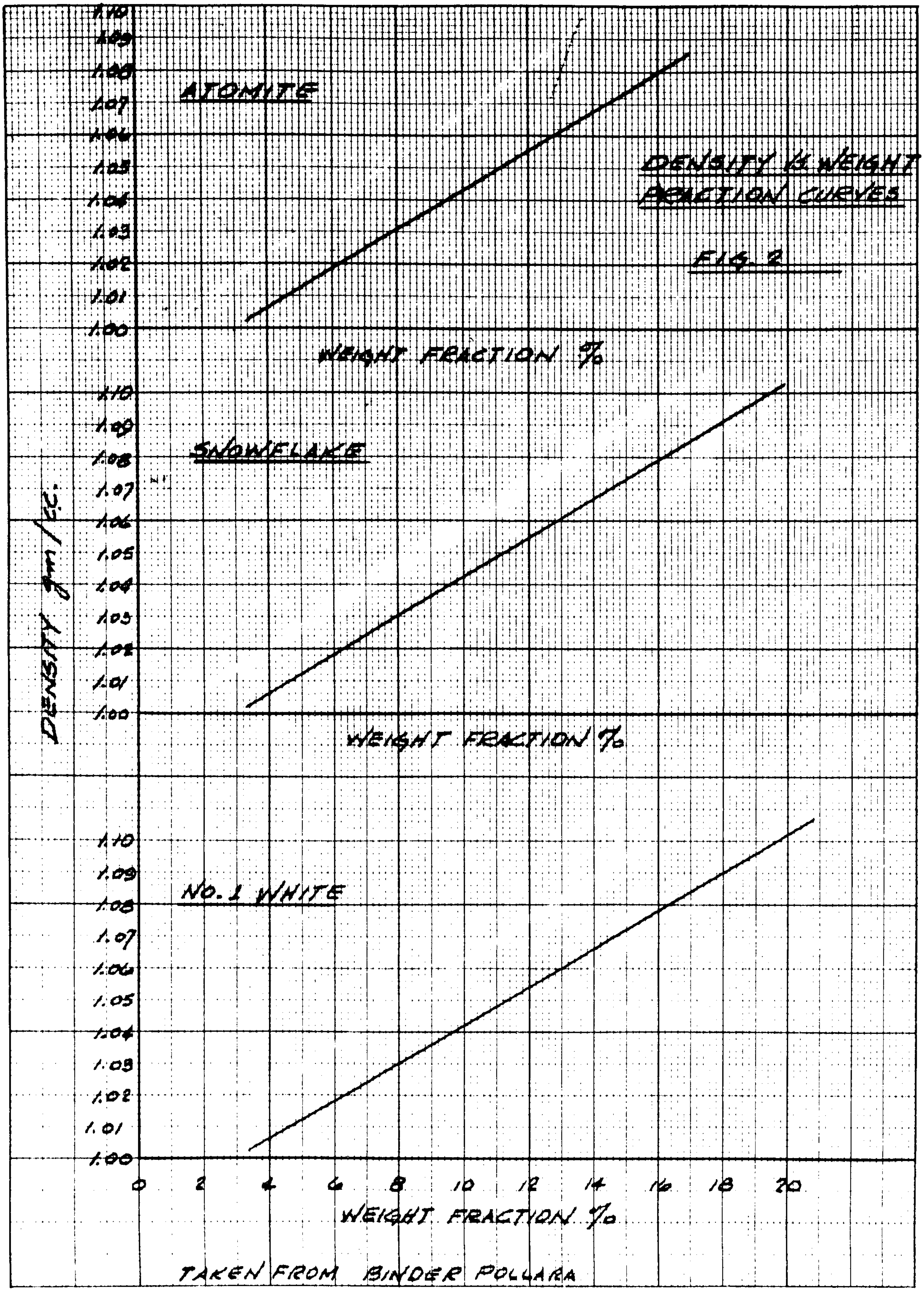
## TABLE I

## PHYSICAL PROPERTIES OF MATERIALS* AND SUPPLIERS

| MATERIAL | SUPPLIER | DENSITY @ 20°C | SPECIFIC HEAT @ 60°C | THERMAL CONDUCTIVITY | AVERAGE PARTICLE SIZE |
|---|---|---|---|---|---|
| | | gm/cc | BTU/LB-°F | BTU / HR-FT-°F | Microns |
| Chalk Powder | | | | | |
| Atomite | Thompson Weinman & Co. Montclair, N. J. | 2.71 (Company) | 0.209 (Perry) | 0.40 (Perry) | 2.5 (Company) |
| Snowflake | | 2.71 (Company) | 0.209 (Perry) | 0.40 (Perry) | 6.0 (Company) |
| Number 1 White | | 2.71 (Company) | 0.209 (Perry) | 0.40 (Perry) | 14.0 (Company) |
| Iron Oxide | Binney & Smith N.Y., N.Y. | 4.06 (Company) | 0.0823 (Company) | 0.257 (Company) | 0.5 (Company) |

*All properties of water from Badger & McCabe
Thermal conductivity of brass (85-15 red brass)
90 BTU/(HR.) (°F) (FT.)

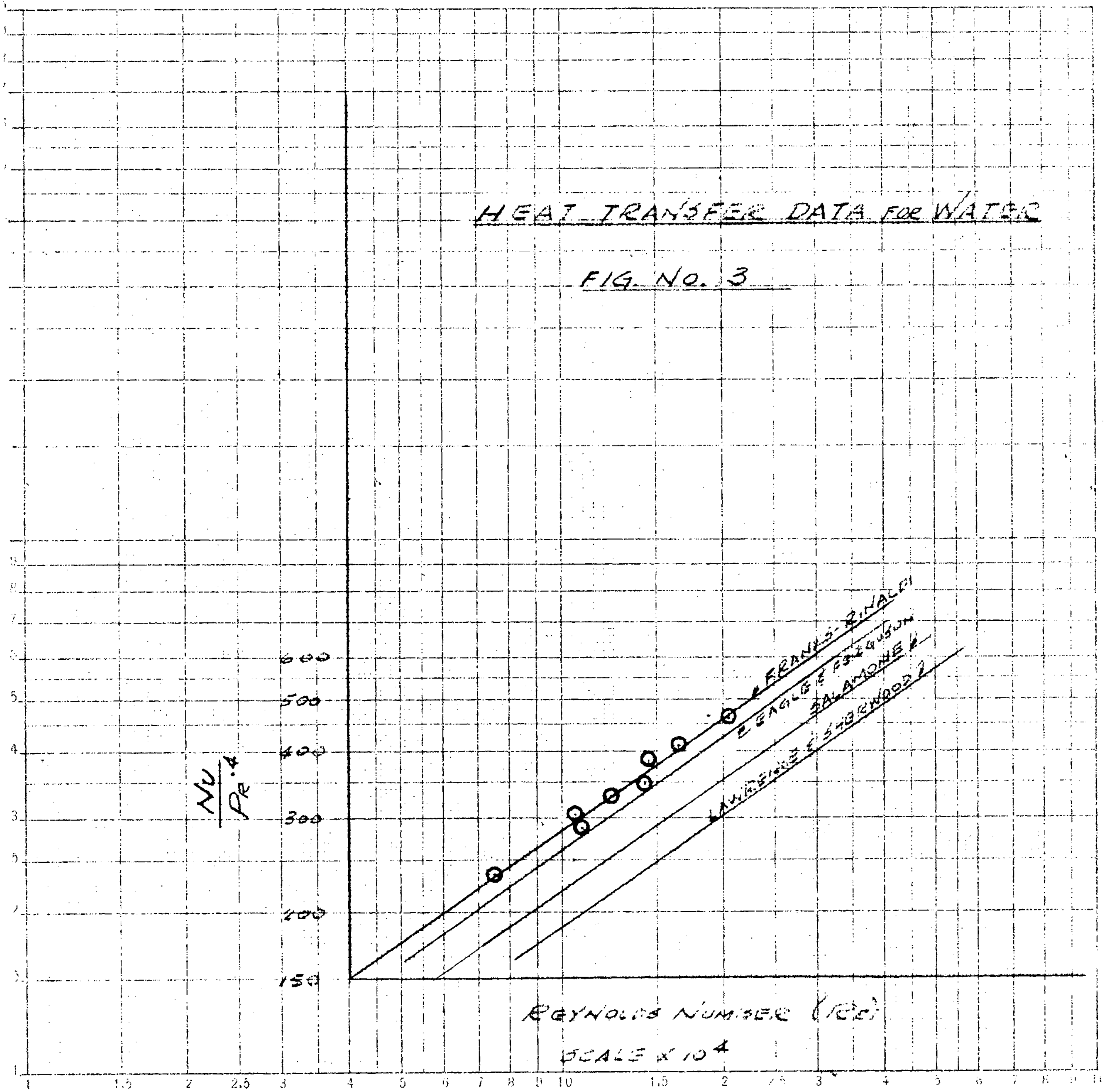

DENSITY VS. WEIGHT % FOR
IRON OXIDE SLURRY
FIG-2
SLURRY DENSITY (g/cc)
1.13
1.12
1.11
1.10
1.09
1.08
1.07
1.06
1.05
1.04
1.03
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
% SLURRY

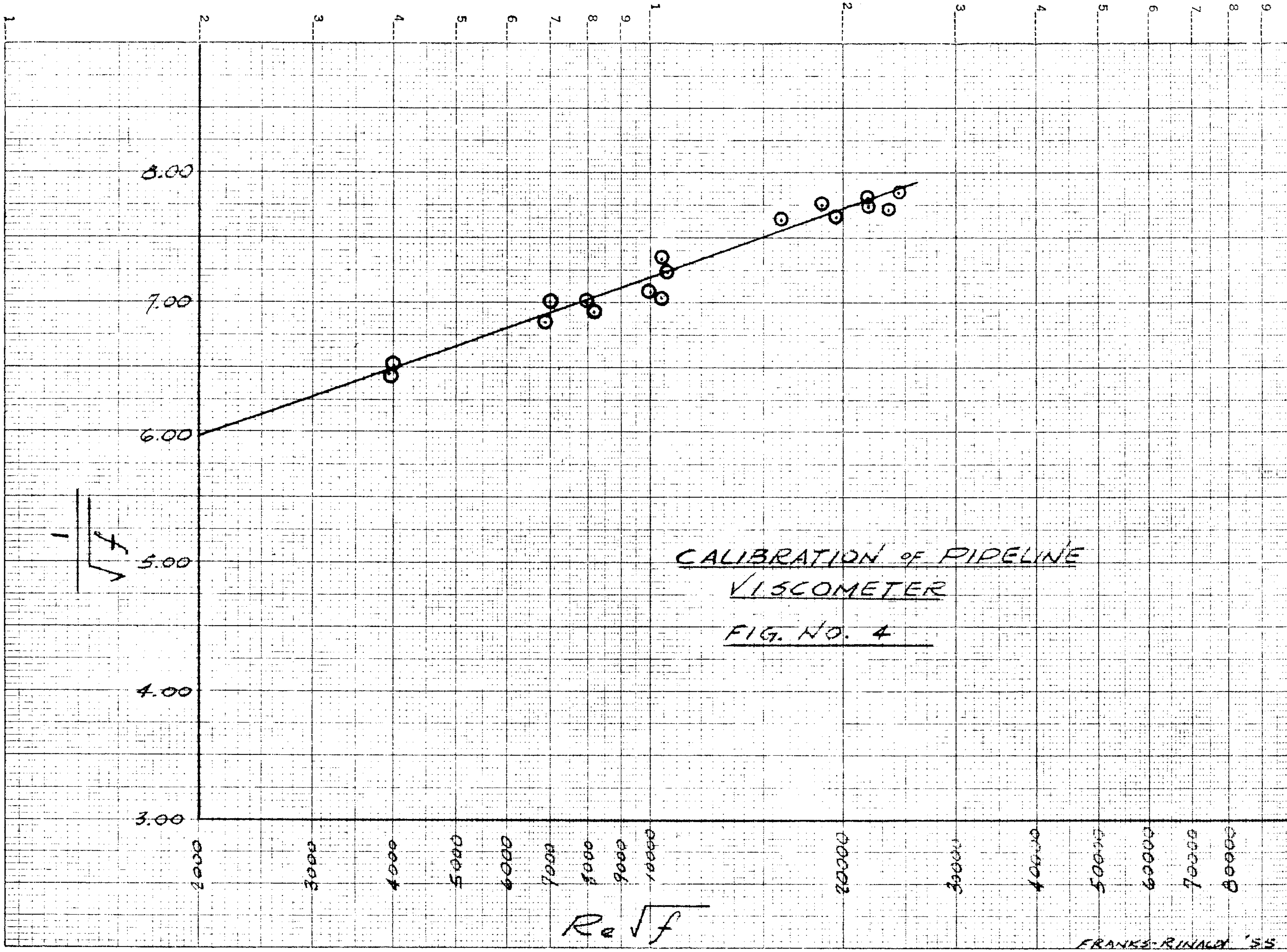



DENSITY VS WEIGHT FRACTION CURVES

FIG. 2

TAKEN FROM BINDER POLLARA


HEAT TRANSFER DATA FOR WATER
FIG. No. 3
Nu / Pr.4
600
500
400
300
200
150
REYNOLDS NUMBER (Re)
SCALE x 10^4
1 FRANKS-RINALDI
2 EAGLE & FERGUSON
3 ALAMONE
LAWRENCE & SHERWOOD




CALIBRATION OF PIPELINE VISCOMETER

FIG. NO. 4

## EXPERIMENTAL PROCEDURE

The fifty gallon drum was filled with approximately two hundred lbs. of water.

Valves on the discharge of the pump were closed and power to the pump turned on. The valve on the recirculating line was then opened to the desired position. The valve controlling flow into the equipment was then set according to the desired manometer reading.

Steam was admitted to the system through a hand valve and constant pressure valve. All cooling water valves were opened, these included, cooling water for the fifty-five gallon drum, the condensate from the steam trap, and the double pipe cooler which was to cool the heated water to the average temperature of the heat section before entering the viscometer.

When the temperature of the water flowing in and out of the heat section, was constant, readings were taken of the thermocouples, viscosity temperature, inlet and outlet water temperature, manometer reading, water rate in pounds collected per interval of time and the condensate rate. Average time allowed for equilibrium was approximately thirty minutes.

From the observed heat transfer water data a plot of $Nu/Pr^{.4}$ versus Reynolds number was constructed to calibrate the equipment for the calculation of effective conductivity, Fig. 3.

From the observed pressure drop water data, a Von Karman plot was constructed. The variables plotted were $\frac{1}{\sqrt{f}}$ versus $Re\sqrt{f}$, Fig. 4. These gave a straight line which agreed fairly well with the Von Karman equation:

$$\frac{1}{\sqrt{f}} = 2.0 \log Re\sqrt{f} - 0.8$$

The water data as noted in Table II was taken in two parts. The first set of data numbered from 101 to 110 was on heat transfer only and was used to construct the plot in figure 3.

The second set of data from 111 to 129 was used to construct the Von Karman plot in figure 4.

After completing the test runs with water, the desired weight of any solids were added to the water in the fifty-five gallon drum and the agitator set in motion. The equipment was allowed to come to equilibrium as was evidenced by the constant temperature readings of the slurry at the inlet and outlet of the heat exchanger.

The readings observed and recorded were the following:

1. Thermocouple readings in millivolts, a total of six readings averaged; the average millivolt reading was converted to degrees F. and corrected to indicate the film coefficient temperature.

2. The water temperature inlet and outlet from the heat section.

3. The viscometer temperature which is controlled by the double pipe cooler to the average temperature of the heat section.

4. Manometer differential.

5. Steam pressure.

6. Steam rate as determined by weighing condensate collected over a measured period of time.

7. Slurry flow rate as determined by weighing a sample over a measured period of time. The method used to collect the slurry was by diverting the flow with quick opening valves having allegedly similar pressure drop characteristics (see discussion of results).

8. Density of the suspension was obtained by weighing in a calibrated volumetric flask.

The density obtained in step eight (8) above was used to determine the weight fraction of the solid in the slurry from previously constructed density versus weight fraction curves, Fig. 2.

The weight fraction data was obtained as follows:

A flask whose weight and volume were known was filled with water and weighed. After the water had been emptied from the flask, a small quantity of dry solids was introduced into the flask and weighed. The flask containing the weighed sample of solids was then filled with water to the known volume mark and weighed again. By subtracting the weight of the flask from all of the observed weight readings, the density of the solid plus water was obtained when divided by the weight of the water having the same volume. Thus, the density of the solid plus liquid was known; the weight fraction was equal to the known weight of solid added, divided by the weight of water plus solid.

