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SUBJECT: PROPOSED SYSTEM FOR ATMOSPHERIC
PRESSURE SLURRY HEAT TRANSFER STUDIES

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I. Literature Review

There are four published studies of the heat transfer characteristics of non-Newtonian fluids.

Bonilla, et al¹, studied heat transfer characteristics of 0 to 18 wt. per cent chalk-water suspensions at Reynolds numbers from 9×10^3 to 3×10^5 . The slurry heat transfer coefficient was $1/3$ that of water at the highest concentrations and lowest Reynolds numbers and approached that of water at the highest concentrations and highest Reynolds number. No shear diagrams were measured and calculated viscosities were used to correlate the data.

Orr and DallaValle² studied the heat transfer characteristics of powdered aluminum, powdered copper, glass beads, Attapulugus clay, and graphite suspended in water and graphite and powdered aluminum suspended in ethylene glycol. Data were taken over a range of Reynolds numbers from 3×10^3 to 3×10^5 and were correlated using an empirical Newtonian viscosity.

Metzner, et al³, studied the heat transfer characteristics of Carbopol and carboxymethyl cellulose solutions over a range of Reynolds numbers from 1 to 10^4 . The experimental data were correlated assuming the fluids were pseudo plastic; however, it appears that the shear diagrams could be fitted equally well with the Bingham plastic relation. This should be done and the correlations proposed by Pigford⁵ and Bailey⁶ for Bingham plastic laminar flow heat transfer should be tested.

Lawson proposed⁴ that heat transfer data for non-Newtonian Bingham plastic slurries in turbulent flow could be correlated with the expression

$$\left(\frac{h}{C_p G}\right) \left(\frac{C_p \eta}{k}\right)^{2/3} = \frac{f}{2} \left(1 - \frac{\tau_y}{\tau_w}\right)^n \quad (1)$$

and suggested on the basis of a momentum-heat transfer analogy that $n = 5/3$.

Lawson confirmed⁷ the validity of Equation 1, using a highly flocculated thorium oxide slurry; however, an exponent of 3 was found to give a better fit to the data. A plot of Lawson's experimental data is given in Fig. 1. Curve A is drawn through data taken with a thorium oxide slurry having a yield stress, τ_y , of 0.16 lb/sq ft and a coefficient of rigidity, η , of 1.4 centipoise; curve B is drawn through data taken with a thorium oxide slurry having a yield stress of 0.34 lb/sq ft and a coefficient of rigidity of 2.0 centipoise; curve C is drawn through data taken with the slurry of curve B after it was deflocculated with sodium silicate; and curve D is drawn through data taken with water. All of Lawson's data were taken in a black iron system over a velocity range of 9 to 25 ft/sec, a single venturi being used for velocity measurements. The Wilson plot method was used to evaluate the heat transfer coefficients.

II. Discussion of Literature

The data of Bonilla, et al., and of Orr and DallaValle give qualitative indications that at low velocities the heat transfer coefficients of Newtonian slurries may be lower than those of water. No information is given that can be applied to the heat transfer characteristics of non-Newtonian slurries.

The data of Metzner, et al., may be of some assistance in testing proposed correlations for heat transfer to Bingham plastics in laminar flow. No other data have been published on laminar flow heat transfer characteristics of Bingham plastics.

The theory and data of Lawson show that the turbulent heat transfer characteristics of Bingham plastics may be correlated by using their measured rheologic properties. However, more and better data are needed in order to test the generality of Lawson's theory and to obtain quantitative information concerning the relationship between the slurry physical properties and the heat transfer characteristics and possible effects of system geometry on this relationship.

III. Proposed Heat Transfer System

The proposed heat transfer system is shown in Fig. 2 with details of the heat exchanger and mixing chamber shown in Figures 3 and 4. The system is to be constructed from two-inch ID copper pipe except for the one-inch and one-quarter inch ID heat exchanger sections. A 100 gpm Moyno pump (from Y-12 salvage) with a steel rotor and medium-hard rubber stator will be tested for use in this system^a. The pressure drop around the one-inch heat exchanger system was estimated for various velocities through the one-inch pipe as

<u>VELOCITY</u> <u>ft/sec</u>	<u>SYSTEM Δp</u> <u>lb/sq in.</u>
10	10
20	37
30	83
40	148

The particular advantages of the proposed system include:

1. The copper heat exchange section will give data more suited to Wilson plot interpretation and will allow one to distinguish whether the very high coefficients of curve A (Figure 1) are indeed real or an inaccuracy as a result of subtracting two large numbers that are very nearly the same.
2. The weigh tank on the slurry stream will give an accurate measure of the velocity over the complete range of velocities to be studied.
3. The weigh tank on the steam condensate line from the inner heat exchange jacket will give an independent check of the overall heat transfer coefficient as determined from the axial Δp and the slurry flow rate.
4. Thermocouples imbedded in the heat exchanger tube walls will give an estimate of the slurry heat transfer coefficient independent of the Wilson plot method.

