BATCH HEAT TRANSFER TO SUSPENSIONS IN AN AGITATED VESSEL

BY

JOHN PHILIP HORZEPA

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JOHN PHILIP HORZEPA

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FACULTY COMMITTEE

APPROVED: ______________________

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ABSTRACT

Batch heat transfer data was experimentally determined for two phase (solid-liquid) systems in a baffled agitated vessel. Three iron oxide and water and two kaolin and water suspensions were evaluated and were found to be pseudoplastic. A total of 231 heating and cooling data points were examined. Each suspension was evaluated using anchor, paddle, propeller and turbine impellers. Various sizes of the latter three impellers were used.

The experimental heat transfer results for suspensions were compared with the Hagedorn and Salamone correlation for pseudoplastic liquids. Only partial agreement with the more dilute suspensions was obtained. Overall, the data for suspensions was shown to deviate as a function of weight percent solids. A dimensionless factor, weight percent liquid divided by weight percent solids, was evaluated which may be used to modify the above mentioned correlation and thus extend its usefullness to two phase systems.

INTRODUCTION

A considerable amount of batch heat transfer information is available in the literature for non-Newtonian liquids. However, there is a paucity of information concerning non-Newtonian suspensions of solids in liquid. These suspensions, however, are receiving ever increasing attention because of the growing necessity for such heat transfer data in the chemical industry.

The most common type suspensions are those based on an aqueous medium. The purpose of this thesis was to determine batch heat transfer coefficients for water based suspensions. Two different solid-water systems were investigated. The system of iron oxide and water was evaluated at 13.1, 24.0 and 33.2 weight percent solids. The system of kaolin and water was evaluated at 18.4 and 24.4 weight percent solids.

These systems were studied in an agitated jacketed vessel. Batch side surface heat transfer coefficients were investigated under various sizes of four basic types of impellers. Anchor, paddles, propellers and disc and vane turbines were studied.

Another purpose of this work was to compare the experimental data with a previously determined correlation for pseudoplastic liquids. Generally speaking, the overall value of the present experimental work could be put to better use through a modification of a previously determined correlation. Therefore, the ultimate correlation would be applicable for a broader range of pseudoplastic systems.

THEORY

Viscosity

This thesis concerns itself with the investigation of jacketed batch heat transfer to suspensions in an agitated vessel. The amount of mixing accomplished depends on the impeller geometry and speed and also on the flow properties of the material under investigation. It is commonly accepted that flow properties may be classified under two broad headings:

1. Newtonian
2. Non-Newtonian

The Newtonian fluids obey the law that shear stress (τ) divided by shear rate ($\dot{\gamma}$) equals a constant. Shear stress is the unit area force necessary to move two parallel planes separated by a small distance of fluid at a given velocity. The shear rate is the relative velocity gradient between the two planes.

Non-Newtonian fluids can be further subdivided into the following categories:

1. Time independent
2. Time dependent
3. Viscoelastic

Of the three, the time independent fluids are probably the most important industrially and are commonly known as pseudoplastic and dilatent fluids. The time independent fluids do not obey the above Newtonian law. Instead shear stress will increase more than a direct proportion with strain for dilatents and less for pseudoplastics. The shear stress at a given shear rate does not change with time for dilatents and pseudoplastics.

Many times a given fluid may behave differently at different shear rates. A fluid may be pseudoplastic at low shear rates, Newtonian at higher shear rates, and eventually may become dilatent at still higher shear rates.

This thesis concerns itself with pseudoplastic materials which can be characterized by the power law equation, first proposed by Ostwald[23]:

$$\tau = k \gamma^{n} \qquad (1)$$

Where n equals the flow behavior index and k is the fluid consistency index. For pseudoplastic fluids the value of n lies between 0 and 1. The more pseudoplastic the material the lower its n value. For Newtonian fluids n = 1 and

$$\tau / \gamma = k \qquad (2)$$

Therefore, k for Newtonians is equal to viscosity (μ). The values n and k can be experimentally determined.

The Einstein formula has been used to determine the viscosity of suspensions.

$$\mu_r = \mu_s/\mu_f = 1 + 2.5\, X_v \qquad (3)$$

Where μ_r is relative viscosity and X_v is the volume fraction of the suspended solid. The suspension's viscosity and the viscosity of the fluid phase are represented by μ_s and μ_f respectively.

Among others the formula assumes the following:

1. Particles are rigid spheres
2. Dilute suspensions
3. Negligible interaction between particles

Therefore, according to the Einstein formula, suspensions of particles dispersed in a Newtonian medium should exhibit Newtonian behavior.

However, the formula applies best to solids in suspension which have specific gravities similar to the suspending medium. High specific gravity solids will tend to settle from the liquid medium if no agitation is supplied. High concentrations of solids, especially non spherical particles will interact with one another. Such systems will often show non-Newtonian behavior and the Einstein formula will not apply. Thus the rheological properties of a suspension are determined to a large extent by the solids concentration and properties.

Therefore, suspension of a solid at low concentrations in a Newtonian medium will tend to be Newtonian and obey the Einstein formula. As the concentration is increased so will particle interactions. This will lead in many cases to the suspensions becoming non-Newtonian and the viscosity will increase at a greater rate than predicted by the formula. The suspension will probably begin exhibiting pseudoplastic or thixotropic behavior. As the solids concentration is raised to high levels dilatency may even occur.

One might also expect that the rheological properties of a given suspension might be a function of the shear rate. For low shear rates there would be little interaction between particles and Newtonian behavior would follow. At increasingly higher shear rates particle interaction would become more important and non-Newtonian flow would result. Goodeve(8) assumed that the non-Newtonian behavior was due to the destruction at increasing shear rates of the internal structure due to internal linkage.

Skelland[23] reports that pseudoplastic behavior for suspensions is consistant with the existence of highly solvated particles. Higher shear rates progressively strip away solvated layers resulting in a smaller effective particle size and thus less interaction and lower apparent viscosities. At low shear rates this effect might be minimized and allow for Newtonian behavior.

Suspensions have also been shown to exhibit a time dependent relationship, either thixotropic or rheopectic. This phenomenon could occur for non spherical particles. At the beginning of a given shear rate the suspension would exhibit a certain shear stress. The suspended particles would then begin to reorient themselves to the flow. Plate like particles might reorient themselves from a random arrangement to a parallel orientation. Thus the shear stress would tend to change with time. Cessation of the shearing rate would allow the particles to resume their randomness. This type of suspension would exhibit a viscosity hysterisis loop.