TABLE NO. II

OBSERVED DATA AND CALCULATED RESULTS FOR WATER

| RUN NO. | WATER TIME (SEC.) | WEIGHT WATER COLLECTED (LBS.) | THERMOCOUPLE READINGS (MV.) #1 | #2 | #3 | #4 | #5 | #6 | WATER TEMP. °C IN | OUT | INLET STEAM PRESSURE (PSIG) | COND'S'TE TEMP. °F | COND'S'TE TIME TO COLLECT (MIN.) | VISCOMETER TEMP. °C | WATER HEAT $\frac{BTU}{HR.} \times 10^3$ | HEAT SECTION Re. No. $\times 10^3$ | $\frac{Nu}{Pr^{.4}}$ | EXP. FILM COEFF. BTU/HR.-FT.$^2$ -°F |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 101 | 99.0 | 100 | 3.46 | 3.11 | 3.27 | 4.04 | 4.39 | 4.22 | 42.80 | 67.90 | 3.0 | 91.0 | 8.0 | 56.0 | 164.3 | 75.3 | 203 | 2350 |
| 102 | 39.3 | 50 | 3.90 | 3.65 | 3.65 | 4.70 | 5.05 | 4.84 | 53.85 | 79.60 | 14.0 | 113.0 | 4.0 | 66.0 | 212.5 | 109.0 | 287 | 3140 |
| 103 | 29.2 | 50 | 3.54 | 3.41 | 3.41 | 4.45 | 4.80 | 4.58 | 54.55 | 75.90 | 10.0 | 113.0 | 6.0 | 66.0 | 237.0 | 144.0 | 383 | 4220 |
| 104 | 33.0 | 50 | 4.38 | 3.17 | 3.35 | 4.44 | 4.58 | 4.60 | 48.90 | 73.20 | 10.3 | 113.0 | 5.0 | 63.0 | 227.0 | 123.0 | 336 | 3760 |
| 105 | 32.4 | 50 | 4.38 | 3.91 | 3.99 | 5.10 | 5.60 | 5.26 | 58.51 | 85.21 | 23.0 | 122.0 | 3.0 | 71.6 | 267.0 | 142.0 | 346 | 3690 |
| 106 | 23.2 | 50 | 4.51 | 4.08 | 3.90 | 5.05 | 5.45 | 5.22 | 62.55 | 84.95 | 22.5 | 127.0 | 3.0 | 74.0 | 314.0 | 205.0 | 464 | 4890 |
| 107 | 28.1 | 50 | 4.04 | 4.00 | 4.05 | 5.10 | 5.50 | 5.25 | 60.00 | 84.90 | 24.0 | 125.0 | 3.25 | 72.0 | 288.0 | 165.0 | 404 | 4300 |
| 108 | 37.2 | 50 | 3.96 | 3.54 | 3.54 | 4.46 | 4.73 | 4.59 | 47.10 | 74.55 | 8.3 | 101.0 | 4.0 | 61.0 | 239.5 | 106.0 | 301 | 3380 |
| 109 | 52.1 | 50 | 4.11 | 3.74 | 3.74 | 4.54 | 4.77 | 4.66 | 42.62 | 76.40 | 8.4 | 95.0 | 5.0 | 60.0 | 210.0 | 75.0 | 230 | 2610 |
| 110 | 22.0 | 50 | 3.45 | 3.28 | 3.47 | 4.42 | 4.75 | 4.56 | 56.10 | 75.35 | 8.5 | 105.0 | 4.0 | 65.0 | 283.0 | 191.0 | 533 | 5830 |

OBSERVED DATA AND CALCULATED RESULTS FOR WATER

| RUN NO. | WATER TIME (SEC.) | WEIGHT WATER COLLECTED (LBS.) | VISCOSITY TEMP. °C | MANOMETER READING (IN.) | Re. No. $\times 10^3$ | FRICTION FACTOR f | $\frac{1}{\sqrt{f}}$ | Re. $\sqrt{f}$ $\times 10^3$ |
|---|---|---|---|---|---|---|---|---|
| 111 | 22.3 | 50 | 15.0 | 62.0 | 72.2 | 0.0194 | 7.18 | 10.00 |
| 112 | 24.0 | 50 | 18.0 | 55.0 | 72.5 | 0.0200 | 7.05 | 10.30 |
| 113 | 118.3 | 35 | 14.0 | 3.13 | 9.25 | 0.0562 | 4.22 | 2.19 |
| 114 | 63.8 | 50 | 16.0 | 9.25 | 25.80 | 0.0237 | 6.50 | 3.97 |
| 115 | 36.6 | 50 | 10.5 | 25.25 | 47.40 | 0.0213 | 6.85 | 6.92 |
| 116 | 29.1 | 50 | 15.0 | 38.50 | 55.20 | 0.0205 | 7.00 | 7.90 |
| 117 | 21.8 | 50 | 16.0 | 62.00 | 75.70 | 0.0186 | 7.36 | 10.30 |
| 118 | 44.4 | 100 | 17.0 | 61.25 | 76.10 | 0.0190 | 7.25 | 10.50 |
| 119 | 29.0 | 50 | 16.0 | 39.22 | 56.90 | 0.0209 | 6.92 | 8.22 |
| 120 | 33.2 | 50 | 16.0 | 29.25 | 49.70 | 0.0202 | 7.05 | 7.05 |
| 121 | 67.2 | 50 | 17.0 | 8.25 | 25.20 | 0.0241 | 6.45 | 3.91 |
| 122 | 59.8 | 50 | 17.0 | 12.60 | 28.30 | 0.0283 | 5.95 | 4.75 |
| 123 | 31.7 | 50 | 61.0 | 57.75 | 183.00 | 0.0169 | 7.70 | 23.80 |
| 124 | 23.0 | 50 | 59.5 | 51.62 | 169.00 | 0.0168 | 7.73 | 21.90 |
| 125 | 26.4 | 50 | 59.5 | 37.25 | 144.00 | 0.0166 | 7.75 | 18.57 |
| 126 | 37.3 | 50 | 70.0 | 20.00 | 120.00 | 0.0172 | 7.64 | 15.70 |
| 127 | 21.5 | 50 | 63.0 | 58.00 | 191.00 | 0.0165 | 7.29 | 24.50 |
| 128 | 24.0 | 50 | 63.0 | 46.50 | 170.50 | 0.0165 | 7.80 | 21.80 |
| 129 | 27.1 | 50 | 62.0 | 38.00 | 149.00 | 0.0171 | 7.64 | 19.50 |

## TABLE NO. III

## OBSERVED DATA FOR SUSPENSIONS

| RUN NO. | SLURRY TIME (SEC.) | WEIGHT SLURRY COLLECTED (LBS.) | MANOMETER READING (IN.) * | THERMOCOUPLE READINGS (MV.) #1 | #2 | #3 | #4 | #5 | #6 | SLURRY TEMP. °C IN | OUT | INLET STEAM PRESSURE (PSIG) | COND'S'TE TEMP. °F | COND'S'TE WEIGHT Lbs.-Oz. | COND'S'TE TIME (MIN.) | VISCOMETER TEMP. °C. | SLURRY WEIGHT Lbs.-Oz. | SLURRY DENSITY TEMP. °C |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ATOMITE | | | | | | | | | | | | | | | | | | |
| 1 | 26.5 | 50 | 48.75 | 3.94 | 3.30 | 3.66 | 4.75 | 5.04 | 4.89 | 56.00 | 79.80 | 13.7 | 98 | 20-9 | 4.0 | 68.0 | 9-10 | 24 |
| 2 | 22.5 | 50 | 63.50 | 3.90 | 3.40 | 3.63 | 4.70 | 4.99 | 4.85 | 59.06 | 80.40 | 13.4 | 100 | 21-7 | 4.0 | 69.0 | 9-10 | 24 |
| 3 | 41.3 | 50 | 20.50 | 4.04 | 3.48 | 3.81 | 4.81 | 5.06 | 4.95 | 49.70 | 80.90 | 13.7 | 93 | 17-7 | 4.0 | 65.5 | 9-10 | 24 |
| 4 | 63.0 | 50 | 10.00 | 4.25 | 3.92 | 4.01 | 4.87 | 5.10 | 5.00 | 43.98 | 82.68 | 13.7 | 80 | 14-9 | 4.0 | 63.6 | 9-10 | 24 |
| 5 | 27.1 | 40 | 28.40 | 4.00 | 3.68 | 3.75 | 4.79 | 5.02 | 4.91 | 51.95 | 80.47 | 13.7 | 95 | 18-14 | 4.0 | 66.0 | 9-10 | 24 |
| 6 | 21.8 | 50 | 62.60 | 3.56 | 3.20 | 3.50 | 4.70 | 5.00 | 4.85 | 56.50 | 78.02 | 12.7 | 114 | 20-12 | 4.0 | 67.0 | 9-4 | 38 |
| 7 | 23.3 | 50 | 52.00 | 3.45 | 3.12 | 3.50 | 4.70 | 4.96 | 4.86 | 52.98 | 76.40 | 12.7 | 112 | 15-1 | 3.0 | 65.0 | 9-4 | 38 |
| 8 | 26.6 | 50 | 42.10 | 3.45 | 3.15 | 3.50 | 4.65 | 4.95 | 4.80 | 51.00 | 76.12 | 12.7 | 112 | 14-13 | 3.0 | 64.0 | 9-4 | 38 |
| 9 | 37.2 | 50 | 22.50 | 3.64 | 3.35 | 3.70 | 4.78 | 5.00 | 4.90 | 47.60 | 78.45 | 12.7 | 105 | 12-16 | 3.0 | 64.0 | 9-4 | 38 |
| 10 | 49.8 | 50 | 13.00 | 3.85 | 3.62 | 3.95 | 4.82 | 5.00 | 4.90 | 48.30 | 82.00 | 12.7 | 88 | 14-7 | 4.0 | 65.0 | 9-4 | 38 |
| 11 | 21.0 | 50 | 62.50 | 3.56 | 3.26 | 3.59 | 4.80 | 5.09 | 4.94 | 55.05 | 77.00 | 13.1 | 104 | 15-8 | 3.0 | 63.5 | 9-9 | 60 |
| 12 | 22.0 | 50 | 58.00 | 3.61 | 3.33 | 3.63 | 4.80 | 5.12 | 4.96 | 56.00 | 78.00 | 13.5 | 104 | 14-15 | 3.0 | 64.0 | 9-9 | 60 |
| 13 | 24.2 | 50 | 49.25 | 3.58 | 3.32 | 3.69 | 4.84 | 5.11 | 4.99 | 54.00 | 77.45 | 13.5 | 104 | 14-11 | 3.0 | 63.4 | 9-9 | 60 |
| 14 | 26.5 | 50 | 38.12 | 3.67 | 3.40 | 3.77 | 4.85 | 5.11 | 5.00 | 52.80 | 77.80 | 13.5 | 101 | 14-0 | 3.0 | 63.0 | 9-9 | 60 |
| 15 | 31.8 | 50 | 26.75 | 3.76 | 3.45 | 3.85 | 4.90 | 5.11 | 5.01 | 51.12 | 78.80 | 13.5 | 93 | 12-12 | 3.0 | 63.0 | 9-9 | 60 |
| 16 | 44.5 | 50 | 14.70 | 3.96 | 3.65 | 4.10 | 4.95 | 5.16 | 5.06 | 49.00 | 80.60 | 13.5 | 79 | 14-4 | 4.0 | 64.0 | 9-9 | 60 |
| SNOWFLAKE | | | | | | | | | | | | | | | | | | |
| 17 | 21.7 | 50 | 59.0 | 3.32 | 2.99 | 3.20 | 4.49 | 5.05 | 4.89 | 50.10 | 68.90 | 14.2 | 98 | 14-11 | 3.0 | 57.0 | 8-8 | 65 |
| 18 | 23.3 | 50 | 50.0 | 3.35 | 3.05 | 3.30 | 4.55 | 5.07 | 4.89 | 49.65 | 69.85 | 14.2 | 102 | 14-5 | 3.0 | 57.5 | 8-8 | 65 |
| 19 | 27.0 | 50 | 39.5 | 3.45 | 3.10 | 3.40 | 4.35 | 5.05 | 4.20 | 49.80 | 71.65 | 13.9 | 99 | 13-14 | 3.0 | 63.0 | 8-8 | 65 |
| 20 | 31.9 | 50 | 29.5 | 3.50 | 3.20 | 3.46 | 4.65 | 5.03 | 4.88 | 48.95 | 73.05 | 13.0 | 93 | 12-13 | 3.0 | 57.5 | 8-8 | 65 |
| 21 | 38.8 | 50 | 20.0 | 3.65 | 3.30 | 3.60 | 4.74 | 5.09 | 4.95 | 47.80 | 73.15 | 13.4 | 90 | 16-0 | 4.0 | 58.0 | 8-8 | 65 |
| 22 | 21.2 | 50 | 59.7 | 3.50 | 3.10 | 3.30 | 4.65 | 5.08 | 4.91 | 54.90 | 72.65 | 14.0 | 118 | 14-8 | 3.0 | 64.0 | 8-9 | 65 |
| 23 | 23.3 | 50 | 50.5 | 3.50 | 3.18 | 3.35 | 4.70 | 5.09 | 4.90 | 54.85 | 73.80 | 14.2 | 113 | 14-8 | 3.0 | 64.0 | 8-9 | 65 |
| 24 | 20.7 | 50 | 61.5 | 3.50 | 3.16 | 3.36 | 4.70 | 5.05 | 4.89 | 56.60 | 74.60 | 14.0 | 113 | 14-15 | 3.0 | 65.0 | 8-11 | 65 |
| 25 | 22.3 | 50 | 53.0 | 3.56 | 3.22 | 3.40 | 4.69 | 5.06 | 4.90 | 56.70 | 75.60 | 13.6 | 113 | 14-4 | 3.0 | 65.0 | 8-12 | 65 |
| 26 | 25.1 | 50 | 42.5 | 3.51 | 3.18 | 3.40 | 4.71 | 5.08 | 4.91 | 52.95 | 74.70 | 14.1 | 113 | 14-8 | 3.0 | 64.0 | 8-14 | 65 |
| 27 | 29.4 | 50 | 31.8 | 3.66 | 3.36 | 3.52 | 4.75 | 5.07 | 4.95 | 56.00 | 78.40 | 14.2 | 113 | 13-2 | 3.0 | 66.0 | 8-10 | 65 |
| 28 | 42.0 | 50 | 16.5 | 3.75 | 3.35 | 3.56 | 4.83 | 5.12 | 4.99 | 47.00 | 77.80 | 14.6 | 113 | 12-10 | 3.0 | 68.0 | 8-14 | 65 |
| 29 | 34.9 | 50 | 23.0 | 3.80 | 3.50 | 3.61 | 4.80 | 5.13 | 4.99 | 56.50 | 80.85 | 14.5 | 93 | 14-2 | 4.0 | 67.0 | 8-12 | 65 |
| 30 | 21.0 | 50 | 60.5 | 3.51 | 3.20 | 3.40 | 4.70 | 5.08 | 4.95 | 56.40 | 75.37 | 14.1 | 104 | 14-14 | 3.0 | 65.0 | 8-14 | 65 |
| 31 | 20.8 | 50 | 63.5 | 3.45 | 3.10 | 3.30 | 4.68 | 5.04 | 4.80 | 54.70 | 73.37 | 14.2 | 106 | 14-13 | 3.0 | 63.5 | 9-4 | 65 |
| 32 | 22.8 | 50 | 52.8 | 3.46 | 3.09 | 3.33 | 4.64 | 4.95 | 4.76 | 53.00 | 73.30 | 13.2 | 106 | 14-8 | 3.0 | 63.0 | 9-4 | 65 |
| 33 | 27.3 | 50 | 36.3 | 3.42 | 3.16 | 3.40 | 4.69 | 5.00 | 4.81 | 50.90 | 74.40 | 14.5 | 102 | 13-14 | 3.0 | 63.0 | 9-5 | 65 |

* Tetrabromoethane

## TABLE NO. III

### OBSERVED DATA FOR SUSPENSIONS

| RUN NO. | SLURRY TIME (SEC.) | WEIGHT SLURRY COLLECTED (LBS.) | MANOMETER READING (IN.)* | THERMOCOUPLE READINGS (MV.) #1 | #2 | #3 | #4 | #5 | #6 | SLURRY TEMP. °C IN | OUT | INLET STEAM PRESSURE (PSIG) | COND'S'TE TEMP. °F | COND'S'TE WEIGHT Lbs.-Oz. | COND'S'TE TIME (MIN.) | VISCOMETER TEMP. °C. | SLURRY WEIGHT Lbs.-Oz. | SLURRY DENSITY TEMP. °C |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SNOWFLAKE(CONT'D) | | | | | | | | | | | | | | | | | | |
| 34 | 39.9 | 50 | 16.88 | 3.75 | 3.35 | 3.55 | 4.01 | 5.09 | 4.95 | 46.80 | 77.45 | 14.5 | 90 | 11-14 | 3.0 | 62.0 | 9-5 | 65 |
| 35 | 40.2 | 50 | 17.00 | 3.80 | 3.40 | 3.60 | 4.80 | 5.05 | 4.92 | 47.50 | 78.30 | 14.5 | 90 | 11-14 | 3.0 | 63.0 | 9-5 | 65 |
| 36 | 19.7 | 50 | 65.75 | 3.70 | 3.20 | 3.43 | 4.70 | 5.04 | 4.85 | 56.90 | 76.40 | 14.8 | 104 | 9-10 | 2.0 | 66.0 | 9-9 | 65 |
| 37 | 22.0 | 50 | 59.50 | 3.69 | 3.20 | 3.41 | 4.70 | 5.00 | 4.80 | 56.38 | 76.38 | 14.0 | [illegible] | 9-10 | 2.0 | 65.5 | 9-9 | 65 |
| 38 | 24.6 | 50 | 42.25 | 3.71 | 3.23 | 3.41 | 4.69 | 5.00 | 4.81 | 53.35 | 76.30 | 13.6 | 100 | 8-14 | 2.0 | 64.5 | 9-10 | 65 |
| 39 | 30.3 | 50 | 29.50 | 3.84 | 3.30 | 3.54 | 4.79 | 5.05 | 4.90 | 52.00 | 78.30 | 14.5 | 99 | 8-2 | 2.0 | 65.0 | 9-10 | 65 |
| 40 | 46.5 | 50 | 14.38 | 4.05 | 3.46 | 3.75 | 4.85 | 5.05 | 4.93 | 47.50 | 80.30 | 14.5 | 83 | 6-10 | 2.0 | 64.5 | 9-11 | 65 |
| NO.1 WHITE | | | | | | | | | | | | | | | | | | |
| 41 | 21.7 | 50 | 58.50 | 3.34 | 2.95 | 3.16 | 4.55 | 5.04 | 4.79 | 50.30 | 68.45 | 14.5 | 100 | 14-15 | 3.0 | 59.5 | 8-10 | 65 |
| 42 | 23.7 | 50 | 48.25 | 3.35 | 2.99 | 3.20 | 4.58 | 4.99 | 4.79 | 49.50 | 69.00 | 14.8 | 97 | 14-11 | 3.0 | 59.5 | 8-10 | 65 |
| 43 | 32.1 | 50 | 30.00 | 3.47 | 3.16 | 3.27 | 4.58 | 5.04 | 4.83 | 46.50 | 70.00 | 14.0 | 93 | 16-2 | 3.5 | 57.5 | 8-10 | 65 |
| 44 | 82.3 | 50 | 5.50 | 3.94 | 3.61 | 3.71 | 4.80 | 5.09 | 4.96 | 36.10 | 77.47 | 14.3 | 73 | 9-13 | 3.0 | 56.7 | 8-10 | 65 |
| 45 | 36.1 | 50 | 22.75 | 3.52 | 3.19 | 3.39 | 4.68 | 5.04 | 4.94 | 45.60 | 72.20 | 14.5 | 91 | 13-8 | 3.0 | 59.0 | 8-10 | 65 |
| 46 | 32.5 | 50 | 27.25 | 3.46 | 3.12 | 3.32 | 4.69 | 5.05 | 4.86 | 46.70 | 72.30 | 13.5 | 93 | 13-12 | 3.0 | 59.7 | 8-15 | 65 |
| 47 | 40.4 | 50 | 18.75 | 3.58 | 3.24 | 3.44 | 4.73 | 5.05 | 4.90 | 44.65 | 74.25 | 14.0 | 91 | 13-4 | 3.0 | 59.5 | 8-15 | 65 |
| 48 | 21.1 | 50 | 59.75 | 3.44 | 3.02 | 3.26 | 4.66 | 5.04 | 4.88 | 51.70 | 71.25 | 14.7 | 100 | 15-8 | 3.0 | 61.5 | 8-15 | 65 |
| 49 | 24.2 | 50 | 47.75 | 3.44 | 3.09 | 3.29 | 4.63 | 5.00 | 4.83 | 50.00 | 71.50 | 13.5 | 97 | 15-1 | 3.0 | 60.6 | 8-15 | 65 |
| 50 | 27.5 | 50 | 37.00 | 3.45 | 3.10 | 3.30 | 4.70 | 5.00 | 4.84 | 49.30 | 72.40 | 13.6 | 95 | 14-8 | 3.0 | 60.8 | 8-15 | 65 |
| 51 | 20.5 | 50 | 60.75 | 3.45 | 3.09 | 3.30 | 4.74 | 5.09 | 4.90 | 52.05 | 72.25 | 14.7 | 100 | 15-15 | 3.0 | 62.0 | 9-5 | 65 |
| 52 | 24.0 | 50 | 48.50 | 3.45 | 3.11 | 3.33 | 4.71 | 5.01 | 4.85 | 50.70 | 72.88 | 13.6 | 97 | 15-3 | 3.0 | 62.0 | 9-5 | 65 |
| 53 | 32.2 | 50 | 27.00 | 3.50 | 3.25 | 3.44 | 4.78 | 5.05 | 5.90 | 47.60 | 74.78 | 13.8 | 93 | 13-5 | 3.0 | 61.0 | 9-5 | 65 |
| 54 | 120.0 | 50 | 3.25 | 4.18 | 3.91 | 4.12 | 4.96 | 5.19 | 5.12 | 34.70 | 83.50 | 14.5 | 72 | 9-11 | 3.0 | 59.0 | 9-5 | 65 |
| 55 | 27.3 | 50 | 37.50 | 3.55 | 3.21 | 3.41 | 4.76 | 5.08 | 4.96 | 50.00 | 74.70 | 14.0 | 95 | 24-4 | 5.0 | 62.5 | 9-5 | 65 |