^aMoyno pumps have been used in ThO_2 -slurry systems at Harwell, England,⁸ and are being tested for similar use at Westinghouse.

5. The two tube diameters (one-quarter inch ID and one-inch ID) bracket the expected range of heat exchanger tube diameters.
6. The variable L/D ratio of the two tubes allow the study of these parameters in the laminar flow range.
7. If the Moyno pump proves satisfactory for use with slurries, the maximum velocity in the one-inch tube would be 37 ft/sec and the variable speed drive would allow velocities as low as 12 ft/sec. By splitting the flow through the by-pass line, the minimum velocity would be that necessary to initiate flow in the Bingham plastic systems to be studied.

The slurry will be cooled by copper coils immersed in the 50 gallon tanks. Three tanks are provided so that the system may be flushed with water without removing the slurry from the storage tank. Quick opening valves are to be used throughout the system except for the valve on the slurry by-pass line.

Rotational viscometer data will be taken during a series of tests in order to demonstrate the uniformity of slurry properties; however, the rheological properties used in correlating the data will be obtained from capillary tube viscometer data.

It is of primary importance that the Moyno pump be given a complete test on slurries. The first construction on the loop will be the storage tanks and the installation of the pump so that the pump testing can then be started.

IV. Estimated Operating Characteristics of Proposed Heat Transfer System

The heat transfer coefficient for a Bingham plastic thorium oxide slurry flowing through a 1/4-inch ID and 1-inch ID copper tube was calculated from Lawson's equation (Equation 1) for turbulent flow and from the equation recommended by Bailey (Equation 2):

$$\frac{h_{am} D}{k} = 1.615 \left(\frac{V_{pc} D^2}{kL} \right)^{1/3} \left(1 + \frac{g_c \tau_y D}{24 \eta V} \right)^{1/3} \quad (2)$$

for laminar flow. The slurry properties were taken as

$$\tau_y = 0.5 \text{ lb/sq ft.}$$

$$\eta = 2 \text{ centipoise}$$

$$\rho = 1.7 \text{ gram/cc}$$

$$k = 0.49 \text{ BTU/(hr) (ft) (}^\circ\text{F) Ref 9.}$$

$$c = 0.54 \text{ BTU/(lb) (}^\circ\text{F) Ref 9.}$$

The results of the calculation are shown in Figure 5. Calculated turbulent heat transfer coefficients for water are included for comparison purposes. The velocity corresponding to the transition from laminar to turbulent flow was estimated from the Hedstrom plot as ~ 5 ft/sec for both tube diameters.

Estimated heat fluxes, axial and radial temperature drops for slurry flowing at 10 and 40 ft/sec are shown in Table I. As can be seen the slurry film is controlling at the low velocity while the steam film controls at the high velocity.

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TABLE I

CALCULATED HEAT FLUXES AND AXIAL AND RADIAL TEMPERATURE
DROPS FOR PROPOSED HEAT EXCHANGE APPARATUS

Mean Slurry Velocity, ft/sec	Mean ΔT , $^{\circ}F$	Mean Slurry Temp., $^{\circ}F$	Steam Coeff., BTU (hr)(sq ft)($^{\circ}F$)	Slurry Coeff., BTU (hr)(sq ft)($^{\circ}F$)	Slurry Film ΔT , $^{\circ}F$	Overall Coeff., BTU (hr)(sq ft)($^{\circ}F$)	Heat Flux, BTU hr	Axial ΔT , $^{\circ}F$
10	70	180	3,000	115	67	110	34,000	2.4
40	70	180	1,600	17,000	6.5	1,555	478,000	8.5

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Fig. 2 PROPOSED SLURRY HEAT TRANSFER SYSTEM

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Fig. 3 HEAT EXCHANGER

Fig. 4 MIXING CHAMBER

Fig. 5 CALCULATED SLURRY HEAT TRANSFER COEFFICIENTS

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