The rheological behavior of the suspensions studied in this work were found for the most part to be pseudoplastic. This is in agreement with the findings of Williamson[6] who reported that the majority of suspensions exhibit shear thinning behavior.

Batch Heat Transfer

Batch heat transfer is a common industrial process. It concerns itself with the transfer of heat to or from a liquid contained in a vessel such as a kettle or tank. The transfer of heat takes place between two discrete streams which normally never come into direct physical contact. The heat transfer takes place through a solid boundary which may be pipe coil wall or the vessel wall itself. The latter type of transfer is commonly called jacketed heat transfer.

The principal heat transfer mechanisms between the vessel wall and the fluid batch is by conduction and convection.[12,4] Conduction takes place when heat flows by momentum transference without mixing. Convection is heat flow by mixing and turbulence. Heat must pass into the fluid by conduction before heat transfer can occur by convection. Natural convection occurs because of a density change in the fluid which causes it to either rise or fall causing currents within the fluid.

Natural convection can be greatly facilitated through mechanical agitation. This is known as forced convection and can be accomplished through a moving impeller or by pumping and recycle. Indeed, batch heat transfer can be shown to be a function of the amount of mixing.

It has long been known (17) that even with turbulent forced convection there still exists a thin quiescent "film" of liquid near the heat transfer surface. The major temperature drop between the vessel wall and batch occurs through this thin film. The thickness of this laminar layer of film can be controlled by the degree of agitation of the main fluid batch. The degree of turbulence in the batch can be characterized by a dimensionless group known as the Reynolds number.

$$N_{Re} = D_a^2 \, N \rho / \mu \qquad (4)$$

Where D_a = impeller diameter; N = impeller revolutions; ρ = batch fluid's density; and μ = the fluid's viscosity. The higher the Reynolds number the thinner will be the laminar film and the higher will be the heat transfer coefficient.

The laminar film thickness cannot be readily determined. However, the rate of heat flow between the vessel wall and the batch can be by the following relationship:

$$dQ/dA = H\ (T_W - T_b) \tag{5}$$

where H is defined as the film heat transfer coefficient; and dQ/dA is a local heat flux density over the heat transfer area; and $T_W - T_b$ represents the temperature difference between the wall and batch, respectively.

Frantisak and Valchar(7) have derived fundamental equations for two phase systems. The equations of continuity, momentum, and energy were developed with certain controlling assumptions. They assumed among others that solid-solid interactions are negligible, mass forces are negligible, two dimensional flow, and that the slip between the solid particles and liquid are negligible. However, the resulting equations were still unsolvable because of the many remaining unknown variables.

As previously stated, theoretical developments in the field of batch mixing and heat transfer have been limited. This mainly results from the complexities of defining the fluid motions involved. Most studies have been empirical correlations developed through dimensional analysis. These have generally resulted in the following general type relationships:

$$\frac{H\,D_t}{K} = \left(\frac{D_a^2\,N}{\mu}\right)^x \left(\frac{C\,\mu}{K}\right)^y \left(\frac{\mu}{\mu_w}\right)^z \qquad (6)$$

LITERATURE SEARCH

A search was made into the available literature to determine previous investigators who have studied non-Newtonian suspensions. A substantial amount of work was found which could be used to characterize rheological properties. However, there is quite a lack of quantitative data pertaining to batch heat transfer properties of non-Newtonian suspensions.

Viscosity

Perry[17] states that the majority of non-Newtonian materials are pseudoplastic. These materials include polymeric solutions, melts, and suspensions of paper pulp or pigments. Perry[17] states further that for suspensions of finely divided particles, less than 50 microns, the flow properties will behave very similar to a single phase fluid and the flow properties can be treated as such. Skellend[23] gives an excellent review of non-Newtonian rheology.

There are many types of viscometers available. However, most are best suited for quality control work and are not readily adaptable to scientifically investigate rheological properties. Skelland[23] aptly describes four types of viscometers suitable for engineering studies:

1. Capillary tube
2. Rotary concentric tube
3. Rotating cylinder in an infinite media
4. Cone and plate

The rotating cylinder in an "infinite" medium is the simplest of the viscometers to use. This type of viscometer is readily available and has been used by other investigators(5,23,9) to correlate with batch mixing. The rotational viscometer has been found suitable for systems obeying the power law equations.

The shear rate at the bob surface can be calculated from:

$$\gamma = 4\pi N/n'' \tag{7}$$

and the shear stress from:

$$\tau = T/2\pi R^2 h \tag{8}$$

where T = torque; R = bob radius; N = bob revolutions; and h = bob height.

Since we know that apparent viscosity is equal to shear stress τ, divided by shear rate γ, we can solve the equation:

$$\tau = k(\gamma)^n \tag{1}$$

for apparent viscosity and get:

$$\mu_a = k(\gamma)^{n-1} \tag{9}$$

Mixing

Perry[17] states that a mixer will do two things within a vessel: fluid circulation and fluid shear. An operating impeller will impart a certain shear rate to the fluid leaving the tips of the mixer. This results in a certain shear stress. The impeller pumping capacity maintains the solids in suspension. The shear rate will be greatest at the impeller and least at the vessel wall. This is especially true at low D_a/D_t ratios. The opposite occurs in pipes where the shear rate is greatest at the wall.

Various correlations have been developed to predict shear rates in an agitated vessel. Metzner and Taylor[13] showed that local shear rates in an agitated vessel were directly proportional to impeller speed for both Newtonian and non-Newtonian systems. This was shown by observing the motions of small particles in an agitated vessel. These studies supported earlier work by Metzner in which the following relationship was postulated:

$$\gamma = kN \tag{10}$$

which states that shear rate is a direct function of impeller speed N. Subsequent experimental work using various impellers resulted in k values between 10 and 13 with the average value being 11.5. Thus the apparent viscosity for pseudoplastic systems can be defined as

$$\mu_a = k \quad (11.5N)^{n-1} \tag{11}$$

where k = the fluid consistency index; and n is the flow behavior index. This shear rate value agrees very closely with the value $4\pi N$ used in rheological work to describe fluid motion using cylindrical bobs.

Suspension Properties

In order to study heat transfer to non-Newtonian suspensions an overall value for the density, specific heat, thermal conductivity and rheological properties of the system must be obtained.