* Tetrabromoethane

## TABLE NO. III

### OBSERVED DATA FOR SUSPENSIONS

| RUN NO. | SLURRY TIME (SEC.) | WEIGHT SLURRY COLLECTED (LBS.) | MANOMETER READING (IN.) * | THERMOCOUPLE READINGS (MV.) #1 | #2 | #3 | #4 | #5 | #6 | SLURRY TEMP. °C IN | OUT | INLET STEAM PRESSURE (PSIG) | COND'S'TE TEMP. °F | COND'S'TE WEIGHT Lbs.-Oz. | COND'S'TE TIME (MIN.) | VISCOMETER TEMP. °C | SLURRY WEIGHT Lbs.-Oz. | SLURRY DENSITY TEMP. °C |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **IRON OXIDE** | | | | | | | | | | | | | | | | | | |
| 56 | 34.2 | 75 | 50.50 | 3.50 | 3.25 | 3.33 | 4.73 | 5.01 | 4.86 | 53.25 | 71.37 | 14.0 | 97 | 14-13 | 3.0 | 62.0 | 8-10 | 65 |
| 57 | 37.0 | 75 | 44.50 | 3.49 | 3.20 | 3.30 | 4.73 | 5.05 | 4.89 | 50.42 | 70.65 | 14.6 | 97 | 19-11 | 4.0 | 61.0 | 8-10 | 65 |
| 58 | 30.0 | 50 | 30.75 | 3.56 | 3.30 | 3.40 | 4.75 | 5.06 | 4.95 | 50.93 | 72.65 | 14.6 | 95 | 14-1 | 3.0 | 62.0 | 8-10 | 65 |
| 59 | 37.3 | 50 | 20.75 | 3.70 | 3.45 | 3.50 | 4.80 | 5.08 | 4.95 | 48.30 | 74.38 | 14.2 | 92 | 13-0 | 3.0 | 62.0 | 8-10 | 65 |
| 60 | 55.3 | 50 | 10.25 | 4.01 | 3.73 | 3.80 | 4.90 | 5.14 | 5.00 | 45.00 | 77.90 | 15.0 | 91 | 11-2 | 3.0 | 63.0 | 8-10 | 65 |
| 61 | 33.0 | 75 | 55.00 | 3.61 | 3.35 | 3.46 | 4.80 | 5.14 | 4.95 | 55.70 | 73.80 | 14.9 | 96 | 16-13 | 3.5 | 60.0 | 8-15 | 65 |
| 62 | 37.0 | 75 | 42.75 | 3.65 | 3.34 | 3.45 | 4.80 | 5.04 | 4.90 | 53.42 | 73.40 | 14.0 | 96 | 15-5 | 3.5 | 65.0 | 8-15 | 65 |
| 63 | 42.8 | 75 | 33.25 | 3.76 | 3.50 | 3.55 | 4.81 | 5.05 | 4.92 | 54.50 | 75.45 | 14.2 | 96 | 13-5 | 3.0 | 66.0 | 8-15 | 65 |
| 64 | 61.0 | 75 | 17.50 | 3.95 | 3.73 | 3.80 | 4.90 | 5.10 | 5.00 | 49.55 | 75.25 | 14.6 | 96 | 11-4 | 3.0 | 68.0 | 8-15 | 65 |
| 65 | 49.9 | 50 | 12.00 | 4.23 | 4.00 | 4.04 | 4.94 | 5.10 | 5.04 | 54.40 | 79.45 | 14.6 | 96 | 9-4 | 3.0 | 74.0 | 8-15 | 65 |
| 66 | 31.0 | 75 | 60.00 | 3.75 | 3.40 | 3.53 | 4.80 | 5.01 | 4.94 | 59.45 | 76.10 | 13.8 | 95 | 13-11 | 3.0 | 68.0 | 9-2 | 65 |
| 67 | 33.6 | 75 | 52.00 | 3.80 | 3.51 | 3.58 | 4.80 | 5.01 | 4.94 | 59.20 | 76.40 | 13.5 | 93 | 13-6 | 3.0 | 69.0 | 9-2 | 65 |
| 68 | 40.4 | 75 | 36.20 | 3.87 | 3.60 | 3.74 | 4.84 | 5.09 | 4.97 | 57.75 | 77.05 | 13.8 | 80 | 11--7 | 3.0 | 70.0 | 9-2 | 65 |
| 69 | 36.0 | 50 | 21.50 | 4.14 | 3.90 | 3.98 | 4.90 | 5.09 | 5.01 | 58.55 | 79.25 | 14.5 | 79 | 6-0 | 2.0 | 75.0 | 9-2 | 65 |
| 70 | 59.2 | 50 | 9.25 | 4.49 | 4.34 | 4.36 | 4.99 | 5.15 | 5.06 | 48.00 | 70.00 | 14.5 | 63 | 8-6 | 4.0 | 65.0 | 9-2 | 65 |
| 71 | 30.2 | 75 | 61.50 | 4.01 | 3.79 | 3.79 | 4.85 | 5.10 | 5.97 | 65.80 | 80.70 | 14.1 | 89 | 16-6 | 4.0 | 75.0 | 9-4 | 65 |
| 72 | 33.0 | 75 | 51.00 | 4.05 | 3.76 | 3.84 | 4.90 | 5.10 | 5.01 | 63.80 | 79.65 | 14.2 | 89 | 8-3 | 2.0 | 75.0 | 9-4 | 65 |
| 73 | 28.2 | 50 | 32.75 | 4.16 | 3.96 | 3.96 | 4.88 | 5.08 | 5.01 | 63.20 | 79.70 | 13.8 | 84 | 6-6 | 2.0 | 76.0 | 9-4 | 65 |
| 74 | 34.0 | 75 | 48.00 | 4.15 | 3.95 | 3.95 | 4.88 | 5.10 | 5.01 | 68.50 | 83.00 | 14.1 | 87 | 7-4 | 2.0 | 80.0 | 9-4 | 65 |

* Tetrabromoethane

TABLE NO. IV

ADDITIONAL VISCOSITY DATA

| RUN NO. | MANOMETER READING(IN.)* | SLURRY TIME (SEC.) | WEIGHT SLURRY COLLECTED (LBS.) | VISCOMETER TEMP. °C | SLURRY WEIGHT Lbs.-Oz. | SLURRY DENSITY TEMP. (°C) |
|---|---|---|---|---|---|---|
| ATOMITE | | | | | | |
| 75 | 59.00 | 31.3 | 75.0 | 65.0 | 9-1 | 65 |
| 76 | 52.25 | 33.6 | 75.0 | 65.0 | 9-1 | 65 |
| 77 | 38.75 | 39.8 | 75.0 | 64.0 | 9-1 | 65 |
| 78 | 17.25 | 41.3 | 50.0 | 64.0 | 9-1 | 65 |
| 79 | 8.00 | 64.7 | 50.0 | 64.0 | 9-1 | 65 |
| 80 | 9.50 | 58.2 | 50.0 | 61.0 | 8-14 | 65 |
| 81 | 18.00 | 39.6 | 50.0 | 61.0 | 8-14 | 65 |
| 82 | 29.25 | 31.0 | 50.0 | 61.0 | 8-14 | 65 |
| 83 | 39.50 | 39.0 | 75.0 | 62.0 | 8-14 | 65 |
| 84 | 59.00 | 31.6 | 75.0 | 62.0 | 8-14 | 65 |
| 85 | 62.50 | 30.4 | 75.0 | 60.0 | 9-9 | 65 |
| 86 | 58.00 | 31.7 | 75.0 | 61.0 | 9-9 | 65 |
| 87 | 49.80 | 34.7 | 75.0 | 60.5 | 9-9 | 65 |
| 88 | 38.10 | 39.8 | 75.0 | 61.0 | 9-9 | 65 |
| 89 | 27.00 | 47.9 | 75.0 | 60.0 | 9-9 | 65 |
| 90 | 15.50 | 67.2 | 75.0 | 60.0 | 9-9 | 65 |
| SNOWFLAKE | | | | | | |
| 91 | 56.75 | 23.0 | 50.0 | 67.0 | 8-7 | 65 |
| 92 | 46.00 | 24.5 | 50.0 | 62.0 | 8-7 | 65 |
| 93 | 34.00 | 28.7 | 50.0 | 62.0 | 8-7 | 65 |
| 94 | 5.75 | 77.9 | 50.0 | 61.0 | 8-7 | 65 |
| 95 | 11.25 | 52.2 | 50.0 | 63.0 | 8-7 | 65 |
| 96 | 63.50 | 19.9 | 50.0 | 61.0 | 9-5 | 65 |
| 97 | 57.50 | 21.0 | 50.0 | 62.0 | 9-5 | 65 |
| 98 | 45.25 | 24.2 | 50.0 | 62.0 | 9-5 | 65 |
| 99 | 26.50 | 32.5 | 50.0 | 62.0 | 9-5 | 65 |
| 100 | 14.75 | 44.6 | 50.0 | 62.0 | 9-5 | 65 |

## EXPERIMENTAL RESULTS

In general, the apparatus as used by these investigators was found to be adequate for the work undertaken. However, there were several shortcomings to the apparatus, some of which were corrected and others which were not, since to correct them would involve major alteration. Some of these recognizable difficulties could have been circumvented but it was felt that the costs of equipment necessary would make them prohibitive. Modifications to flow arrangement were made to partially negate the influence of these difficulties.

It is well to note that many of the aforementioned difficulties were not of the nature that could be detected upon only visual inspection of the equipment, but manifested themselves only after the "feel" of the equipment was had. Consequently, these investigators were compelled to rerun several slurries, and also water, for heat transfer data and particularly for pressure drop.

Considerable difficulty was experienced in keeping the flow rate constant to the exchanger, and since this is the most important single factor in bringing the equipment to thermal equilibrium, was a matter of serious concern. From calculations it was found that a manometer fluctuation of ¼" could not be tolerated. After considerable investigation it was finally deduced that the pressure drop in the system was varying when the slurry was diverted to the weighing tank from normal recirculation. By process of elimination it was found that the quick opening valves used for diverting flow of slurry from slurry tank to weighing drum were inherently different insofar as pressure deop was concerned. In order to alleviate this difficulty these valves were removed and a piece of hose was used for the diversion of flow.

Keeping the flow rate constant was still more difficult at low rates of flow, and at very low flow rates was almost impossible. This explains the lack of data for flow rates of below 50,000 Reynolds number. At low flow rates particle fall-out from the slurry is more pronounced. This precipitated material probably coats out on the pipe constricting the flow area thereby causing fluctuations in the flow rate.

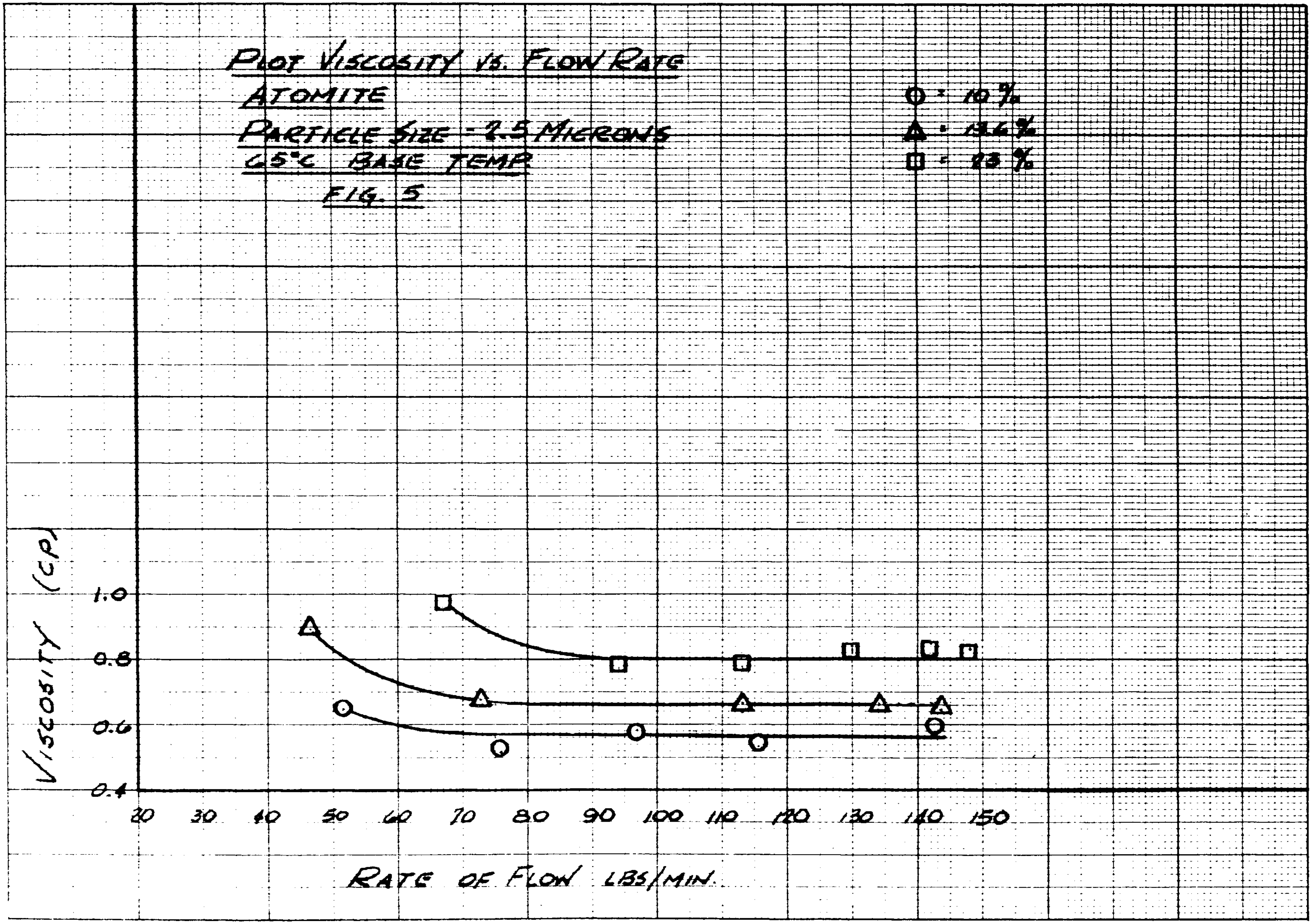
The method for obtaining data was as indicated in the section marked "Experimental Procedure", that is, both heat transfer and viscosity data were taken simultaneously for each run. Since difficulty was experienced in obtaining proper manometer readings, the cause of which was previously described, the results for viscosity for runs 1 through 16 and 22 through 35 were unreliable and could be taken with no degree of certainty. In order to arrive at more accurate figures for viscosity, additional runs were made for viscosity for atomite and snowflake chalk and curves plotted showing viscosity versus flow rate. In preparing slurries for this additional data approximation to the weight percent of the slurries of the formal runs were made. In this way the viscosity for the formal runs was estimated from these plots by interpolation. Additional viscosity data was also taken for water in order to have a more accurate Von Karman type plot in the calibration of the pipe line viscometer.

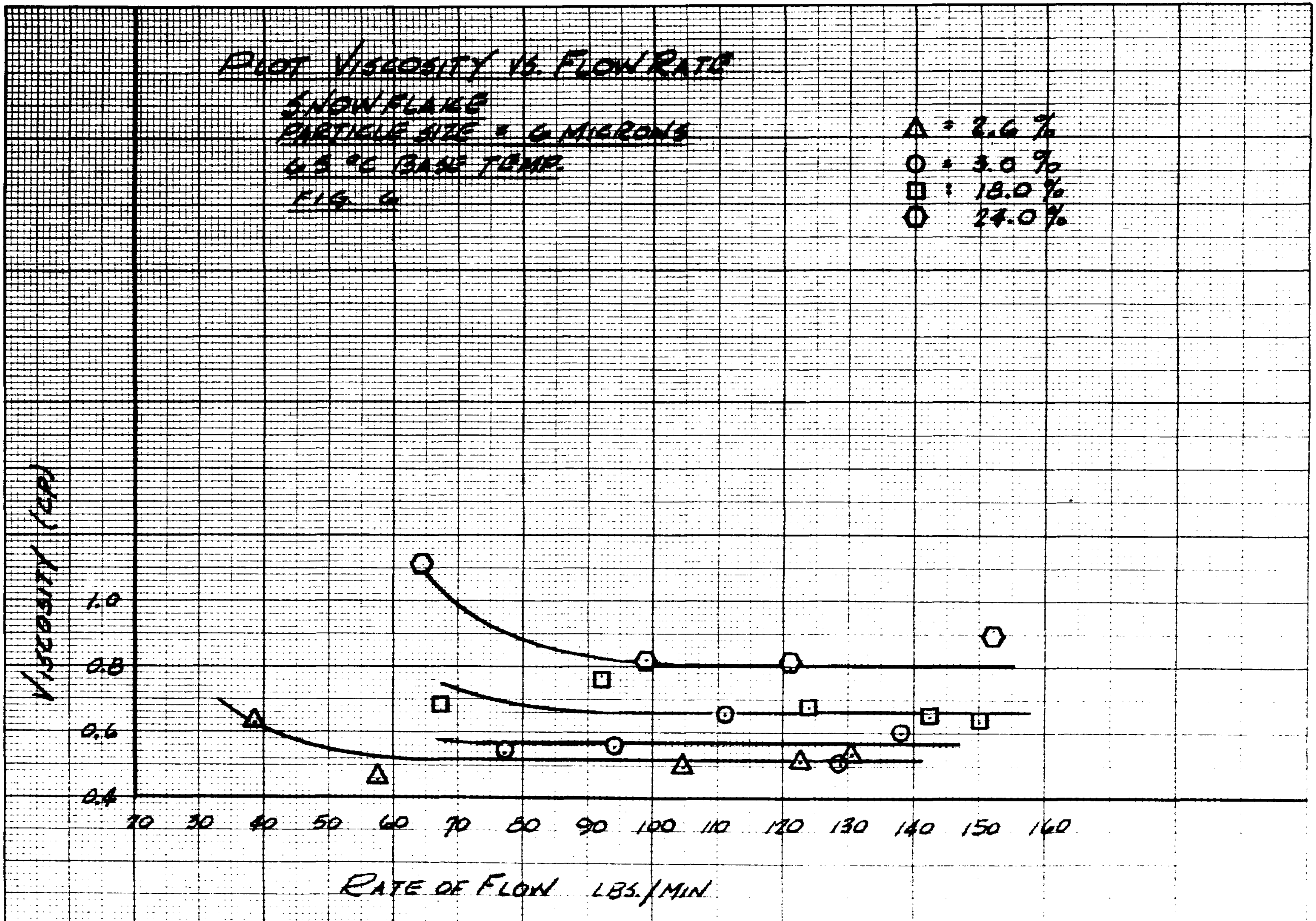
Reference to Table VII "Correlated Results" shows that per cent deviation of the calculated value of "h" from experimental value of "h" is completely out of order for runs 70 through 74.

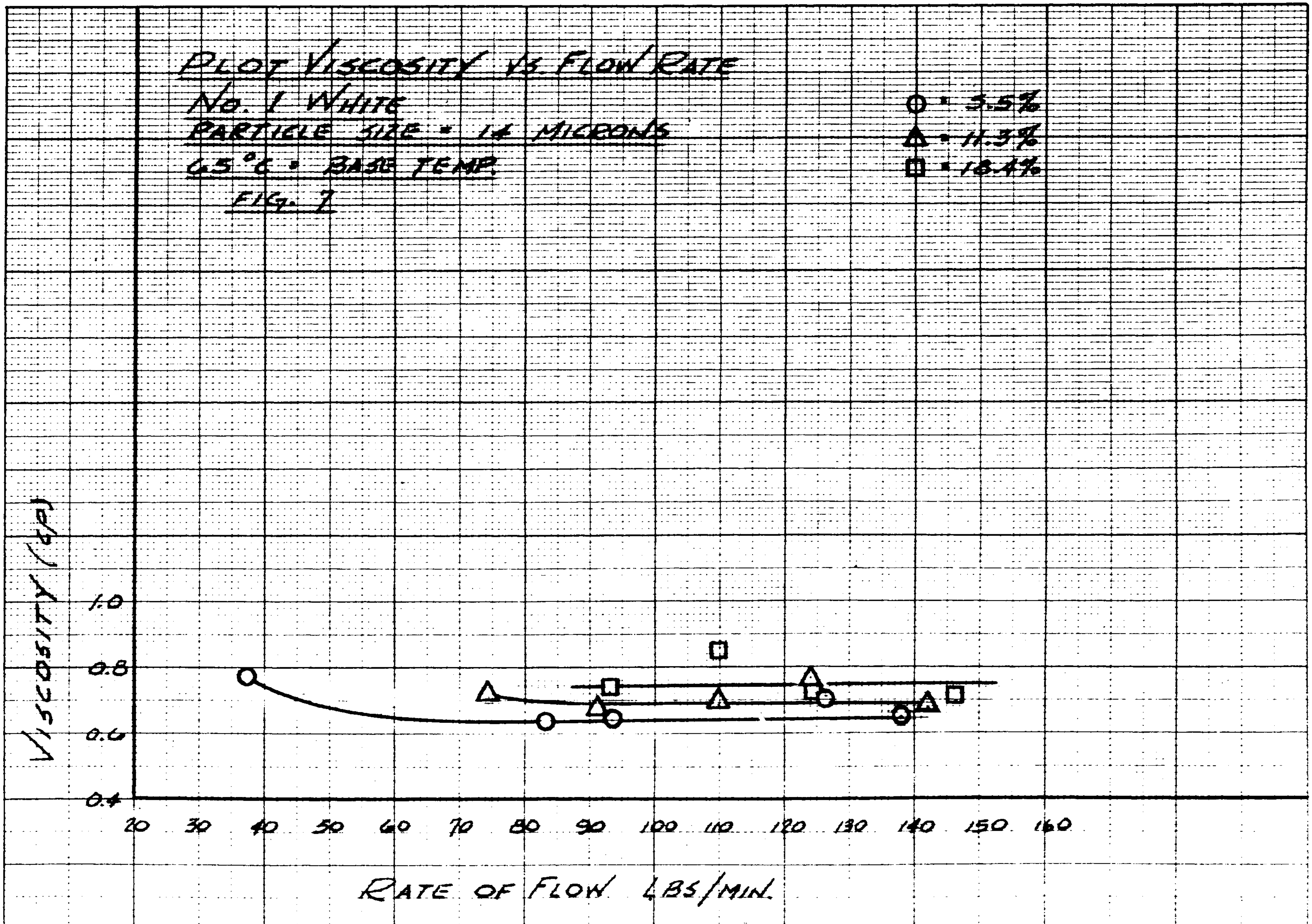
This does not conclude that the experimental equation for "h" developed is incorrect in some ranges since the large deviation obtained in these runs are due to a plainly assignable cause. These runs were made with an iron oxide slurry of extremely high percent solids for a material such as this. When such highly concentrated slurries are used, particle fall-out becomes increasingly more pronounced and significant. These particles tend to coat out on the tube surface invalidating any thermal analogies which are drawn concerning a heat transfer mechanism such as used here. Since there is an assignable cause for these deviations, the inferences to be drawn from them into correlations of results were disregarded.

The deviations of calculated film coefficients from experimental ones for the remainder of the data appear to give satisfactory results, the average deviation of all runs being in the range of 5 to 6%. Larger deviations of 15 to 20% are probably due to particle fall-out as described before due to the high concentration of slurries. These deviations, it may be noted, have been recorded as + and - depending on how they fell referenced to the experimental value of film coefficient. This was done so as to facilitate the correlation of experimental results as described under section marked "Correlation". Statistically, if the sum of the deviations equals o or close to o, the experimental equation used in calculating film coefficients is representative of the data. This was the case in the results of this experiment.

In his thesis, Salamone has presented a discussion of probable error using experimental technique of this nature. Since the equipment used for gathering data of this report, and the materials used, were substantially the same, Salamone's figure of 10% overall error is applicable to this report.


PLOT VISCOSITY VS. FLOW RATE
ATOMITE
PARTICLE SIZE - 2.5 MICRONS
65°C BASE TEMP.
FIG. 5
○ = 10%
△ = 13.6%
□ = 23%
VISCOSITY (CP)
1.0
0.8
0.6
0.4
20 30 40 50 60 70 80 90 100 110 120 130 140 150
RATE OF FLOW LBS/MIN.


PLOT VISCOSITY VS. FLOW RATE
SNOWFLAKE
PARTICLE SIZE = 6 MICRONS
65 °C BASE TEMP.
FIG. 6
△ : 2.6 %
○ : 3.0 %
□ : 18.0 %
⬡ 24.0 %
VISCOSITY (CP)
1.0
0.8
0.6
0.4
20 30 40 50 60 70 80 90 100 110 120 130 140 150 160
RATE OF FLOW LBS./MIN


PLOT VISCOSITY VS FLOW RATE
NO. 1 WHITE
PARTICLE SIZE = 14 MICRONS
65°C = BASE TEMP.
FIG. 7
○ = 3.5%
△ = 11.3%
□ = 18.4%
VISCOSITY (cp)
1.0
0.8
0.6
0.4
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
RATE OF FLOW LBS/MIN.
38

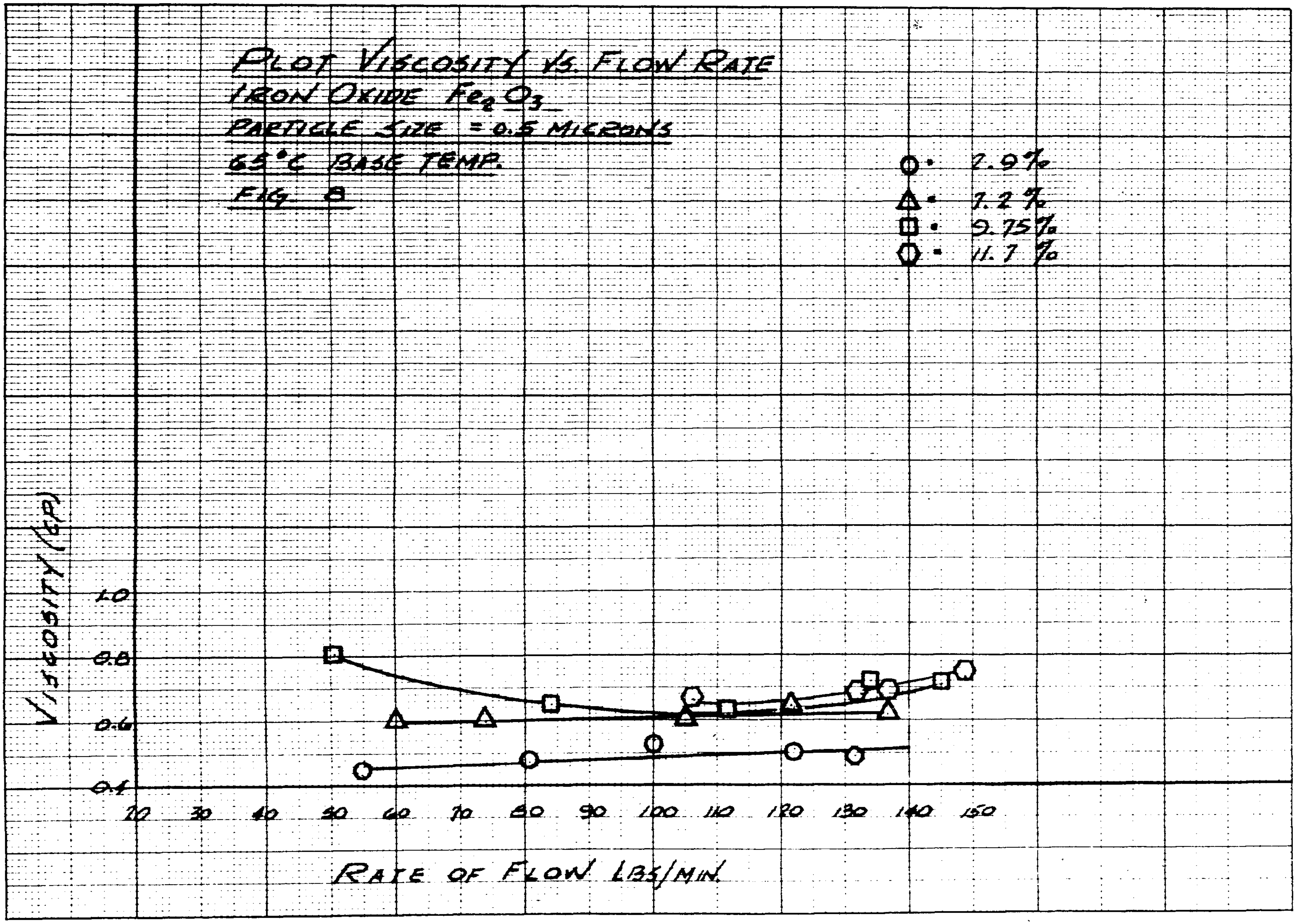

PLOT VISCOSITY VS. FLOW RATE
IRON OXIDE Fe2O3
PARTICLE SIZE = 0.5 MICRONS
65°C BASE TEMP.
FIG. 8
2.9%
7.2%
9.75%
11.7%
VISCOSITY (CP)
1.0
0.8
0.6
0.4
20 30 40 50 60 70 80 90 100 110 120 130 140 150
RATE OF FLOW LBS/MIN.

TABLE NO. V

CALCULATED RESULTS FOR SUSPENSIONS

| RUN NO. | DENSITY LBS./FT.$^3$ | WEIGHT % SOLIDS | MEAN. Sp. HEAT BTU/LBS.°F | FLOW RATE LBS./MIN | APPARENT VISCOSITY CP. (HEAT SECT.) | SLURRY HEAT BTU/HR. x $10^3$ | VISCOMETER FRICTION FACTOR | HEAT SECTION Re. No. x $10^3$ | EXP. FILM COEFF. * | EFFECTIVE THERMAL CONDUCT. ** | VISCOSITY CORRECTED TO 65°C (CP.) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 65.6 | 11.4 | 0.9115 | 113.0 | 0.601 | 264.5 | | 107.5 | 4520 | 0.559 | 0.630 |
| 2 | 65.6 | 11.4 | 0.9115 | 131.0 | 0.588 | 275.0 | | 127.0 | 5220 | 0.611 | 0.630 |
| 3 | 65.6 | 11.4 | 0.9115 | 72.7 | 0.635 | 223.2 | | 69.6 | 3190 | 0.514 | 0.640 |
| 4 | 65.6 | 11.4 | 0.9115 | 47.7 | 0.843 | 182.0 | | 35.6 | 2250 | 0.475 | 0.820 |
| 5 | 65.6 | 11.4 | 0.9115 | 88.5 | 0.620 | 248.0 | | 86.0 | 4030 | 0.600 | 0.630 |
| 6 | 67.3 | 15.2 | 0.8739 | 138.0 | 0.688 | 279.0 | | 119.0 | 5250 | 0.585 | 0.710 |
| 7 | 67.3 | 15.2 | 0.8739 | 129.0 | 0.710 | 285.0 | | 111.0 | 5000 | 0.580 | 0.710 |
| 8 | 67.3 | 15.2 | 0.8739 | 113.0 | 0.728 | 267.0 | | 97.4 | 4620 | 0.580 | 0.710 |
| 9 | 67.3 | 15.2 | 0.8739 | 80.8 | 0.743 | 235.0 | | 85.0 | 3420 | 0.405 | 0.720 |
| 10 | 67.3 | 15.2 | 0.8739 | 60.3 | 0.800 | 192.0 | | 46.0 | 2570 | 0.487 | 0.800 |
| 11 | 70.2 | 23.2 | 0.8220 | 143.0 | 0.800 | 279.0 | | 107.5 | 4610 | 0.516 | 0.810 |
| 12 | 70.2 | 23.2 | 0.8220 | 129.0 | 0.785 | 269.0 | | 97.4 | 4470 | 0.571 | 0.810 |
| 13 | 70.2 | 23.2 | 0.8220 | 124.0 | 0.800 | 259.0 | | 94.0 | 3940 | 0.475 | 0.810 |
| 14 | 70.2 | 23.2 | 0.8220 | 113.0 | 0.810 | 251.0 | | 85.4 | 3620 | 0.455 | 0.810 |
| 15 | 70.2 | 23.2 | 0.8220 | 94.3 | 0.810 | 231.5 | | 71.0 | 3195 | 0.455 | 0.810 |
| 16 | 70.2 | 23.2 | 0.8220 | 67.7 | 0.970 | 190.0 | | 31.4 | 2300 | 0.598 | 0.970 |
| 17 | 62.4 | 3.0 | 0.9727 | 138.0 | 0.643 | 272.0 | 0.01745 | 131.0 | 4120 | 0.356 | 0.601 |
| 18 | 62.4 | 3.0 | 0.9727 | 128.9 | 0.533 | 274.0 | 0.0170 | 148.0 | 4070 | 0.354 | 0.493 |
| 19 | 62.4 | 3.0 | 0.9727 | 111.0 | 0.704 | 255.0 | 0.0180 | 96.5 | 3870 | 0.440 | 0.652 |
| 20 | 62.4 | 3.0 | 0.9727 | 94.0 | 0.586 | 238.0 | 0.0185 | 98.0 | 3380 | 0.391 | 0.555 |
| 21 | 62.4 | 3.0 | 0.9727 | 77.3 | 0.559 | 221.5 | 0.0190 | 84.5 | 2920 | 0.383 | 0.533 |
| 22 | 62.8 | 4.4 | 0.9628 | 141.0 | 0.581 | 260.0 | | 149.0 | 4210 | 0.345 | 0.570 |
| 23 | 62.8 | 4.4 | 0.9628 | 129.0 | 0.576 | 253.0 | | 137.0 | 4060 | 0.361 | 0.570 |
| 24 | 63.7 | 6.4 | 0.9494 | 145.0 | 0.585 | 267.5 | | 152.0 | 4630 | 0.400 | 0.590 |
| 25 | 64.2 | 8.0 | 0.9367 | 134.5 | 0.589 | 257.0 | | 138.9 | 4520 | 0.428 | 0.605 |
| 26 | 65.0 | 9.9 | 0.9217 | 119.5 | 0.637 | 258.0 | | 115.0 | 4060 | 0.414 | 0.625 |
| 27 | 63.2 | 5.0 | 0.9605 | 102.0 | 0.555 | 237.0 | | 112.5 | 3710 | 0.460 | 0.575 |
| 28 | 65.0 | 9.9 | 0.9217 | 71.4 | 0.670 | 219.0 | | 65.3 | 2920 | 0.452 | 0.640 |
| 29 | 64.2 | 8.0 | 0.9367 | 86.0 | 0.573 | 211.0 | | 91.9 | 3320 | 0.413 | 0.605 |
| 30 | 65.0 | 9.9 | 0.9217 | 143.0 | 0.632 | 270.0 | | 144.0 | 4630 | 0.475 | 0.640 |
| 31 | 67.9 | 17.1 | 0.8650 | 143.3 | 0.713 | 250.0 | | 119.0 | 4140 | 0.460 | 0.700 |
| 32 | 67.9 | 17.1 | 0.8650 | 131.6 | 0.720 | 249.0 | | 111.5 | 4110 | 0.427 | 0.700 |
| 33 | 68.4 | 18.3 | 0.8550 | 110.0 | 0.736 | 239.0 | | 91.3 | 3720 | 0.452 | 0.710 |
| 34 | 68.4 | 18.3 | 0.8550 | 75.2 | 0.963 | 213.0 | | 47.8 | 2720 | 0.479 | 0.920 |
| 35 | 68.4 | 18.3 | 0.8550 | 74.7 | 0.963 | 213.0 | | 47.4 | 2890 | 0.539 | 0.920 |
| 36 | 70.2 | 23.0 | 0.8180 | 152.3 | 0.915 | 262.0 | 0.01815 | 102.0 | 4590 | 0.325 | 0.915 |
| 37 | 70.2 | 23.0 | 0.8180 | 136.4 | 1.500 | 241.0 | 0.0204 | 55.5 | 4060 | 0.619 | 1.500 |
| 38 | 70.6 | 24.1 | 0.8090 | 121.0 | 0.795 | 243.0 | 0.0185 | 93.0 | 4080 | 0.514 | 0.795 |
| 39 | 70.6 | 24.1 | 0.8090 | 99.2 | 0.820 | 228.0 | 0.0193 | 74.0 | 3420 | 0.441 | 0.820 |
| 40 | 71.0 | 25.2 | 0.8020 | 64.6 | 1.110 | 183.0 | 0.0221 | 35.7 | 2320 | 0.486 | 1.110 |