The density and specific heat of each component can be determined or found in the literature. Both density and specific heat can be considered as additive properties by weight averaging.[(23)] Orr and Dalla Valle[(16)] found this to be the case in their heat transfer studies to suspensions.

Thermal conductivity cannot be handled as a weighted average. One of the earliest works on the thermal conductivity of suspensions was done by Tareef[25] who postulated that thermal conductivity is analogous to that of electrical conductivity. Therefore, his method of finding the thermal conductivities of suspensions was based on a thermal analog for Maxwell's equation for electrical conductivities:

$$K_b = K_f \quad \frac{2K_f - K_{s'} - 2X_v \ (K_f - K_{s'})}{2K_f + K_{s'} + X_v \ (K_f - K_{s'})} \qquad (12)$$

where K_b represents the entire batch suspension and K_f and $K_{s'}$ are the thermal conductivities of the fluid and solid, respectively, and X_v is the solids volume fractions. This equation has been checked by other investigators[16] and found to give good agreement compared to experimental determinations.

<u>Heat Transfer</u>

Batch heat transfer to fluids in agitated vessels is a common industrial practice. Most of the earlier correlations were developed to correlate heat transfer data for various basic impeller types. Most workers have developed correlations similar to the following:

$$N_{Nu} = C \ N_{Re}^{b} \ N_{Pr}^{c} \ N_{V}^{d} \qquad (13)$$

For Newtonian fluids the generally accepted constants for the Reynolds and Prandtl numbers have been:

$$N_{Re} = 2/3$$

$$N_{Pr} = 1/3$$

The viscosity term N_V was originally used by Sieder and Tate[22] to correlate heat transfer data in pipes. N_V is the ratio of the batch fluid viscosity at the wall temperature to that of the bulk batch fluid viscosity at the batch temperature.[4] The coefficient of the viscosity term has not been as clearly defined as the first two. The value of C has generally been found to be a function of the impeller type and also, probably the system's geometry.

This type of dimensional analysis has been resorted to because of the unwielding complexities involved in defining the parameters associated with batch mixing. Hagedorn[9] gives an excellent summary of past heat transfer investigations. This type of work has also been reviewed by Chapman and Holland.[4]

A number of studies have been made characterizing the heat transfer to aqueous slurries in pipes[24, 16, 19]. These studies were usually dimensional analysis type correlations in which the slurries were characterized according to solids content and physical properties of the solids.

Bonilla[3] studied heat transfer to suspensions in pipes. Bonilla reported that a plot of $N_{Nu}/N_{Pr}^{1/3}$ versus N_{Re} for chalk water slurries decreased as a function of increasing solids content. Bonilla made some simplifying assumptions, such as using the thermal conductivity of the fluid medium only and also he calculated his viscosities from a theoretical relationship.

Orr and Dalla Valle[16] also studied heat transfer in pipes to solids suspended in water and ethylene glycol. Calculated values were used for viscosity, these values were checked with a Saybolt type viscometer and were reported to be Newtonian. They also successfully experimentally checked Tareef's electrical analog method of determining thermal conductivities of suspensions.

J.J. Salamone[19] theoretically studied heat transfer to non-Newtonian suspensions in pipes. Through dimensional analysis he determined that heat transfer was dependent on the average particle diameter divided by the pipe diameter, or $(D_{s'}/D_p)^C$. The constant C was then experimentally determined to be 0.05. Thus the low value of the constant indicates that the heat transfer properties were not very dependent on particle size over moderate ranges. This was substantiated by Bauman.[1]

Salamone and Newman[19] experimentally studied heat transfer to water suspensions of finely divided copper, carbon, chalk and silica in pipes. Their method of measuring viscosities using a pipe line viscometer was more realistic than that used by previous investigators. Their aqueous slurries were found to be non-Newtonian and pseudoplastic in behavior. They used dimensional analysis to develop the following equation to describe heat transfer in pipes:

$$\frac{HD}{K_f} = 0.131 \left(\frac{Dv_s \rho_s}{\mu_s}\right)^{0.62} \left(\frac{\mu_s C_f}{K_f}\right)^{0.72} \left(\frac{K_{s'}}{K_f}\right)^{0.05} \left(\frac{D_p}{D_{s'}}\right)^{0.05} \left(\frac{C_{s'}}{C_f}\right)^{0.35} \qquad (14)$$

The last three dimensionless groups characterize the solids used. Of the three terms the last one, the specific heat of the solid divided by the specific heat of the fluid was the most important.

Binder and Pollara[2] also studied heat transfer to suspensions in pipes. They found that the ratio of the thermal conductivity of the solid to that of the fluid, $K_{s'}/K_f$, does not significantly affect heat transfer unless the ratio is very large in magnitude.

Only a sparse amount of empirical data is available characterizing heat transfer to two phase batch liquid-solid systems. Frantisak[7] studied heat transfer to Newtonian solid-liquid suspensions in an agitated vessel. The slurry viscosities used by Frantisak were taken to be a function only of the solid's volume concentration, X_v and were determined as follows:

$$\mu_{slurry} = \mu_{liquid} \left(1 + 2.5\, X_v + 7.54\, X_v^2 \right) \tag{15}$$

Although many previous investigators (24,2) have shown suspensions, especially concentrated ones, such as Frantisak used to be non-Newtonian in behavior. Frantisak used the dimensionless group $\frac{X_v}{1-X_v}$ and found that the Nusselt number was inversely proportional to the group raised to the 0.04 power. Frantisak used a computer linear regression analysis to determine and develop the following correlation:

$$N_{Nu} = 0.575\, (N_{Re})^{0.60}\, (N_{Pr})^{0.26} \left(\frac{D_t}{D_a}\right)^{0.33} \left(\frac{C_s'}{C_f}\right)^{0.13} \left(\frac{\rho_s'}{\rho_f}\right)^{-0.16} \left(\frac{X_v}{1-X_v}\right)^{-0.04} \tag{16}$$

Hagedorn and Salamone (9) have made an extensive study of batch heat transfer to pseudoplastic systems. They started by analyzing the momentum, mass, and energy equations for the cylindrical jacketed wall in an agitated vessel. The equations were then solved dimensionally. Substituting the appropriate dimensionless groups resulted in the following.

$$N_{Nu} = C\, N_{Re}^{\left(\frac{1-2a}{1+n} + a\right)}\, N_{Pr}^{a}\, (D_t/D_a)^c\, n^d \tag{17}$$

A dimensionless quantity was further added to account for a viscosity difference between the fluid at the wall and the overall batch. Also, the equation was expanded to account for impeller geometry, thus resulting in the following:

$$N_{Nu} = C\, N_{Re}^{\left(\frac{1-2a}{1+n} + a\right)}\, N_{Pr}^{a}\, (\mu/\mu_w)^b\, (D_t/D_a)^c\, (W_a/D_a)^d\, n^e \tag{18}$$

This relationship used an apparent viscosity which was developed by Hagedorn to be,

$$\mu_a = K\, N^{n-1} \tag{19}$$

Hagedorn tested his theoretically derived equation for predicting heat transfer data. He used water, glycerine, and pseudoplastic solutions of Carbopol having flow behavior indexes between 0.69 and 0.36. Various types of impellers were used.