* BTU/Hr.-FT.$^2$--°F
** BTU/Hr.-FT.--°F

## TABLE NO. V

## CALCULATED RESULTS FOR SUSPENSIONS

| RUN NO. | DENSITY LBS./FT.$^3$ | WEIGHT % SOLIDS | MEAN. Sp. HEAT BTU/LBS.°F | FLOW RATE LBS./MIN. | APPARENT VISCOSITY CP. (HEAT SECT.) | SLURRY HEAT BTU/HR. x $10^3$ | VISCOMETER FRICTION FACTOR | HEAT SECTION Re. No. x $10^3$ | EXP. FILM COEFF. * | EFFECTIVE THERMAL CONDUCT. ** | VISCOSITY CORRECTED TO 65°C (CP.) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 41 | 63.4 | 5.5 | 0.9565 | 138.0 | 0.702 | 258.0 | 0.01770 | 120.0 | 4230 | 0.395 | 0.648 |
| 42 | 63.4 | 5.5 | 0.9565 | 126.6 | 0.710 | 255.0 | 0.01790 | 109.0 | 3800 | 0.367 | 0.655 |
| 43 | 63.4 | 5.5 | 0.9565 | 93.5 | 0.710 | 227.0 | 0.01885 | 80.6 | 3000 | 0.350 | 0.640 |
| 44 | 63.4 | 5.5 | 0.9565 | 36.5 | 0.868 | 147.0 | 0.02380 | 25.7 | 1430 | 0.336 | 0.765 |
| 45 | 63.4 | 5.5 | 0.9565 | 83.1 | 0.685 | 229.0 | 0.01935 | 74.0 | 2830 | 0.360 | 0.630 |
| 46 | 65.6 | 11.3 | 0.9108 | 92.4 | 0.710 | 232.5 | 0.01905 | 79.9 | 3460 | 0.483 | 0.660 |
| 47 | 65.6 | 11.3 | 0.9108 | 74.3 | 0.770 | 217.0 | 0.02015 | 59.1 | 2800 | 0.440 | 0.710 |
| 48 | 65.6 | 11.3 | 0.9108 | 142.0 | 0.704 | 286.1 | 0.01760 | 123.5 | 4470 | 0.436 | 0.670 |
| 49 | 65.6 | 11.3 | 0.9108 | 124.0 | 0.820 | 256.0 | 0.01850 | 92.8 | 3880 | 0.427 | 0.775 |
| 50 | 65.6 | 11.3 | 0.9108 | 109.0 | 0.729 | 248.0 | 0.01850 | 91.8 | 3660 | 0.426 | 0.684 |
| 51 | 68.4 | 18.4 | 0.8547 | 146.4 | 0.724 | 273.0 | 0.01755 | 123.8 | 4220 | 0.394 | 0.694 |
| 52 | 68.4 | 18.4 | 0.8547 | 125.0 | 0.762 | 255.0 | 0.01935 | 100.1 | 4280 | 0.494 | 0.705 |
| 53 | 68.4 | 18.4 | 0.8547 | 93.2 | 0.769 | 232.0 | 0.01935 | 72.0 | 3230 | 0.468 | 0.720 |
| 54 | 68.4 | 18.4 | 0.8547 | 25.0 | 2.870 | 112.4 | 0.03380 | 5.3 | 1067 | 0.622 | 2.640 |
| 55 | 68.4 | 18.4 | 0.8547 | 110.0 | 0.895 | 251.0 | 0.01930 | 75.0 | 3650 | 0.475 | 0.860 |
| 56 | 63.3 | 2.9 | 0.9764 | 131.5 | 0.510 | 251.5 | 0.01680 | 157.3 | 3810 | 0.301 | 0.490 |
| 57 | 63.3 | 2.9 | 0.9764 | 122.0 | 0.555 | 261.0 | 0.01720 | 134.6 | 3700 | 0.321 | 0.518 |
| 58 | 63.3 | 2.9 | 0.9764 | 100.0 | 0.558 | 229.0 | 0.01800 | 109.6 | 3130 | 0.301 | 0.540 |
| 59 | 63.3 | 2.9 | 0.9764 | 80.5 | 0.495 | 222.0 | 0.01820 | 99.5 | 2860 | 0.313 | 0.470 |
| 60 | 63.3 | 2.9 | 0.9764 | 54.3 | 0.458 | 188.6 | 0.01920 | 72.3 | 2120 | 0.281 | 0.435 |
| 61 | 65.6 | 7.2 | 0.9413 | 136.5 | 0.615 | 251.0 | 0.01760 | 136.0 | 3730 | 0.306 | 0.615 |
| 62 | 65.6 | 7.2 | 0.9413 | 121.5 | 0.660 | 247.0 | 0.01780 | 112.0 | 3580 | 0.329 | 0.644 |
| 63 | 65.6 | 7.2 | 0.9413 | 105.1 | 0.600 | 224.0 | 0.01790 | 107.2 | 3180 | 0.203 | 0.600 |
| 64 | 65.6 | 7.2 | 0.9413 | 73.8 | 0.620 | 193.0 | 0.01910 | 72.7 | 2175 | 0.255 | 0.594 |
| 65 | 65.6 | 7.2 | 0.9413 | 60.2 | 0.580 | 153.4 | 0.01990 | 63.6 | 1735 | 0.214 | 0.600 |
| 66 | 67.0 | 9.8 | 0.9205 | 145.0 | 0.676 | 239.0 | 0.01740 | 131.0 | 3900 | 0.317 | 0.705 |
| 67 | 67.0 | 9.8 | 0.9205 | 134.0 | 0.690 | 228.1 | 0.01760 | 119.0 | 3440 | 0.315 | 0.720 |
| 68 | 67.0 | 9.8 | 0.9205 | 111.5 | 0.600 | 215.0 | 0.01770 | 113.6 | 3050 | 0.271 | 0.620 |
| 69 | 67.0 | 9.8 | 0.9205 | 84.0 | 0.610 | 173.1 | 0.01850 | 84.0 | 2160 | 0.216 | 0.645 |
| 70 | 67.0 | 9.8 | 0.9205 | 50.6 | 0.879 | 110.5 | 0.02195 | 35.2 | 910 | 0.111 | 0.805 |
| 71 | 68.0 | 11.7 | 0.9005 | 148.9 | 0.650 | 216.0 | 0.01710 | 140.0 | 3550 | 0.350 | 0.730 |
| 72 | 68.0 | 11.7 | 0.9005 | 136.5 | 0.602 | 210.5 | 0.01704 | 138.0 | 3110 | 0.229 | 0.660 |
| 73 | 68.0 | 11.7 | 0.9005 | 106.4 | 0.594 | 170.5 | 0.01771 | 109.6 | 2310 | 0.182 | 0.653 |
| 74 | 68.0 | 11.7 | 0.9005 | 132.0 | 0.585 | 186.5 | 0.01700 | 137.6 | 2990 | 0.217 | 0.675 |

* BTU/Hr. – FT$^2$-°F

** BTU/Hr.– FT-°F

# TABLE NO. VI

## ADDITIONAL RE-RUN DATA FOR VISCOSITY CALCULATED

## CALCULATED RESULTS

| RUN NO. | DENSITY LBS./FT.$^3$ | FLOW RATE LBS./MIN. | WEIGHT % SOLIDS | VISCOMETER FRICTION FACTOR | HEAT SECTION Re. No. x $10^3$ | APPARENT VISCOSITY (CP) | VISCOSITY CORR. TO 65°C |
|---|---|---|---|---|---|---|---|
| ATOMITE | | | | | | | |
| 75 | 66.5 | 143.5 | 13.6 | 0.01731 | 136.1 | 0.645 | 0.645 |
| 76 | 66.5 | 134.0 | 13.6 | 0.01760 | 123.6 | 0.661 | 0.661 |
| 77 | 66.5 | 113.0 | 13.6 | 0.01825 | 102.1 | 0.676 | 0.664 |
| 78 | 66.5 | 72.6 | 13.6 | 0.01980 | 64.6 | 0.687 | 0.676 |
| 79 | 66.5 | 46.4 | 13.6 | 0.02240 | 31.4 | 0.905 | 0.890 |
| 80 | 65.1 | 51.5 | 10.0 | 0.02120 | 46.1 | 0.682 | 0.641 |
| 81 | 65.1 | 75.7 | 10.0 | 0.01855 | 84.3 | 0.549 | 0.516 |
| 82 | 65.1 | 96.8 | 10.0 | 0.01845 | 95.4 | 0.619 | 0.583 |
| 83 | 65.1 | 115.5 | 10.0 | 0.01875 | 124.5 | 0.562 | 0.538 |
| 84 | 65.1 | 142.5 | 10.0 | 0.01721 | 137.9 | 0.630 | 0.603 |
| 85 | 70.2 | 148.0 | 23.0 | 0.01815 | 100.2 | 0.903 | 0.835 |
| 86 | 70.2 | 142.0 | 23.0 | 0.01830 | 96.8 | 0.899 | 0.849 |
| 87 | 70.2 | 130.0 | 23.0 | 0.01855 | 90.3 | 0.880 | 0.825 |
| 88 | 70.2 | 113.0 | 23.0 | 0.01900 | 83.6 | 0.826 | 0.776 |
| 89 | 70.2 | 94.0 | 23.0 | 0.01940 | 69.2 | 0.830 | 0.769 |
| 90 | 70.2 | 67.0 | 23.0 | 0.02190 | 39.1 | 1.045 | 0.965 |
| SNOWFLAKE | | | | | | | |
| 91 | 62.35 | 130.5 | 2.6 | 0.01670 | 162.0 | 0.522 | 0.534 |
| 92 | 62.35 | 122.5 | 2.6 | 0.01730 | 139.5 | 0.537 | 0.512 |
| 93 | 62.35 | 104.5 | 2.6 | 0.01760 | 123.0 | 0.520 | 0.495 |
| 94 | 62.35 | 38.5 | 2.6 | 0.02200 | 35.7 | 0.660 | 0.621 |
| 95 | 62.35 | 57.5 | 2.6 | 0.01930 | 74.7 | 0.470 | 0.455 |
| 96 | 68.35 | 150.1 | 18.0 | 0.01735 | 132.5 | 0.675 | 0.635 |
| 97 | 68.35 | 142.5 | 18.0 | 0.01745 | 128.0 | 0.680 | 0.645 |
| 98 | 68.35 | 124.1 | 18.0 | 0.01810 | 107.0 | 0.710 | 0.675 |
| 99 | 68.35 | 92.3 | 18.0 | 0.01095 | 69.5 | 0.814 | 0.775 |
| 100 | 68.35 | 67.2 | 18.0 | 0.02020 | 58.7 | 0.700 | 0.665 |

## CORRELATION

The method utilized to correlate the results of the data in this report was of a statistical nature.

The equation was assumed to be of the exponential type:

$$\frac{hD}{K_f} = Z\left(Re\right)^b\left(P_r\right)^y\left(\frac{C_s}{C_f}\right)^J\left(\frac{K_s}{K_f}\right)^n\left(\frac{D_s}{D}\right)^r$$

If in a group of runs, using the same material throughout, a ratio such as the following may be written:

$$\frac{(hD/K_f)_1}{(hD/K_f)_2} = \frac{Z\,(Re)_1^b (P_r)_1^y (C_s/C_f)_1^J (K_s/K_f)_1^n (D_s/D)_1^r}{Z\,(Re)_2^b (P_r)_2^y (C_s/C_f)_2^J (K_s/K_f)_2^n (D_s/D)_2^r} \quad \begin{matrix}\text{RUN 1}\\ \text{RUN 2}\end{matrix}$$

Since for one particular material the groups $\left(\frac{K_s}{K_f}\right)$ $\left(\frac{C_s}{C_f}\right)$ $\left(\frac{D}{D_s}\right)$ cancel out along with the constant Z, the following remains:

$$\frac{(hD/K_f)_1}{(hD/K_f)_2} = \frac{(Re)_1^b\,(P_r)_1^y}{(Re)_2^b\,(P_r)_2^y}$$

And further $P_r = \frac{C_f\,\mu_b}{K_f}$

$$\frac{h_1}{h_2} = \frac{(Re)_1^b}{(Re)_2^b}\,\frac{(\mu_b)_1^y}{(\mu_b)_2^y}$$

Or

$$\log(h_1/h_2) = b\,\log(Re_1/Re_2) + y\,\log(\mu_{b1}/\mu_{b2})$$

may be solved for the exponents b and y using an additional equation made up similarly from two other runs. All the data in this report was utilized in solving the exponents of b and y, i.e., the exponent for Reynolds number and Prandtl number.

In solving for the exponent of $(D/D_S)$, the runs from slurries having particles of different diameter were utilized.

The equation may be written as follows:

$$\frac{h_A}{h_S} = \frac{(Re)_A^b \; (Pr)_A^y \; (D_S)_A^r}{(Re)_S^b \; (Pr)_S^y \; (D_S)_S^r} \qquad \begin{matrix} \text{ATOMITE} \\ \text{SNOWFLAKE} \end{matrix}$$

Since b and y were found previously, all that need be found is the value of the exponent r which may be found by solving the above equation in the following form:

$$\log\left(\frac{h_A}{h_S}\right) = b \log\left(\frac{Re_A}{Re_S}\right) + y \log\left(\frac{\mu_{bA}}{\mu_{bS}}\right) + r \log\left(\frac{D_{SA}}{D_{SF}}\right)$$

The exponents for the remaining groups were solved by utilizing slurries having different specific heat and thermal conductivity.

The equation from two runs is as follows:

$$\frac{h_{CHALK}}{h_{Fe_2O_3}} = \left(\frac{Re}{Re}\right)^b \left(\frac{Pr}{Pr}\right)^y \left(\frac{C_S/C_f}{C_S/C_f}\right)^J \left(\frac{K_S/K_f}{K_S/K_f}\right)^n \left(\frac{D_S/D}{D_S/D}\right)^r$$

which is solved simultaneously with another equation made up similarly from two other runs of chalk and copper from J J. Salamone (12).

From the exponents for the various dimensionless groups obtained by Salamone (12), Binder and Pollara (19), and these investigators, the following equation results:

$$\frac{hD}{K_f} = 0.027 \left(R_e\right)^{.76} \left(P_r\right)^{.75} \left(\frac{C_s}{C_f}\right)^{.38} \left(\frac{K_s}{K_f}\right)^{.056} \left(\frac{D}{D_s}\right)^{.076}$$

The data in figure 10 was plotted with the ordinate equal to

$$\frac{\dfrac{hD}{K_f}}{\left(\dfrac{C_f \mu_b}{K_f}\right)^{.75} \left(\dfrac{K_s}{K_f}\right)^{.056} \left(\dfrac{D}{D_s}\right)^{.076} \left(\dfrac{C_s}{C_f}\right)^{.38}}$$

and Reynolds number as the abscissa. The curve drawn through the points was selected mainly on the premise that data obtained at high Reynolds numbers were more reliable than low Reynolds number. The mean of these data was found by arithmetic average. It was found that the data of this report and the data of J. J. Salamone (12), when treated according to the method described previously, i.e., averaging the ratios of the runs and solving by simultaneous equations, gave a value of .76 for the slope of the line to be drawn through the plotted data. Hence, by this method an intercept of .027 was obtained, which is equivalent to the constant of the Dittus-Boelter equation used for simple Newtonian fluids.

It may be seen from figure 10 that the line drawn through the plotted data represents the bulk of the data in the heavily concentrated portion of the plot, and at lower Reynolds numbers as well.

## TABLE NO. VII

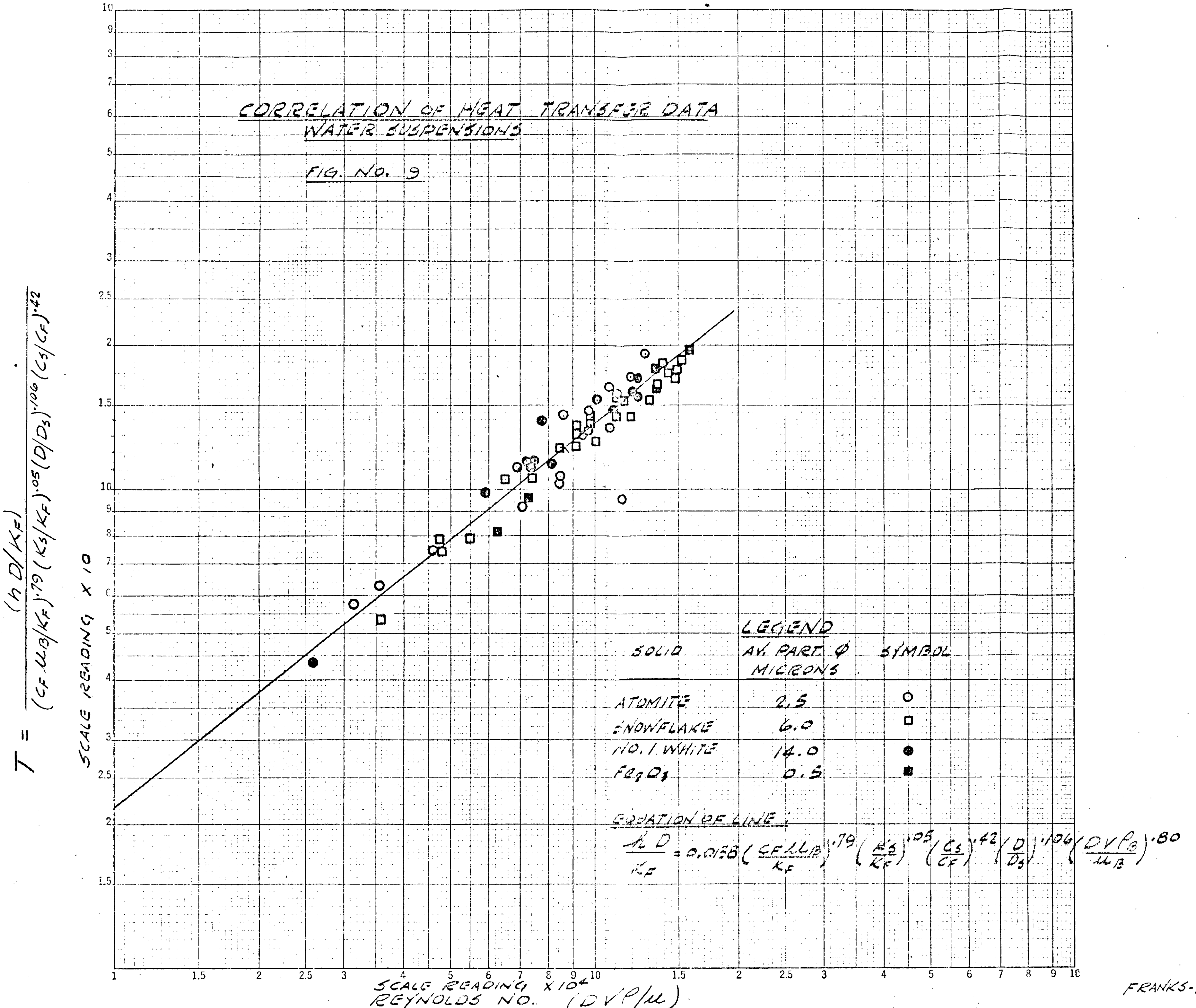
### CORRELATED RESULTS

| RUN NO. | Re. x $10^3$ | Re.$^{.8}$ x $10^2$ | $\left(\frac{C_f\ \mu_b}{K_f}\right)^{.79}$ | $\left(\frac{K_s}{K_f}\right)^{.05}$ | $\left(\frac{C_s}{C_f}\right)^{.42}$ | $\left(\frac{D}{D_s}\right)^{.106}$ | CALC. h | EXPER. h | % DEV. | $\frac{hD}{K_f}$ / $\left(C_f\ \mu_b/K_f\right)^{.79}\left(K_s/K_f\right)^{.05}\left(C_s/C_f\right)^{.42}\left(D/D_s\right)^{.106}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| ATOMITE | | | | | | | | | | |
| 1 | 107.5 | 10.59 | 2.93 | 1.00 | 0.52 | 2.51 | 4000 | 4520 | -11.5 | 164.0 |
| 2 | 127.0 | 12.11 | 2.88 | 1.00 | 0.52 | 2.51 | 4500 | 5220 | -13.8 | 193.0 |
| 3 | 69.6 | 7.49 | 3.06 | 1.00 | 0.52 | 2.51 | 3000 | 3190 | - 6.0 | 111.0 |
| 4 | 35.6 | 4.39 | 3.84 | 1.00 | 0.52 | 2.51 | 2120 | 2250 | - 5.8 | 62.4 |
| 5 | 86.0 | 8.88 | 3.00 | 1.00 | 0.52 | 2.51 | 3440 | 4030 | -14.6 | 142.6 |
| 6 | 119.0 | 11.48 | 3.26 | 1.00 | 0.52 | 2.51 | 4850 | 5250 | - 7.6 | 171.0 |
| 7 | 111.0 | 10.79 | 3.35 | 1.00 | 0.52 | 2.51 | 4660 | 5000 | - 6.8 | 159.0 |
| 8 | 97.4 | 9.79 | 3.40 | 1.00 | 0.52 | 2.51 | 4300 | 4620 | - 6.9 | 144.6 |
| 9 | 85.0 | 8.78 | 3.46 | 1.00 | 0.52 | 2.51 | 3930 | 3420 | 15.0 | 105.1 |
| 10 | 46.0 | 5.38 | 3.68 | 1.00 | 0.52 | 2.51 | 2500 | 2570 | - 2.7 | 74.5 |
| 11 | 107.5 | 10.59 | 3.68 | 1.00 | 0.52 | 2.51 | 5040 | 4610 | 9.3 | 133.3 |
| 12 | 97.4 | 9.79 | 3.62 | 1.00 | 0.52 | 2.51 | 4580 | 4470 | 2.5 | 131.4 |
| 13 | 94.0 | 9.52 | 3.67 | 1.00 | 0.52 | 2.51 | 4440 | 3940 | 12.6 | 114.2 |
| 14 | 85.4 | 8.82 | 3.71 | 1.00 | 0.52 | 2.51 | 4200 | 3620 | 16.0 | 103.7 |
| 15 | 71.0 | 7.61 | 3.71 | 1.00 | 0.52 | 2.51 | 3630 | 3195 | 13.6 | 91.7 |
| 16 | 31.4 | 3.95 | 4.26 | 1.00 | 0.52 | 2.51 | 2170 | 2300 | - 5.6 | 57.5 |
| SNOWFLAKE | | | | | | | | | | |
| 17 | 131.0 | 12.41 | 3.09 | 1.00 | 0.52 | 2.31 | 4460 | 4120 | 8.3 | 153.7 |
| 18 | 148.0 | 13.68 | 2.66 | 1.00 | 0.52 | 2.31 | 4300 | 4070 | 5.7 | 177.0 |
| 19 | 96.5 | 9.72 | 3.31 | 1.00 | 0.52 | 2.31 | 3830 | 3870 | - 1.0 | 135.0 |
| 20 | 98.0 | 9.84 | 2.78 | 1.00 | 0.52 | 2.31 | 3250 | 3380 | - 4.0 | 140.7 |
| 21 | 84.5 | 8.74 | 2.77 | 1.00 | 0.52 | 2.31 | 2890 | 2920 | - 1.0 | 122.0 |
| 22 | 149.0 | 13.76 | 2.85 | 1.00 | 0.52 | 2.31 | 4660 | 4210 | 10.5 | 171.0 |
| 23 | 137.0 | 12.86 | 2.84 | 1.00 | 0.52 | 2.31 | 4350 | 4060 | 7.1 | 165.0 |
| 24 | 152.0 | 13.98 | 2.87 | 1.00 | 0.52 | 2.31 | 4760 | 4630 | 2.8 | 186.6 |
| 25 | 138.9 | 13.00 | 2.87 | 1.00 | 0.52 | 2.31 | 4440 | 4520 | 1.8 | 182.0 |
| 26 | 115.0 | 11.18 | 3.07 | 1.00 | 0.52 | 2.31 | 4080 | 4060 | 0 | 152.5 |
| 27 | 112.5 | 10.99 | 2.73 | 1.00 | 0.52 | 2.31 | 3570 | 3710 | - 3.8 | 157.0 |
| 28 | 65.3 | 7.12 | 3.20 | 1.00 | 0.52 | 2.31 | 2710 | 2920 | - 7.2 | 105.3 |
| 29 | 91.9 | 9.35 | 2.82 | 1.00 | 0.52 | 2.31 | 3140 | 3320 | - 5.4 | 136.0 |
| 30 | 144.0 | 13.39 | 3.04 | 1.00 | 0.52 | 2.31 | 4860 | 4630 | 5.0 | 176.0 |
| 31 | 119.0 | 11.49 | 3.36 | 1.00 | 0.52 | 2.31 | 4600 | 4140 | 11.0 | 142.0 |
| 32 | 111.5 | 10.91 | 3.39 | 1.00 | 0.52 | 2.31 | 4400 | 4110 | 7.0 | 140.4 |
| 33 | 91.3 | 9.30 | 3.50 | 1.00 | 0.52 | 2.31 | 3870 | 3720 | 4.0 | 122.5 |
| 34 | 47.8 | 5.50 | 4.25 | 1.00 | 0.52 | 2.31 | 2790 | 2720 | 2.6 | 74.4 |
| 35 | 47.4 | 5.50 | 4.25 | 1.00 | 0.52 | 2.31 | 2780 | 2890 | - 3.8 | 78.5 |
| 36 | 101.5 | 10.12 | 4.08 | 1.00 | 0.52 | 2.31 | 4930 | 4590 | 7.5 | 130.0 |
| 37 | 54.85 | 6.19 | 6.00 | 1.00 | 0.52 | 2.31 | 4410 | 4060 | 8.7 | 78.2 |
| 38 | 92.6 | 9.41 | 3.65 | 1.00 | 0.52 | 2.31 | 4090 | 4080 | 0 | 129.0 |
| 39 | 74.0 | 7.86 | 3.74 | 1.00 | 0.52 | 2.31 | 3500 | 3420 | 2.4 | 105.5 |
| 40 | 35.9 | 4.40 | 4.74 | 1.00 | 0.52 | 2.31 | 2460 | 2320 | 6.0 | 56.7 |

# TABLE NO. VII

## CORRELATED RESULTS

| RUN NO. | Re. x $10^3$ | Re.$^{.8}$ x $10^2$ | $\left(\frac{C_f \mu_b}{K_f}\right)^{.79}$ | $\left(\frac{K_s}{K_f}\right)^{.05}$ | $\left(\frac{C_s}{C_f}\right)^{.42}$ | $\left(\frac{D}{D_s}\right)^{.106}$ | CALC. h | EXPER. h | % DEV. | $\dfrac{hD/K_f}{\left(\frac{C_f \mu_b}{K_f}\right)^{.79}\left(K_s/K_f\right)^{.05}\left(C_s/C_f\right)^{.42}\left(D/D_s\right)^{.106}}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| **No. 1 WHITE** | | | | | | | | | | |
| 41 | 120.0 | 11.70 | 3.32 | 1.00 | 0.52 | 2.11 | 4200 | 4230 | 0 | 160.0 |
| 42 | 109.0 | 10.71 | 3.35 | 1.00 | 0.52 | 2.11 | 3920 | 3800 | 3.2 | 143.6 |
| 43 | 80.6 | 8.42 | 3.35 | 1.00 | 0.52 | 2.11 | 3070 | 3000 | 2.3 | 113.2 |
| 44 | 25.7 | 3.36 | 3.91 | 1.00 | 0.52 | 2.11 | 1430 | 1430 | 0 | 46.3 |
| 45 | 74.0 | 7.86 | 3.26 | 1.00 | 0.52 | 2.11 | 2790 | 2830 | -1.4 | 110.0 |
| 46 | 79.5 | 8.35 | 3.35 | 1.00 | 0.52 | 2.11 | 2720 | 3460 | -21.0 | 130.8 |
| 47 | 59.1 | 6.56 | 3.57 | 1.00 | 0.52 | 2.11 | 2550 | 2800 | -9.0 | 99.3 |
| 48 | 123.5 | 11.84 | 3.32 | 1.00 | 0.52 | 2.11 | 4290 | 4470 | -4.0 | 170.5 |
| 49 | 92.8 | 9.42 | 3.74 | 1.00 | 0.52 | 2.11 | 3840 | 3880 | -1.0 | 131.0 |
| 50 | 91.8 | 9.34 | 3.41 | 1.00 | 0.52 | 2.11 | 3460 | 3660 | -5.4 | 135.6 |
| 51 | 123.8 | 11.86 | 3.40 | 1.00 | 0.52 | 2.11 | 4400 | 4220 | -4.3 | 157.0 |
| 52 | 100.1 | 10.00 | 3.53 | 1.00 | 0.52 | 2.11 | 3850 | 4280 | -10.0 | 153.4 |
| 53 | 72.0 | 7.69 | 3.56 | 1.00 | 0.52 | 2.11 | 2980 | 3230 | -7.8 | 114.8 |
| 54 | 5.3 | .90 | 10.10 | 1.00 | 0.52 | 2.11 | 973 | 1067 | -8.8 | 13.4 |
| 55 | 75.0 | 7.94 | 4.02 | 1.00 | 0.52 | 2.11 | 3480 | 3650 | -4.7 | 114.8 |
| **IRON OXIDE** | | | | | | | | | | |
| 56 | 157.3 | 14.36 | 2.57 | 0.981 | 0.367 | 2.94 | 3700 | 3810 | -2.9 | 195.0 |
| 57 | 134.6 | 12.68 | 2.75 | 0.981 | 0.367 | 2.94 | 3500 | 3700 | -5.4 | 177.0 |
| 58 | 109.6 | 10.71 | 2.76 | 0.981 | 0.367 | 2.94 | 2960 | 3130 | -5.4 | 149.0 |
| 59 | 99.5 | 9.96 | 2.52 | 0.981 | 0.367 | 2.94 | 2500 | 2860 | -12.5 | 149.2 |
| 60 | 72.3 | 7.71 | 2.37 | 0.981 | 0.367 | 2.94 | 1680 | 2120 | -20.0 | 117.5 |
| 61 | 136.0 | 12.79 | 2.98 | 0.981 | 0.367 | 2.94 | 3820 | 3730 | 2.4 | 164.6 |
| 62 | 112.0 | 10.95 | 3.15 | 0.981 | 0.367 | 2.94 | 3450 | 3580 | -3.6 | 149.4 |
| 63 | 107.2 | 10.57 | 2.92 | 0.981 | 0.367 | 2.94 | 3080 | 3180 | -3.1 | 143.0 |
| 64 | 72.7 | 7.75 | 3.00 | 0.981 | 0.367 | 2.94 | 2320 | 2175 | 6.7 | 95.3 |
| 65 | 63.2 | 6.95 | 2.85 | 0.981 | 0.367 | 2.94 | 1980 | 1735 | 14.2 | 80.0 |
| 66 | 131.0 | 12.41 | 3.21 | 0.981 | 0.367 | 2.94 | 3970 | 3900 | 1.8 | 160.0 |
| 67 | 119.0 | 11.49 | 3.27 | 0.981 | 0.367 | 2.94 | 3760 | 3440 | 9.3 | 138.2 |
| 68 | 113.6 | 11.08 | 2.92 | 0.981 | 0.367 | 2.94 | 3220 | 3050 | 5.6 | 137.2 |
| 69 | 84.0 | 8.70 | 2.96 | 0.981 | 0.367 | 2.94 | 2570 | 2160 | 18.9 | 96.0 |
| 70 | 35.2 | 4.32 | 3.96 | 0.981 | 0.367 | 2.94 | 1710 | 910 | | 30.2 |
| 71 | 140.0 | 13.09 | 3.12 | 0.981 | 0.367 | 2.94 | 4080 | 3550 | | 149.6 |
| 72 | 138.0 | 12.94 | 2.94 | 0.981 | 0.367 | 2.94 | 3800 | 3110 | | 139.0 |
| 73 | 109.6 | 10.71 | 2.91 | 0.981 | 0.367 | 2.94 | 3120 | 2310 | | 104.2 |
| 74 | 137.6 | 12.91 | 2.97 | 0.981 | 0.367 | 2.94 | 3830 | 2990 | | 132.2 |


CORRELATION OF HEAT TRANSFER DATA
WATER SUSPENSIONS
FIG. NO. 9
LEGEND
SOLID
AV. PART. Ø MICRONS
SYMBOL
ATOMITE 2.5
SNOWFLAKE 6.0
NO. 1 WHITE 14.0
$Fe_2O_3$ 0.5
EQUATION OF LINE:
$\frac{hD}{K_F} = 0.0158\left(\frac{C_F \mu_B}{K_F}\right)^{.79}\left(\frac{K_S}{K_F}\right)^{.05}\left(\frac{C_S}{C_F}\right)^{.42}\left(\frac{D}{D_S}\right)^{.106}\left(\frac{DV\rho_B}{\mu_B}\right)^{.80}$
$T = \frac{(hD/K_F)}{(C_F\mu_B/K_F)^{.79}(K_S/K_F)^{.05}(D/D_S)^{.106}(C_S/C_F)^{.42}}$
SCALE READING X 10
SCALE READING X $10^4$
REYNOLDS NO. $(DV\rho/\mu)$

## TABLE NO. VIII

## CORRELATION OF DATA OF SALAMONE, BINDER - POLLARA, FRANKS - RINALDI

$$\frac{hD}{K_f} = Z \,(Re.)\left(\frac{C_f \mu_b}{K_f}\right)\left(\frac{K_s}{K_f}\right)\left(\frac{C_s}{C_f}\right)\left(\frac{D}{D_s}\right)$$

| Exponent For Groups Determined By: | $Z$ | $(Re.)$ | $\left(\frac{C_f \mu_b}{K_f}\right)$ | $\left(\frac{K_s}{K_f}\right)$ | $\left(\frac{C_s}{C_f}\right)$ | $\left(\frac{D}{D_s}\right)$ |
|---|---|---|---|---|---|---|
| J. J. Salamone | 0.131 | 0.62 | 0.72 | 0.05 | 0.35 | 0.050 |
| Binder - Pollara | 0.346 | 0.70 | 0.72 | 0.08 | 0.35 | -0.152 |
| Franks - Rinaldi | 0.0138 | 0.80 | 0.79 | 0.05 | 0.42 | 0.106 |