The original theoretical correlation was developed assuming flow patterns generated by a propeller agitator. Further refinements were made in the correlation to obtain a better fit with the actual experimental results. A semi-empirical correlation was finally arrived at which gave the best fit for the more pseudoplastic systems tested. This relationship was as follows:

$$N_{Nu} = C \; (N_{Re})^{(1.30/n+1)} \; N_{Pr}^{0.28} \; (\mu/\mu_w)^{0.30/n^{0.75}} \; (D_t/D_a)^{(-0.50)} (W_a/D_a)^{0.50na} \quad (20)$$

where C and a were evaluated separately for each impeller tested. This correlation was based on the apparent viscosity defined earlier by Metzner as:

$$\mu_a = k \; (11.5N)^{n-1} \quad (11)$$

The Hagedorn correlation gave an overall error of less than 11%.

EXPERIMENTAL

The experimental portion of this thesis involved the following:

1. Selection of materials
2. Brookfield viscosity determinations
3. Determining batch heat transfer data
4. Heat transfer and mixing calculations

Materials

A total of five different water-solid suspensions were studied. These were as follows:

Solid Phase	Weight Percent Solids
Iron oxide	33.2
"	24.0
"	13.1
Kaolin	24.4
"	18.4

Both solids were used as is, and no attempt was made at using a dispersant to obtain higher solids contents. Most known dispersants will degrade at the higher temperatures used in this study. The highest solids contents used for both the iron oxide and kaolin suspensions were found to be the upper limit for feasible equipment operation.

A high purity, red iron oxide (Fe_2O_3) pigment was used in this study. The pigment was commercially available from Charles F. Pfizer Company (code number R 8098). The pigment particles are reported by the manufacturer to be essentially spheroidal in shape. The average particle diameter has been previously studied(15) and was reported to be 0.20 μm ± 0.10 μm.

The second solid studied was a kaolin clay manufactured by Engelhard Minerals and Chemicals Corporation. The kaolin is commercially known as ASP200. ASP200 is reported to have an average equivalent spherical diameter of 0.55 μm. It is composed of flat white crystals from which virtually all moisture, sand, mica, and water soluble salts have been removed. The kaolin is non-hygroscopic and is essentially inert and water insoluble. The manufacturer reports the following chemical analysis:(25)

Component	Weight %
Silicon (SiO_2)	45.4
Aluminum (Al_2O_3)	38.8
Iron (Fe_2O_3)	0.3
Titanium (TiO_2)	1.5
Calcium (CaO)	0.1
Sodium (Na_2O)	0.1
Potassium (K_2O)	Trace
Water of hydration	13.8

Table No. 1 lists pertinent data necessary for heat transfer data for both the kaolin and iron oxide pigments.

Viscosity

Suspension viscosities were measured using a Brookfield LVT-5X-600 Synchro-Lectric Viscometer. This instrument consists of a syncronous motor which drives a cylindrical spindle. The rpm can be adjusted through a gear train which is controlled by a speed selector knob. Shaft speeds of 3, 6, 15, 30, 60, 120, 300 and 600 revolutions per minute can be readily attained. Thus a two hundred fold range of shear rates

TABLE NO. 1

SOLIDS' PROPERTIES

	Kaolin	Iron Oxide
Avg. Particle size, µm	0.55 [28]	0.20 [15]
Specific gravity	2.58 [28]	5.15 [15]
Thermal Conductivity Btu / hr. ft.^{2} (°F/ft.)	0.110 [24]	0.277 [10]
Specific heat capacity Btu / lb. °F	0.224 [24]	0.148+0.00034T [10] (T = °C)

can be attained. The torque supplied to the spindle at a given rpm is transmitted through a calibrated spiral spring which is attached to a read out dial. The dial gives a measure of the percentage of full scale torque which, for this instrument was 3368.5 dyne centimeters.

The shear rate can be determined as follows:

$$\gamma_\omega = 4\pi N/n'' \tag{7}$$

where N is the rotational speed of the spindle, n" is a measure of non-Newtonian behavior and can be found by taking the slope of a logarithmic plot of torque versus spindle revolutions. This relationship is applicable when the diameter of the spindle is small compared to that of the container.

The torque reading is a measure of the shear stress occurring at the cylindrical walls of the spindle and also at the ends of the spindle. What is wanted is a measure of the shear stress at the walls of the cylinder only. To correct for this end effect, Hagedorn and Salamone determined an effective cylinder height which was somewhat larger than the actual cylinder's height. Thus the shear stress was determined as follows:

$$\tau_\omega = T'/2\pi R^2 h_e \tag{21}$$

Where T' is the torque, R is the cylinder radius, and h_e is the effective cylinder height.

This method of determining an effective cylinder height was also used by Metzner[14] and was used by the author for the present work. The Brookfield viscometer was checked and calibrated before use according to accepted practices outlined by the manufacturer.

Viscosity measurements were taken in triplicate for all five suspensions used in this study. Viscosity data was taken for each suspension at three or more different temperatures.

Each suspension was immersed in a water bath and the temperature during the viscosity measurements was maintained to within ± 1°F. The suspension was kept fully agitated between measurements to prevent settling of the suspended solids. The apparent viscosity was determined by:

$$\mu_a = \tau / \gamma \qquad (22)$$

The shear stress, τ , divided by the shear rate, γ , equaled the apparent viscosity. These viscosities are plotted as a function of shear rate for each suspension in Figure Numbers 1 to 5 .

Heat Transfer Equipment and Data Determinations

The basic equipment used in this study was previously built by Donald Hagedorn as part of his Doctoral Thesis requirements. The equipment was an insulated fifteen gallon 316 stainless steel vessel, which was fully jacketed on its sides and dished bottom. Agitation was supplied through a three quarter horse power DC shunt motor mounted on a frictionless bearing above the vessel. A half inch agitator shaft was located centrally and impellers could be fastened at an infinite number of positions along its length.

Shaft speeds could be varied between 75 - 2500 RPM through a Reliance VS Jr., Style "EF" electronic motor controller. During the present study the impeller speeds were always below 700 RPM. The mixing power consumed was readily determined with a 0 - 25 pound scale which was attached to a

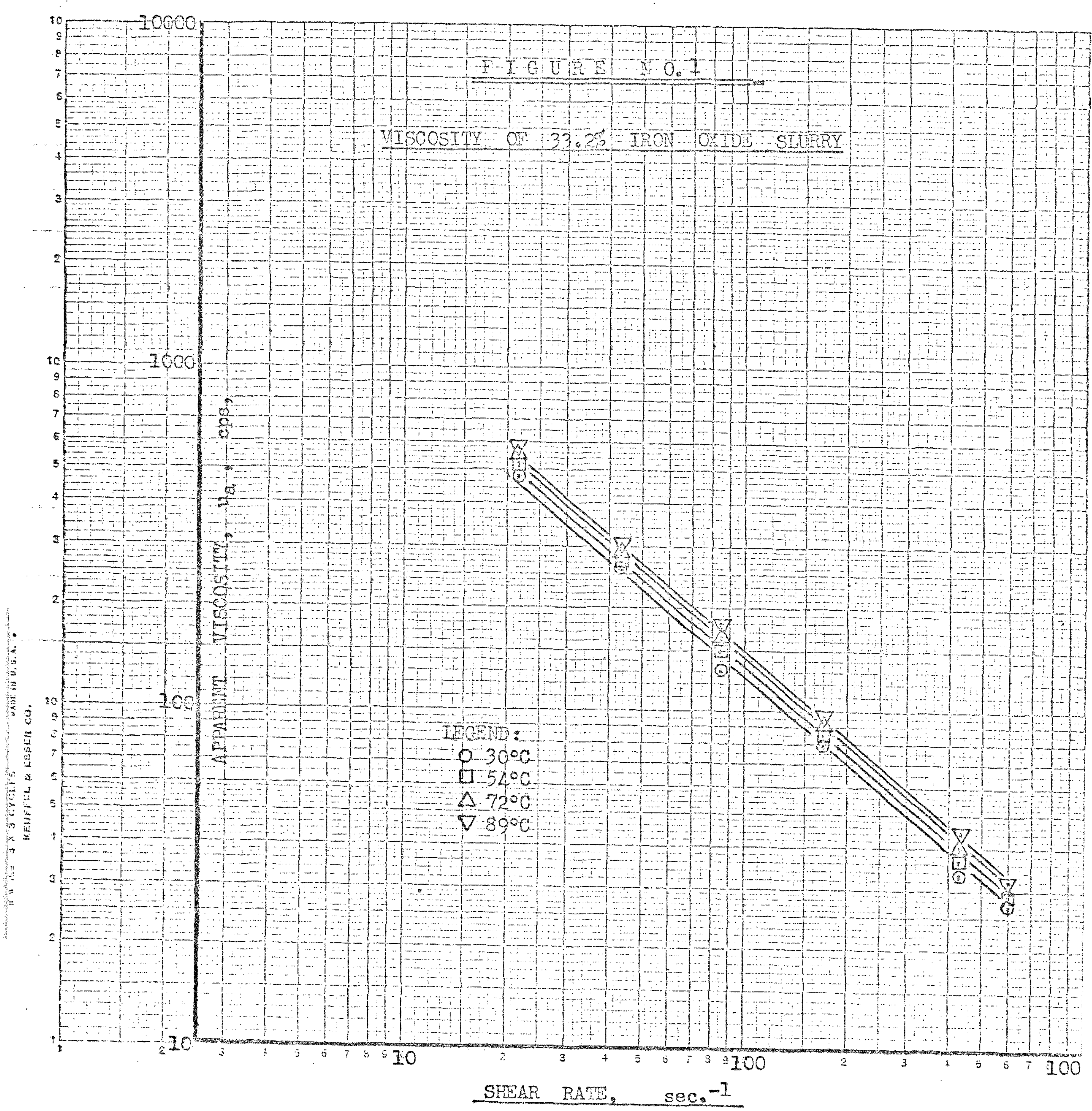
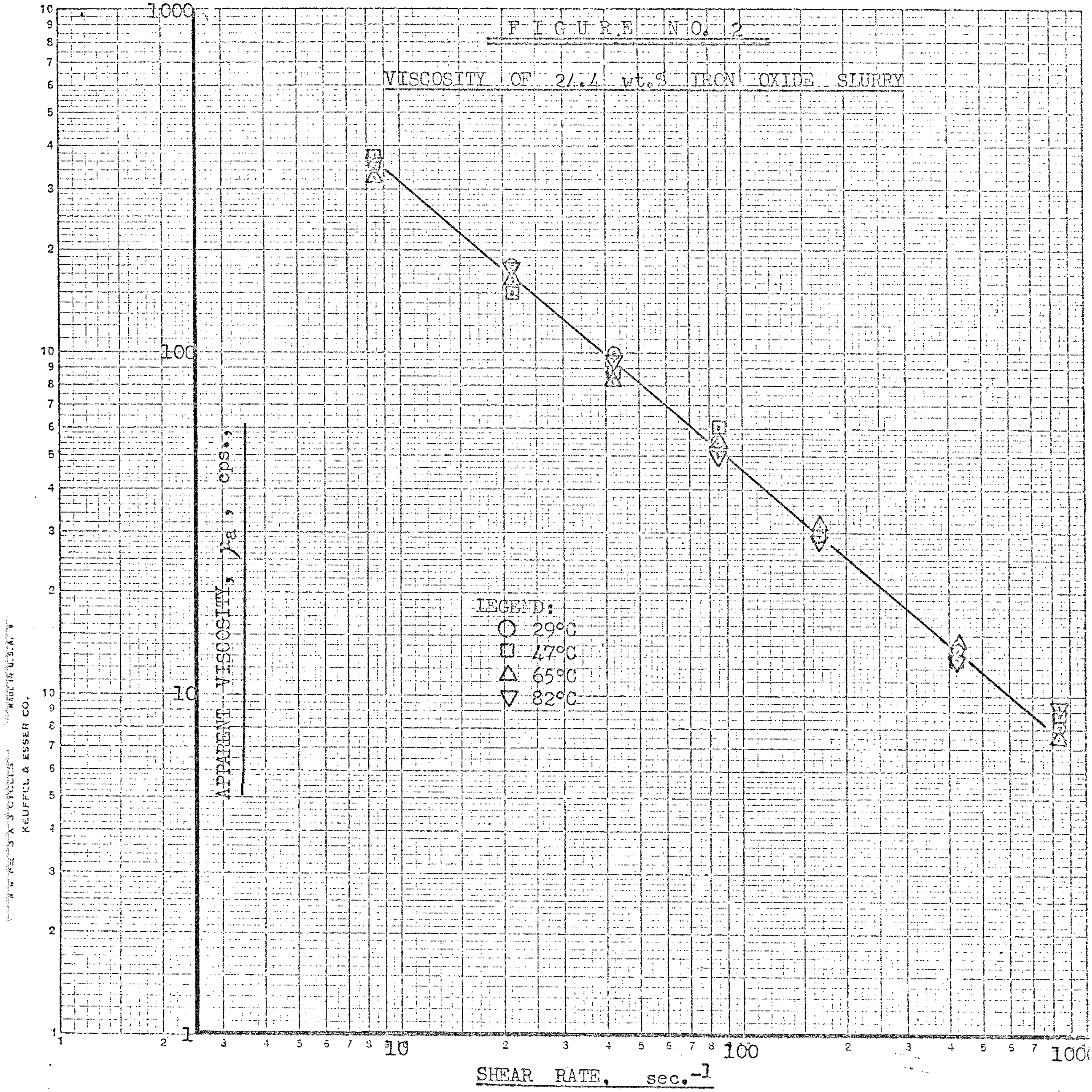