Weighted Arithmetic Average For Exponents

| | $\left(\frac{C_f \mu_b}{K_f}\right)$ | $\left(\frac{K_s}{K_f}\right)$ | $\left(\frac{C_s}{C_f}\right)$ | $\left(\frac{D}{D_s}\right)$ |
|---|---|---|---|---|
| | 0.746 | 0.0563 | 0.376 | 0.0755 |
| ROUNDED TO → | 0.75 | 0.056 | 0.380 | 0.076 |

Let T

$$T = \frac{\frac{hD}{K_f}}{\left(\frac{C_f \mu_b}{K_f}\right)^{0.75}\left(\frac{K_s}{K_f}\right)^{.056}\left(\frac{C_s}{C_f}\right)^{.38}\left(\frac{D}{D_s}\right)^{.076}}$$

SALAMONE DATA: COPPER "A"

| RUN NO. | T | Re. No. x $10^3$ |
|---|---|---|
| 19 | 145.0 | 101.2 |
| 20 | 129.0 | 88.6 |
| 21 | 122.0 | 79.0 |
| 22 | 101.5 | 61.0 |
| 23 | 75.0 | 39.1 |
| 24 | 54.0 | 23.3 |
| 25 | 148.0 | 109.3 |
| 26 | 141.0 | 101.0 |
| 27 | 137.0 | 91.9 |
| 28 | 116.0 | 81.0 |
| 29 | 140.0 | 65.0 |
| 30 | 76.0 | 40.1 |
| 31 | 161.0 | 114.2 |
| 32 | 148.0 | 100.0 |
| 33 | 137.0 | 91.6 |
| 34 | 123.5 | 78.1 |
| 35 | 109.0 | 67.2 |
| 36 | 76.0 | 38.5 |
| 37 | 147.0 | 110.5 |
| 38 | 141.5 | 103.4 |
| 39 | 134.5 | 93.2 |
| 40 | 129.0 | 80.4 |
| 41 | 111.0 | 67.2 |
| 42 | 83.0 | 42.8 |
| 43 | 157.0 | 117.8 |
| 44 | 148.5 | 109.4 |
| 45 | 143.5 | 98.2 |
| 46 | 127.0 | 83.2 |
| 47 | 111.0 | 66.6 |
| 48 | 69.1 | 34.1 |
| 49 | 159.0 | 127.8 |
| 50 | 155.0 | 119.6 |
| 51 | 138.0 | 104.0 |
| 52 | 127.0 | 88.2 |
| 53 | 108.0 | 64.6 |
| 54 | 169.5 | 34.9 |

SALAMONE DATA (CONT'D) COPPER "B"

| RUN NO. | T | Re. No. x $10^{3}$ |
|---|---|---|
| 55 | 154.0 | 122.0 |
| 56 | 148.0 | 106.5 |
| 57 | 132.0 | 89.0 |
| 58 | 104.0 | 68.8 |
| 59 | 95.0 | 50.8 |
| 60 | 38.4 | 13.3 |
| 61 | 175.0 | 136.0 |
| 62 | 167.0 | 122.5 |
| 63 | 151.0 | 106.5 |
| 64 | 130.0 | 83.2 |
| 65 | 101.0 | 53.9 |

SALAMONE DATA (CONT'D) COPPER "C"

| | | |
|---|---|---|
| 66 | 179.0 | 132.5 |
| 67 | 145.0 | 100.8 |
| 68 | 132.5 | 84.2 |
| 69 | 116.0 | 68.1 |
| 70 | 101.0 | 47.4 |
| 71 | 180.0 | 136.8 |
| 72 | 157.0 | 109.8 |
| 73 | 133.5 | 85.6 |
| 74 | 110.0 | 61.1 |
| 75 | 81.0 | 37.9 |

SALAMONE DATA (CONT'D) SILICA

| | | |
|---|---|---|
| 76 | 136.0 | 116.0 |
| 77 | 128.0 | 106.5 |
| 78 | 119.0 | 95.2 |
| 79 | 105.0 | 79.2 |
| 80 | 83.1 | 55.2 |
| 81 | 137.0 | 112.6 |
| 82 | 124.0 | 99.5 |
| 110 | 141.0 | 116.2 |
| 111 | 129.5 | 103.0 |
| 112 | 116.0 | 86.2 |
| 113 | 87.2 | 58.1 |

SALAMONE DATA (CONT'D) CARBON

| RUN NO. | T | Re. No. x $10^3$ |
|---|---|---|
| 83 | 158.0 | 125.4 |
| 84 | 143.0 | 113.5 |
| 85 | 124.0 | 94.2 |
| 86 | 108.5 | 75.0 |
| 87 | 74.0 | 47.2 |
| 88 | 103.0 | 79.8 |

SALAMONE DATA (CONT'D) ATOMITE CHALK

| RUN NO. | T | Re. No. x $10^3$ |
|---|---|---|
| 89 | 185.0 | 143.8 |
| 90 | 155.0 | 119.6 |
| 91 | 152.0 | 109.2 |
| 92 | 123.0 | 83.3 |
| 93 | 104.0 | 66.5 |
| 94 | 157.0 | 117.0 |
| 95 | 128.0 | 105.5 |
| 96 | 127.0 | 87.2 |
| 97 | 106.0 | 70.6 |
| 98 | 85.5 | 53.6 |
| 99 | 141.5 | 105.3 |
| 100 | 125.1 | 92.8 |
| 101 | 117.2 | 82.5 |
| 102 | 103.0 | 69.2 |
| 103 | 84.0 | 53.1 |
| 104 | 55.4 | 31.1 |

BINDER - POLLARA DATA COPPER

| RUN NO. | T | Re. No. x $10^3$ |
|---|---|---|
| 1 | 193.0 | 54.0 |
| 2 | 138.0 | 31.3 |
| 3 | 166.0 | 45.1 |
| 4 | 126.5 | 34.2 |
| 5 | 100.0 | 22.2 |
| 6 | 92.3 | 24.8 |
| 7 | 57.9 | 12.6 |

## FRANKS - RINALDI DATA ATOMITE CHALK

| RUN NO. | T | Re. No. x $10^{-3}$ |
|---|---|---|
| 1 | 202.0 | 107.5 |
| 2 | 237.0 | 127.0 |
| 3 | 137.0 | 69.6 |
| 4 | 78.5 | 35.6 |
| 5 | 177.0 | 86.0 |
| 6 | 214.0 | 119.0 |
| 7 | 199.0 | 111.0 |
| 8 | 181.0 | 97.4 |
| 9 | 132.0 | 85.0 |
| 10 | 94.0 | 46.0 |
| 11 | 167.0 | 107.5 |
| 12 | 165.0 | 97.4 |
| 13 | 144.0 | 94.0 |
| 14 | 129.0 | 85.4 |
| 15 | 116.0 | 71.0 |
| 16 | 73.3 | 31.4 |

## FRANKS - RINALDI DATA (CONT'D) SNOWFLAKE CHALK

| | | |
|---|---|---|
| 17 | 188.0 | 131.0 |
| 18 | 216.0 | 148.0 |
| 19 | 165.0 | 96.5 |
| 20 | 172.0 | 98.0 |
| 21 | 149.0 | 84.5 |
| 22 | 209.0 | 149.0 |
| 23 | 202.0 | 137.0 |
| 24 | 227.0 | 152.0 |
| 25 | 222.0 | 138.9 |
| 26 | 186.0 | 115.0 |
| 27 | 192.0 | 112.5 |
| 28 | 128.5 | 65.3 |
| 29 | 166.0 | 91.9 |
| 30 | 215.0 | 144.0 |
| 31 | 174.0 | 119.0 |
| 32 | 172.0 | 111.5 |
| 33 | 150.0 | 91.3 |
| 34 | 91.0 | 47.8 |
| 35 | 96.0 | 47.4 |
| 36 | 159.0 | 101.5 |
| 37 | 96.0 | 54.9 |
| 38 | 158.0 | 92.6 |
| 39 | 105.5 | 74.0 |
| 40 | 56.5 | 35.9 |

## BINDER - POLLARA DATA (CONT'D) ATOMITE CHALK

| RUN NO. | T | Re. No. x $10^3$ |
|---|---|---|
| 1 | 74.5 | 38.6 |
| 2 | 143.5 | 76.5 |
| 3 | 31.0 | 1.04 |
| 4 | 45.5 | 16.6 |
| 5 | 73.5 | 34.4 |
| 6 | 104.0 | 54.1 |
| 7 | 91.7 | 48.0 |
| 8 | 81.0 | 39.6 |
| 9 | 82.5 | 37.2 |
| 10 | 61.5 | 25.4 |
| 11 | 31.0 | 98.0 |

## BINDER - POLLARA DATA (CONT'D) SNOWFLAKE CHALK

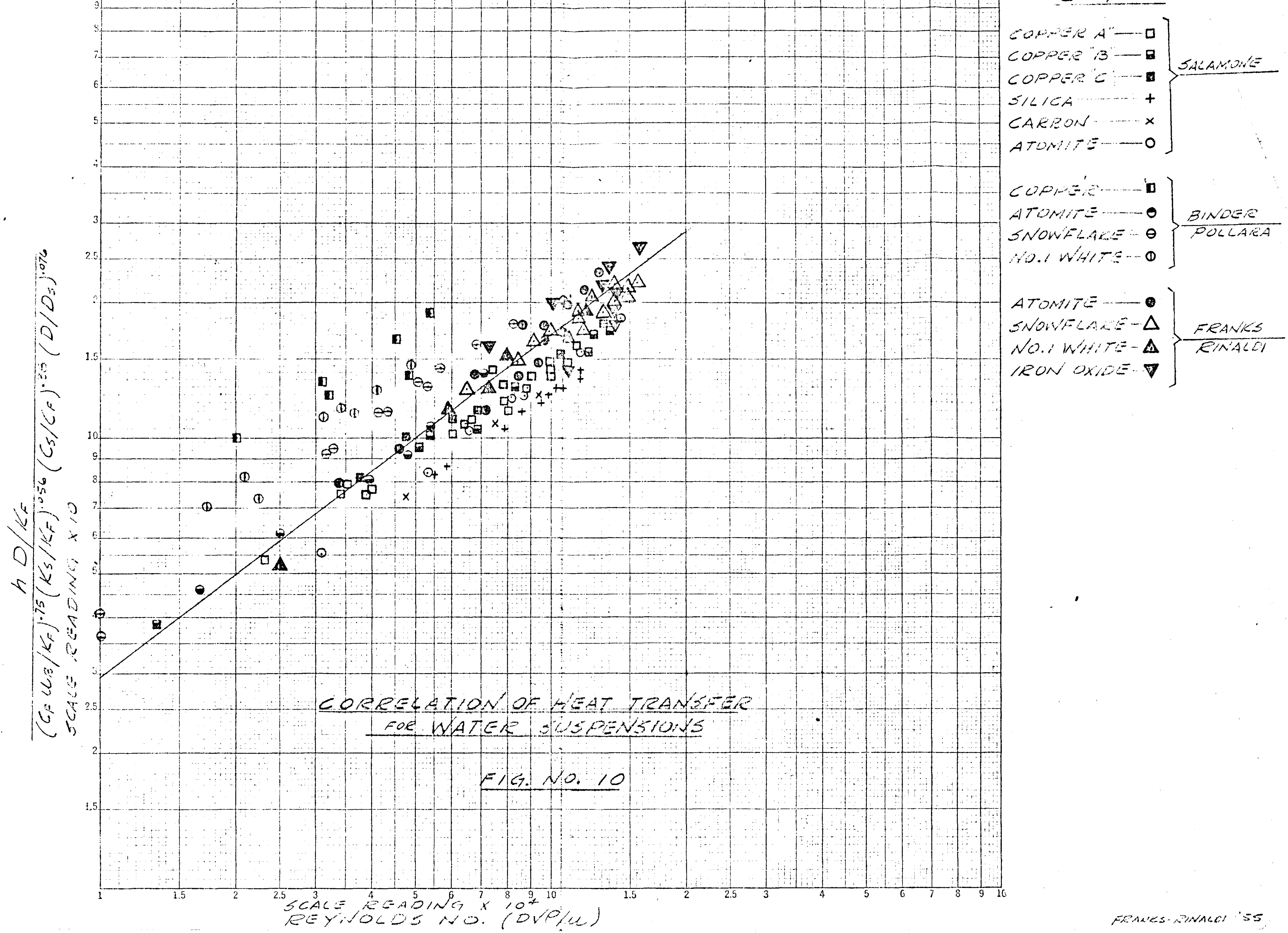
| RUN NO. | T | Re. No. x $10^3$ |
|---|---|---|
| 1 | 185.0 | 72.4 |
| 2 | 130.0 | 48.1 |
| 3 | 135.5 | 50.4 |
| 4 | 113.0 | 40.6 |
| 5 | 92.0 | 31.8 |
| 6 | 40.4 | 9.95 |
| 7 | 36.4 | 10.2 |
| 8 | 71.0 | 22.3 |
| 9 | 95.2 | 33.6 |
| 10 | 118.0 | 43.1 |
| 11 | 143.0 | 56.8 |
| 12 | 161.5 | 64.3 |

## BINDER - POLLARA DATA (CONT'D) No. 1 WHITE CHALK

| RUN NO. | T | Re. No. x $10^3$ |
|---|---|---|
| 1 | 114.0 | 36.2 |
| 2 | 117.0 | 34.8 |
| 3 | 112.0 | 31.2 |
| 4 | 82.7 | 21.7 |
| 5 | 69.9 | 17.2 |
| 6 | 145.0 | 48.8 |
| 7 | 95.0 | 31.6 |
| 8 | 128.0 | 40.5 |
| 9 | 73.0 | 22.2 |
| 10 | 67.5 | 21.3 |

FRANKS - RINALDI DATA (CONT'D) No. 1 WHITE CHALK

| RUN NO. | T | Re. No. x $10^3$ |
|---|---|---|
| 41 | 190.0 | 120.0 |
| 42 | 170.0 | 109.0 |
| 43 | 134.0 | 80.6 |
| 44 | 54.5 | 25.7 |
| 45 | 130.5 | 74.0 |
| 46 | 155.0 | 79.5 |
| 47 | 117.5 | 59.1 |
| 48 | 202.0 | 123.5 |
| 49 | 155.0 | 92.8 |
| 50 | 161.0 | 91.8 |
| 51 | 186.5 | 123.8 |
| 52 | 182.0 | 100.1 |
| 53 | 136.5 | 72.0 |
| 54 | 15.9 | 5.3 |
| 55 | 136.0 | 75.0 |
| 56 | 267.0 | 157.3 |
| 57 | 242.0 | 134.6 |
| 58 | 204.0 | 109.6 |
| 59 | 204.0 | 99.5 |
| 60 | 161.0 | 72.3 |
| 61 | 225.0 | 136.0 |
| 62 | 204.0 | 112.0 |
| 63 | 196.0 | 107.2 |
| 64 | 130.5 | 72.7 |
| 65 | 109.5 | 63.2 |
| 66 | 219.0 | 131.0 |
| 67 | 139.0 | 119.0 |
| 68 | 188.0 | 113.6 |
| 69 | 131.5 | 84.0 |
| 70 | 41.4 | 35.2 |
| 71 | 205.0 | 140.0 |
| 72 | 191.0 | 138.0 |
| 73 | 142.5 | 109.6 |
| 74 | 181.0 | 137.6 |




CORRELATION OF HEAT TRANSFER FOR WATER SUSPENSIONS

FIG. NO. 10

## DISCUSSION OF RESULTS

The heat transfer film coefficient is expressed in terms of three dimensionless groups, namely, Nusselt, Reynolds and Prandtl for fluids. Additional dimensionless groups have been found to be of significance in this investigation. These are the ratios of the specific heat of the solid to the specific heat of the suspending medium $C_s/C_f$, the ratio of thermal conductivity of the solid to that of the suspending medium $K_s/K_f$, and the ratio of the tube diameter to the suspended particle diameter $D/D_s$.

The results obtained in this investigation gave an exponent for the Reynolds group equal to 0.80, while the exponent of the Prandtl group was 0.79. Chu et al (5) stated,

> "The degree of pseudoplasticity of the fluid may be regarded as a measure of its deviation from simple Newtonian behavior. It is a reasonable inference that the degree of pseudoplasticity may also be a measure of the difference between the observed coefficient of heat transfer for the pseudoplastic fluid, and the value of the heat transfer coefficient predicted for a simple Newtonian fluid of similar viscosity by the already established relations."

Salamone (12) and Binder-Pollara (19) contend that the pseudoplastic characteristics of slurries have a significant effect on the magnitude of the heat transfer film coefficient.

It may be seen from the results obtained in this present investigation that the product of the Reynolds group and the Prandtl group in effect render the viscosity of the fluid virtually insignificant, i.e., viscosity $\mu_b^{.01}$. Hence, a reasonable inference indicates that in Salamone's derived equation, an exact value of viscosity is not necessary since even large deviations from true viscosity lead to small errors.

The $C_s/C_f$ group bears an exponent of 0.42 indicating that the convective transport of heat contributes significantly to the mechanism of heat transfer. Thus, materials having high specific heats cause more heat to be transferred to the bulk of the fluid.

The magnitude of the exponent for the $D/D_s$ group was determined to be 0.05 by Salamone and 0.106 by these authors. Salamone's value tends to minimize the importance of this group whereas the value of 0.105 renders this group very significant. Thus it follows that the smaller the particle diameter of the suspended solid the greater the value of the heat transfer film coefficient.

$K_s/K_f$ exponent was found to be 0.05. The significance of this group is solely dependent upon the material being suspended and the suspending medium and hence may or may not be significant. For the materials used in this report the $K_s/K_f$ group was of little consequence.

However, for materials such as the copper particles used by Salamone, this group is of definite importance. The increase in the value of the film coefficient using this group amounts to approximately 37% which indicates its degree of importance. Since copper possesses perhaps the highest thermal conductivity of commercial metals, then the value of 37% increase is probably the upper limit of increase which may be expected in a heat transfer mechanism such as this.