FIGURE NO. 1
VISCOSITY OF 33.2% IRON OXIDE SLURRY
APPARENT VISCOSITY, μa, cps.
10000
1000
100
10
10
100
1000
SHEAR RATE, sec.-1
LEGEND:
○ 30°C
□ 54°C
△ 72°C
▽ 89°C
KEUFFEL & ESSER CO.
3 X 3 CYCLES
MADE IN U.S.A.


F I G U R E N O. 2
VISCOSITY OF 24.4 wt.% IRON OXIDE SLURRY
APPARENT VISCOSITY, μ_a, cps.,
SHEAR RATE, sec.$^{-1}$
LEGEND:
29°C
47°C
65°C
82°C
1000
100
10
1
10
100
1000
KEUFFEL & ESSER CO.
MADE IN U.S.A.

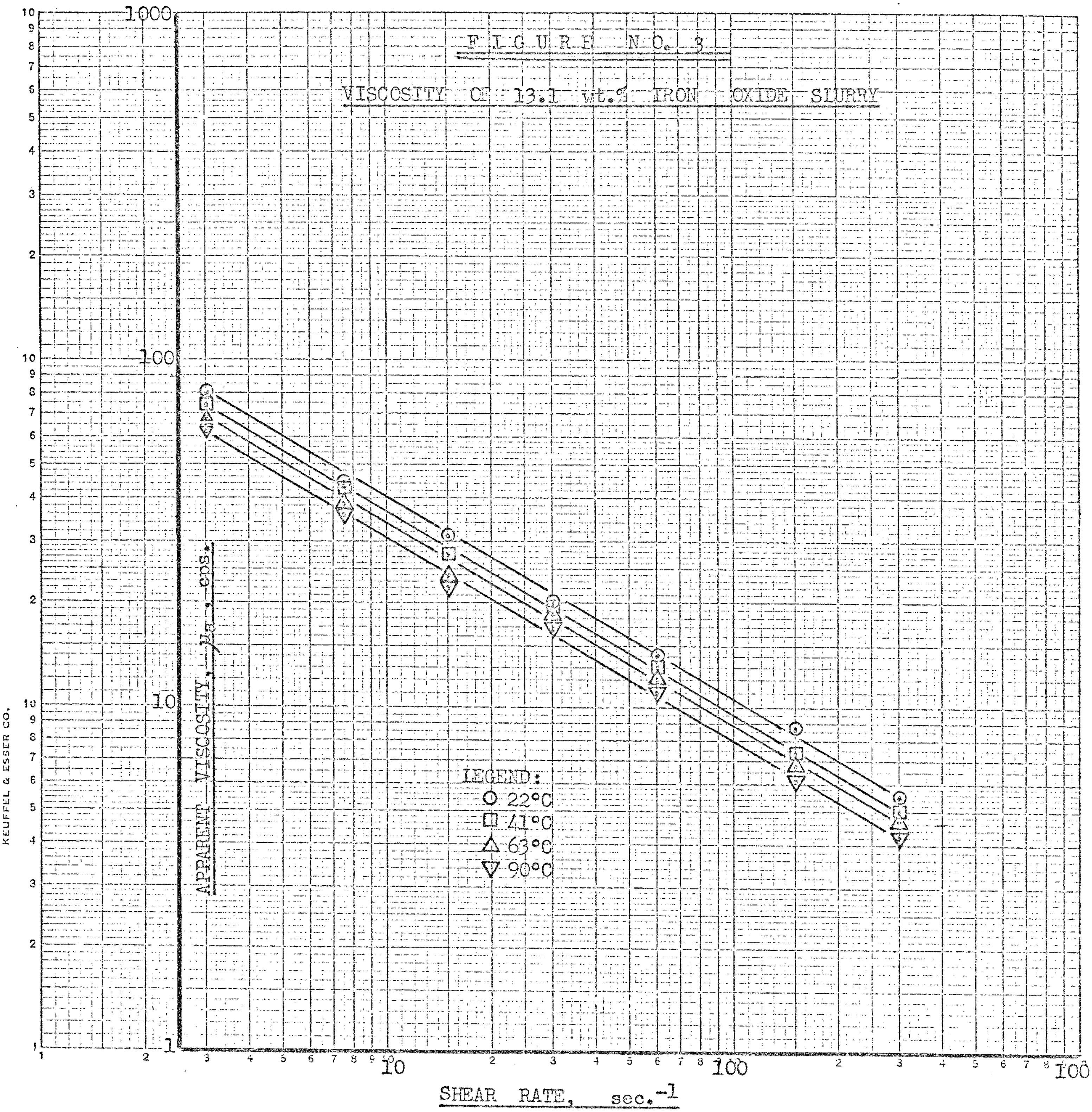


FIGURE NO. 3
VISCOSITY OF 13.1 wt.% IRON OXIDE SLURRY
APPARENT VISCOSITY, μ_a, cps.
SHEAR RATE, sec.$^{-1}$
LEGEND:
○ 22°C
□ 41°C
△ 63°C
▽ 90°C
1000
100
10
1
10
100
1000
KEUFFEL & ESSER CO.

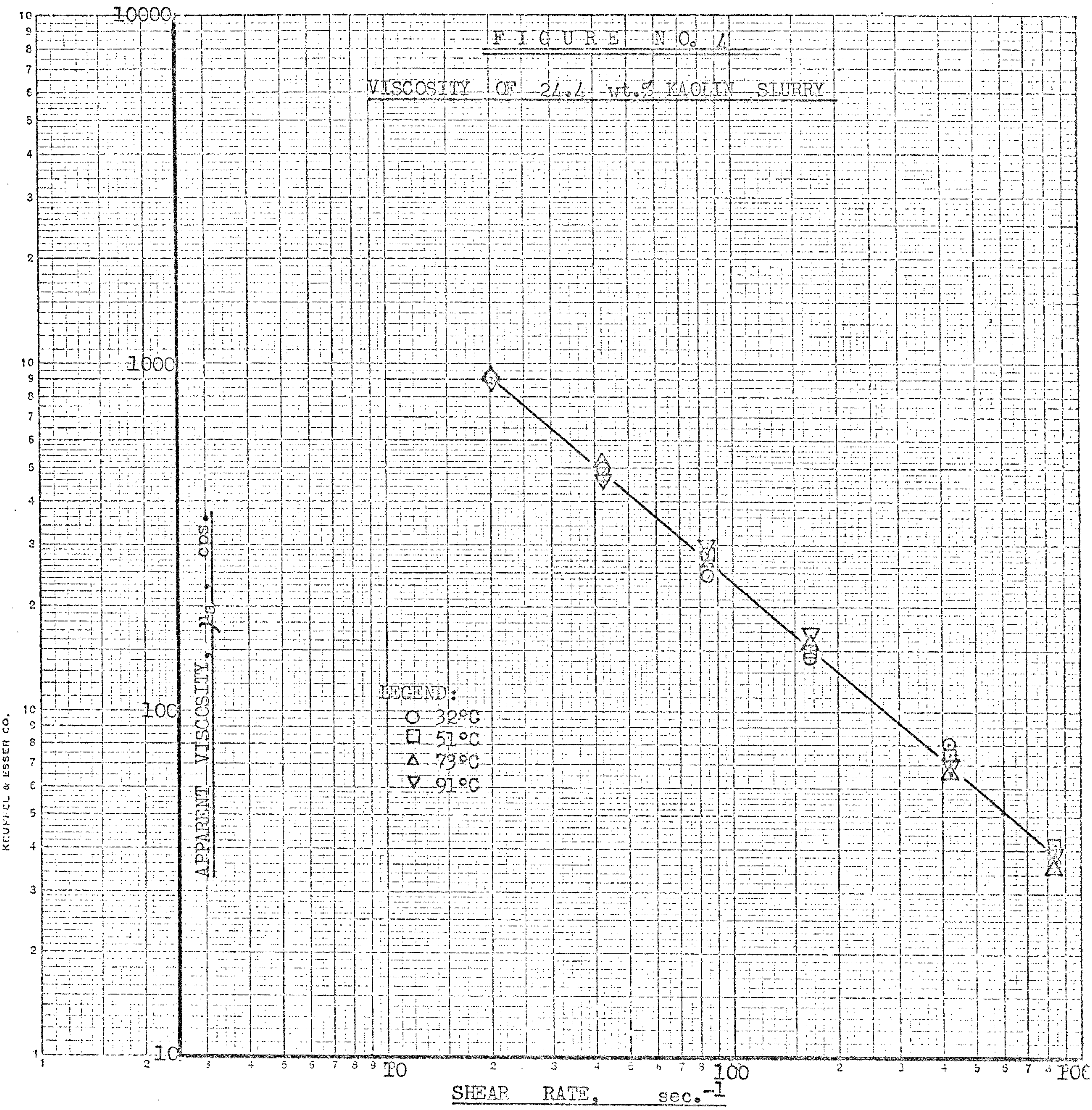


FIGURE NO. 4
VISCOSITY OF 24.4 wt.% KAOLIN SLURRY
10000
1000
100
10
APPARENT VISCOSITY, μa, cps.
LEGEND:
○ 32°C
□ 51°C
△ 73°C
▽ 91°C
10
100
1000
SHEAR RATE, sec.⁻¹
KEUFFEL & ESSER CO.