The values of the heat transfer film coefficients obtained by these investigators were somewhat higher than those of Salamone but not as high as these of Binder-Pollara. The results in this report agreed within 12% of Salamone's, the greatest difference being the slope of the line drawn through the plotted data, (see Fig. 10).

It is possible that the difference in the method of installation of thermocouple leads in the apparatus used accounted for these differences as pointed out in Binder-Pollara thesis. However, this difference of 12% cannot be definitely attributed to this since 12% lies within the expected degree of accuracy for this investigation.

Inspection of the final equation developed indicates a close similarity to the Dittus-Boelter equation with added correction groups $D/D_s$ , $C_s/C_f$ , $K_s/K_f$. The most notable exception is the exponent for the Prandtl group which is approximately double that of the exponent for the Prandtl group in the Dittus-Boelter equation. It is obvious from the above that the Dittus-Boelter equation is inadequate for the calculation of film coefficients for slurries, unless the correction groups are used and the Prandtl group exponent modified.

An additional possible correction factor which must be investigated concerns the shape of the particle suspended. As was seen in the derivation of the Salamone equation, the particles were assumed to be of spheroidal shape. If heat transfer, in a mechanism such as this, is at all dependent upon particle surface area, then considerable error can be introduced by the assumption of spheroidal particles. In commercial operations, where solid particles are used, such as catalysis, the shape factors most frequently encountered are in the range of 1.0 to 1.75. This means that generally particle surface area may be as much as 75% greater than that possessed by a perfect sphere. The effect of particle shape is a phase of the mechanism that has not yet been ascertained. This poses a consideration that may lead to considerable investigation, but is dependent upon finding a suitable method for determining particle shape.

The conclusions draw in this investigation are predicated upon the fact that the particles used are insoluble dorat least relatively insoluble in the suspending medium. Sufficient industrial applications exist to warrant the investigation of solutions composed of particles soluble in the suspending medium, insofar as heat transfer is concerned. Various concentrations of solutions could be used in addition to saturated and supersaturated solutions.

## DISCUSSION OF CORRELATED RESULTS

As may be seen from the discussion under section entitled "Correlations" that a different method was used for obtaining the values of the various exponents, than was used by Salamone (12) and Binder-Pollara (19). This method was specifically adopted by these authors in order to include the major portion of the data so that conclusions drawn would be representative of the data as a whole. This method differed from that of Salamone and Binder-Pollara in that their method was selective and limited; actually the values obtained were only representative of the few runs used to obtain results.* As evidence of this, calculations using all of Salamone's data gave a value of 0.72 compared with a value of 0.57 to 0.62 obtained by Salamone for the exponent of Reynolds number group. The range of this value manifests the inadequacy of the method upon which the Salamone correlations are predicated.

Inspection of the final Correlation Plot (FIG. 10) on which is plotted data of Salamone, Binder-Pollara and these authors, reveals the complete disagreement of the Binder-Pollara data with the bulk of the data obtained by Salamone and these authors.

*From page 59 Salamone Thesis, "There is no theoretical justification for the broken line of Fig. 21 as this suggests that the error lies in the slope and intercept."

Furthermore, it may be noted that the data below Reynolds number of 50,000 correlates satisfactorily when the Binder-Pollara data is disregarded. The bulk of Binder-Pollara data, although in disagreement from the bulk of data, does show symmetry; sufficiently to induce the conclusion that a constant error must have been committed in experimental technique.

## SUMMARY AND CONCLUSIONS

Although water suspensions of solid particles such as chalk, and iron oxide behave as pseudoplastic non-Newtonian materials in that viscosity decreases with increasing flow rate to a limiting value, the results of this investigation show that the viscosity is not as critical as previously believed. This is evidenced by noting the values of the exponents of the Prandtl and Reynolds groups.

In using this expression for design, if a method is devised for estimating viscosity, then the viscosity obtained may be used for calculation of film coefficient. If the viscosity used is within approximately 15% of the actual, this deviation will lead to little error.

The final equation developed (equation 4) is now based upon more than two hundred runs of slurries composed of a rather large variety of physical properties. The bulk of the data falls within 12% of the mean of these points; well within the limits of the accuracy to be expected in an investigation of this nature. Hence, the equation developed can be used in the design of heat transfer equipment for slurries and reasonable degree of accuracy can be expected. It has been mentioned by Salamone that the equation may be used with equal success with pipelines varying from 3/8" to 1½" dia. (I.P.S.).

Caution should be exercised in using the developed equation for design purposes, especially when using suspending mediums other than water. Still another case that requires particular caution is the one when high slurry concentrations are used. From the work conducted it is reasonably certain that materials of about 2.4 density or less could be safely used in slurry concentration up to approximately 20%. Not enough data is available for predicting the upper limit of concentration when materials of higher density are used, and as a consequence this phase offers considerable room for further investigation.

These authors feel that the amount of data above 50,000 Reynolds number is presently sufficient to formulate the conclusions herein drawn regarding water suspensions of solids, but are fully aware of the fact that the range below 50,000 Reynolds number presents considerable work for future investigations.

Furthermore, a great deal of work is to be done using suspending mediums other than water. Due to the extensive industrial applications which could result, it is suggested that hydrocarbon oils might be good suspending mediums to begin with.

## LIST OF SYMBOLS AND UNITS

a. . . . . . . . . . . . . . Constant, dimensionless.

A. . . . . . . . . . . . . . Heat transfer surface, sq.ft.

b. . . . . . . . . . . . . . Constant, no dimensions.

B. . . . . . . . . . . . . . Square feet of suspended solid surface per unit volume of slurry, sq.ft./cu.ft.

C, $C_f$. . . . . . . . . . . Specific heat of fluid or suspending medium, BTU/($LB_m$($^oF$).

$C_s$ . . . . . . . . . . . . Specific heat of suspended solid, BTU/($LB_m$) ($^oF$)

D. . . . . . . . . . . . . . Pipe diameter, ft.

$D_s$ . . . . . . . . . . . . Average diameter of suspended solid particles, ft.

e. . . . . . . . . . . . . . Constant, dimensionless.

f. . . . . . . . . . . . . . Friction factor, dimensionless, constant, no dimensions.

g. . . . . . . . . . . . . . Constant, no dimensions.

$g_c$ . . . . . . . . . . . . Dimensional constant, 32.2 ($LB_m$) (Ft.)/($LB_f$) $(SEC)^2$.

h. . . . . . . . . . . . . . Film coefficient of heat transfer, BTU/ (HR)-(Sq.ft.) ($^oF$).

i. . . . . . . . . . . . . . Constant, dimensionless.

j. . . . . . . . . . . . . . Constant, dimensionless.

K, $K_f$. . . . . . . . . . . Thermal conductivity of fluid or suspending medium. BTU/(HR) ($^oF$) (Ft.).

$K_b$ . . . . . . . . . . . . Bulk thermal conductivity of suspension, BTU/(HR) ($^oF$) (Ft.).

$K_e$ . . . . . . . . . . . . Effective thermal conductivity of suspension, BTU/(HR) ($^oF$) (Ft.).

$K_s$ . . . . . . . . . . . .Thermal conductivity of suspended solid, BTU/(HR) (°F) (Ft.).

L. . . . . . . . . . . . .Length of pipe, ft., any linear dimension.

M. . . . . . . . . . . . .Any mass dimension.

N. . . . . . . . . . . . .Constant, dimensionless.

$\Delta$ P. . . . . . . . . . . .Pressure drop over a length of pipe, lbs./sq.ft.

q. . . . . . . . . . . . .Heat transfer rate, BTU/Hr.

r. . . . . . . . . . . . .Constant, dimensionless.

t. . . . . . . . . . . . .Temperature, °F, any temperature dimension.

$\Delta t_m$ . . . . . . . . . . . .Logarithmic mean temperature difference between average inside pipe surface temperature and inlet and outlet slurry temperature, °F.

v. . . . . . . . . . . . .Linear velocity, ft/sec.

$v_b$ . . . . . . . . . . . .Linear velocity of suspension, based on the bulk density of the suspension ft/sec.

x. . . . . . . . . . . . .Weight fraction of solid.

Z. . . . . . . . . . . . .Constant, dimensionless.

$N_u$ . . . . . . . . . . . .Nusselt number, h D/k, dimensionless.

$P_r$ . . . . . . . . . . . .Prandtl number, $C_f\mu/k$, dimensionless.

Re . . . . . . . . . . . .Reynolds number, DV $\rho_b/\mu_b$, dimensionless.

$\phi$ . . . . . . . . .Volume fraction of solid.

$\phi'$ . . . . . . . . .Volume fraction of solid in sedimented bed.

$\rho$, $\rho_f$ . . . . . . . . .Density of fluid, $LB_m$/cu.ft.

$\rho_b$ . . . . . . . . .Bulk density of suspension, $LB_m$/cu.ft.

$\rho_s$ . . . . . . . . Density of solid, $LB_m$/cu.ft.

$\mu$ . . . . . . . . Viscosity of fluid.

$\mu_w$ . . . . . . . . Viscosity of fluid at wall temperature.

$\mu_B$ . . . . . . . . Apparent bulk viscosity of suspension.

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# APPENDIX

# SAMPLE CALCULATIONS

## SAMPLE RUN NO. 49 (No. 1 White) *

1. **SLURRY DENSITY:** Weight Of Water @ 65°C To Fill Volumetric Flask = 8.6 Lbs.

$$\text{Slurry Density} = 62.37 \frac{(8.938)}{8.5} = 65.6 \text{ Lbs./Ft.}^3$$

2. **WEIGHT % SOLIDS:** $65.6 \text{ Lbs./Ft.}^3 = \frac{65.6}{62.43} \text{ gm/cc} = 1.05 \text{ gm/cc}$

From Fig. 2 Wt. % Chalk = 11.3%

3. **MEAN SPECIFIC HEAT:** $= 1 - (1 - C_s)x$

$$= 1 - (1 - 0.21).113 = 0.9108$$

4. **FLOW RATE:** = 124.0 Lbs./Min.

5. **SLURRY HEAT:** = q = (Rate) (Temp.Rise) (SP.HT.)

$$= (124.0)\ (60)\ (1.8)\ (71.50 - 50.60)\ (0.9108)$$

q = 256,000 BTU/HR.

6. **VISCOMETER FRICTION FACTOR:**

$$\Delta P = \frac{47.75}{12} (62.4)\ (2.9638 - 0.995) = 489 \text{ Lbs/Sq. Ft.}$$

$$f = \frac{\Delta P}{\rho_b} \quad \frac{D}{L} \quad \frac{2\,gc}{V_b^2} \qquad \text{where } V_b = \text{Rate}/60\ (\text{Area})(\rho_b)$$

$$f = \frac{(64.4)\ (489)\ (65.6)\ (0.622/12)^5}{(6.95)\ (6.0)}$$

$$f = 0.01850$$

$$V_b = \frac{124}{60\ (0.785)\ D^2\ \rho_b}$$

$$V_b = 2.64/D^2\ \rho_b$$

* Calculations Of Water Runs The Same

SAMPLE CALCULATIONS (CONT'D)

7. APPARENT VISCOSITY:

$$\frac{1}{\sqrt{f}} = \frac{1}{\sqrt{0.01850}} = 7.35$$

From Fig. 4 $\quad Re.\sqrt{f} = 12.50 \times 10^3$

$$Re. = 12.50 \times 10^3 / \sqrt{0.01850} = 91{,}800 = \frac{DV_b \rho_b}{\mu_b}$$

$$\mu_b \text{ (Viscometer)} = \frac{D \left(\frac{2.64}{\rho_b D^2}\right) (\rho_b)}{0.000672 \ (91{,}800)}$$

$$= \frac{2.64}{0.000672 \ (0.622/12) \ (91{,}800)}$$

$$= 0.829 \text{ CP.}$$

Average Temp. In Heat Section = 61.05°C
Viscometer Temp. = 60.6°C
Viscosity Water At 61.05°C = 0.4618 CP.
Viscosity Water At 60.6°C = 0.4645

$\mu_b$ Corrected To Heat Sect. Temp. $= 0.829 \times \frac{.4619}{.4645} = 0.820$ CP.

8. HEAT SECTION REYNOLDS NUMBER:

$$Re = \frac{DV_b \rho_b}{\mu_b} = \frac{D \left(\frac{2.64}{D^2 \rho_b}\right) (\rho_b)}{\mu_b}$$

$$= \frac{2.64}{0.000672 \ (0.820) \ (0.622/12)}$$

$$= 92{,}800$$

## SAMPLE CALCULATIONS (CONT'D)

### 9. EXPERIMENT FILM COEFFICIENT OF HEAT TRANSFER:

$h = q/A \Delta t_m$

$q = 256{,}000$ BTU/HR. (See Calc.5)

$A = (3.14)\ (0.622/12)\ (8.0) = 1.30\ FT.^2$

(Theor.) or $1.30 \times 1.0625 = 1.38$

(Mill Tolerance Can Give Thickness 12.5 % Less Or Average 6.25 % Less)

Arithmetic Average Of All Millivolt Readings Is 4.047 MV. Equivalent To An Outer Surface Temperature Of 207.86°F

$$\text{Drop In Temp. Across Wall } ^\circ F = \frac{q\ (\text{Pipe Wall Thick.})}{K_{Metal}\ A_{Average}}$$

K For Brass = 90 BTU/(HR.) (°F) (FT.)

$$^\circ F = \frac{(256{,}000\ (0.109/12)}{(90)\ (1.38)\ (0.731/0.622)} = 16.0^\circ F$$

Average Inner Temperature $207.86 - 16.0 = 191.86^\circ F$

$$\Delta t_m = \frac{(191.86 - 123.10) - (191.86 - 160.70)}{\ln \dfrac{191.86 - 123.10}{191.86 - 160.70}}$$

$\Delta t_m = 47.7^\circ F$

$h = 256{,}000 / (1.38)\ (47.7)$

$h = 3880$ BTU/(HR.) (SQ.FT.) (°F)

SAMPLE CALCULATIONS (CONT'D)

10. EFFECTIVE THERMAL CONDUCTIVITY:

For Re. = 92,800 Ordinate Of Fig. 3 = 265

$$265 = (hD/K_e) / (C_b \mu_b / K_e)^{0.4}$$

$$K_e = \left( \frac{1}{265} \frac{(hD)}{(C_b \mu_b)^{.4}} \right)^{1.667}$$

$$K_e = \left\{ \frac{1}{265} \frac{(3880)\ (0.622/12)}{(0.9108)\ (0.820 \times 2.42)^{0.4}} \right\}^{1.667}$$

$$K_e = 0.427 \text{ BTU/(HR.) (FT.) } (^{\circ}F)$$

11. CALCULATED FILM COEFFICIENT USING DEVELOPED EQUATION:

$$\frac{hD}{K_f} = 0.0138 \left( \frac{DV_b \rho_b}{\mu_b} \right)^{0.8} \left( \frac{C_f \mu_b}{K_f} \right)^{0.79} \left( \frac{K_s}{K_f} \right)^{0.05} \left( \frac{C_s}{C_f} \right)^{0.42} \left( \frac{D}{D_s} \right)^{0.106}$$

$$\frac{h\ (0.622/12)}{(0.373)} = 0.0138\ (92.8 \times 10^3)^{0.8} \left[ \frac{(1.00)\ (0.820 \times 2.42)}{0.373} \right]^{0.79} \left[ \frac{(0.40)}{0.373} \right]^{0.05} \left[ \frac{(0.209)}{1.00} \right]^{0.42} \left[ \frac{(0.622/12)}{(4.61 \times 10^{-5})} \right]^{0.106}$$

$$h = 3840 \text{ BTU/(HR.) } (^{\circ}F) \text{ (SQ.FT.)}$$

## TABLE NO. IX

The following table shows the combination of runs used in determining various exponents for the equation of this report by the method described under section marked "Correlation."

### REYNOLDS NUMBER EXPONENT

**ATOMITE**

Runs: 1 and 3, 5 and 7, 9 and 11, 13 and 15 - Averaged For Equation 1

Runs: 2 and 4, 6 and 8, 10 and 12, 14 and 16 - Averaged For Equation 2

Equation 1 and 2 solved simultaneously yield exponent 0.777

**SNOWFLAKE**

Runs: 17 and 19, 21 and 23, 25 and 27, 29 and 39, 33 and 35

Averaged For Equation 1

Runs: 18 and 20, 22 and 24, 26 and 28, 30 and 32, 34 and 36, 38 and 40

Averaged For Equation 2

Equation 1 and 2 solved simultaneously yield exponent 0.785

**No. 1 WHITE**

Runs: 41 and 43, 45 and 47, 49 and 51 - Averaged For Equation 1

Runs: 42 and 46, 48 and 50, 52 and 55 - Averaged For Equation 2

Equation 1 and 2 solved simultaneously yield exponent 0.837

**IRON OXIDE**

Runs: 57 and 59, 61 and 63, 65 and 67, 69 and 71 - Averaged For Equation 1

Runs: 56 and 58, 60 and 62, 64 and 66, 68 and 70, 72 and 74

Averaged For Equation 2

Equation 1 and 2 solved simultaneously yield exponent 0.790

PRANDTL GROUP EXPONENT

Using equations developed from groupings listed under Reynolds Number Exponent above, an exponent of 0.79 is obtained for this group.

$D/D_s$ GROUP

SNOWFLAKE - No. 1 WHITE

Runs: 17 and 41, 22 and 50, 24 and 43, 26 and 51

ATOMITE - No. 1 WHITE

Runs: 1 and 41, 15 and 50, 3 and 43, 12 and 51

Solving simultaneously yields exponent For $D/D_s$ 0.106

$C_s/C_f$ and $K_s/K_f$ GROUPS

ATOMITE

Runs: 1, 15, 3, 12

IRON OXIDE

Runs: 57, 61, 65, 71

SALAMONE COPPER "B"

Runs: 57, 61, 62, 64

SNOWFLAKE

Runs: 17, 22, 24, 26

Solving three simultaneous equations yields the following exponents:

$\left(\frac{C_s}{C_f}\right)$ Exponent = 0.42

$\left(\frac{K_s}{K_f}\right)$ Exponent = 0.05 (Rounded From 0.047)

$Z$ (Intercept) = 0.0131