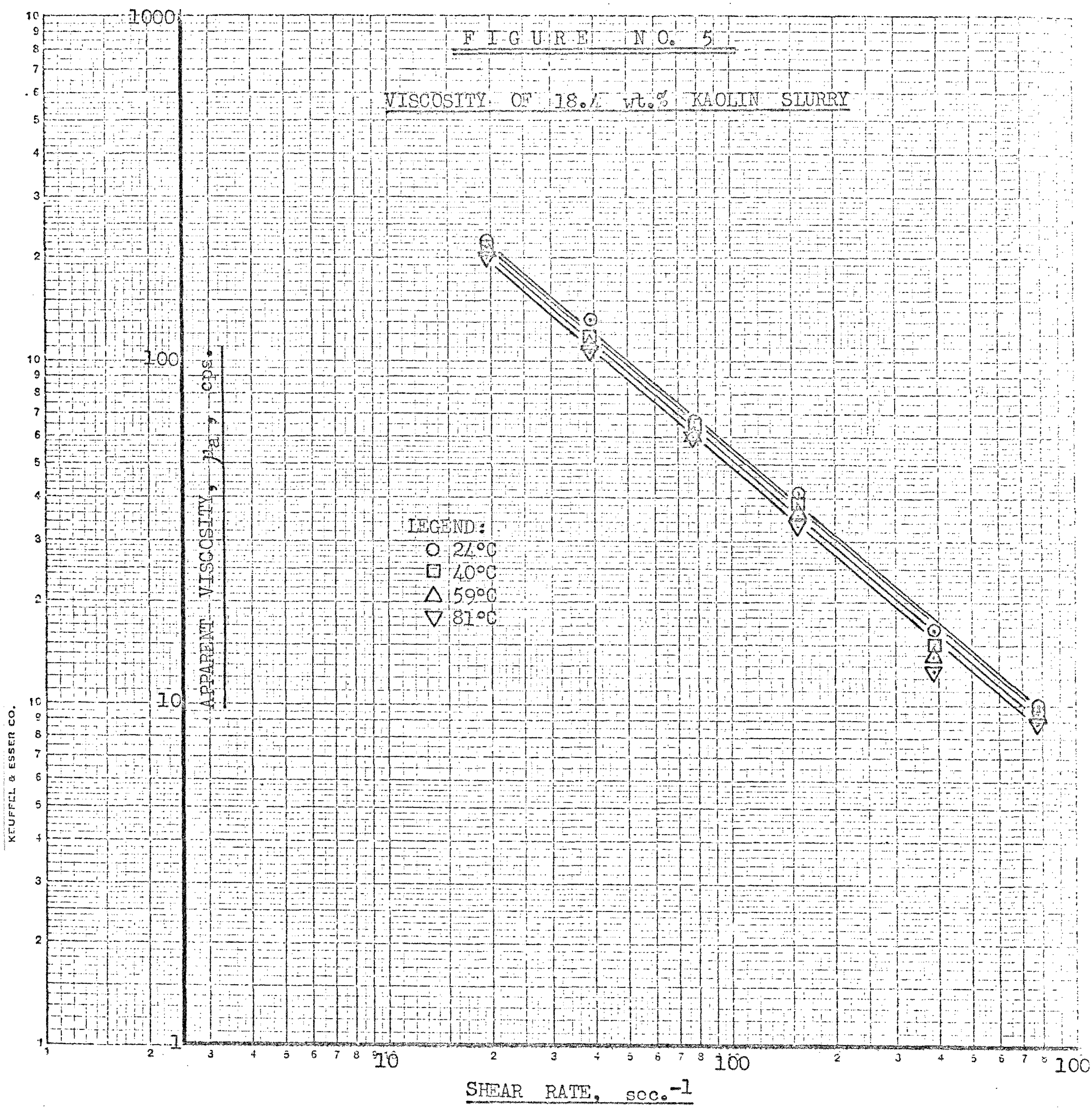


FIGURE NO. 5
VISCOSITY OF 18.4 wt.% KAOLIN SLURRY
APPARENT VISCOSITY, μ_a, cps.
SHEAR RATE, sec.$^{-1}$
LEGEND:
○ 24°C
□ 40°C
△ 59°C
▽ 81°C
KEUFFEL & ESSER CO.

moment arm in the form of a 6-1/2 inch pulley at the base of the motor. The torque used in mixing caused the motor to turn slightly on its mount and transmit the force to the scale.

During the course of this study it was shown that the mixer motor was only capable of delivering about 1/4 horsepower usable power within the low range of speeds tested. This power reduction with speed is inherent with this type of shunt motor. This power limitation reduced the amount of experimental data obtainable especially with the more concentrated suspensions.

Vortexing was minimized by four 1 by 20 inch baffles attached to the inside vessel walls. Other pertinent vessel dimensions were the following:

Diameter	14 inch
Height of cylindrical side	20 inch
Depth of dish	2 inch
Heat transfer area used	6.2 $ft.^2$
Volume used	1.512 $ft.^3$

Three thermocouples were used to measure batch temperatures and three thermocouples were used to measure wall temperatures. Thermocouples were also used to measure jacket inlet and outlet temperatures. All eight thermocouples were connected to a Westronic MIIB/J/DV.5M twelve point strip chart recorder which prints a temperature point every five seconds. The chart speed was adjusted for one half inch per minute.

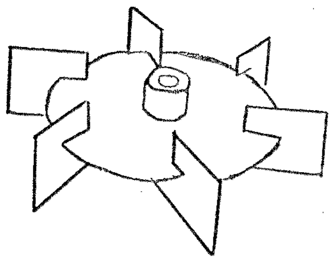
The three batch thermocouples measured temperatures at three different levels. Wall temperature measurements were made possible by three thermocouples embedded in the vessel's wall at various levels. Grooves were milled into the cylindrical wall at various positions around the perimeter. The sheathed iron constantan thermocouple wires were cemented into each groove (one thermocouple per groove). The tip of each sheath was bent slightly to make it flush with the vessel's wall. The cement used, Thermon T-85, was choosen because its thermal conductivity was similar to 316 stainless steel.

During a run the fluid level was kept at 3-1/2 inches from the vessel's top. Therefore, the wall thermocouples were submerged at 2-1/2, 9 and 14-1/2 inches below the liquid surface. The batch thermocouples were then at 3-1/2, 11-1/2 and 20 inches below liquid level. The multiple batch and wall temperature measurements tended to minimize temperature variations within the vessel. The thermocouples were calibrated prior to use.

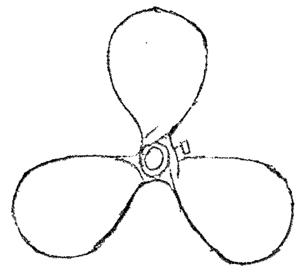
Four basic impeller designs were studied. The impellers are shown pictorially in Figure No. 6 and the basic impeller dimensions used are given in Table No. 2 . Each impeller was mounted on a half inch shaft. Hagedorn and Salamone report that the impeller height significantly effects the heat transfer results, all other factors being equal. Therefore, the relative impeller positions recommended in the afore mentioned work were adhered to in this study. These were as follows:

FIGURE NO. 6

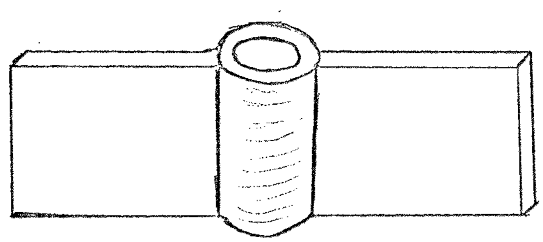
IMPELLERS



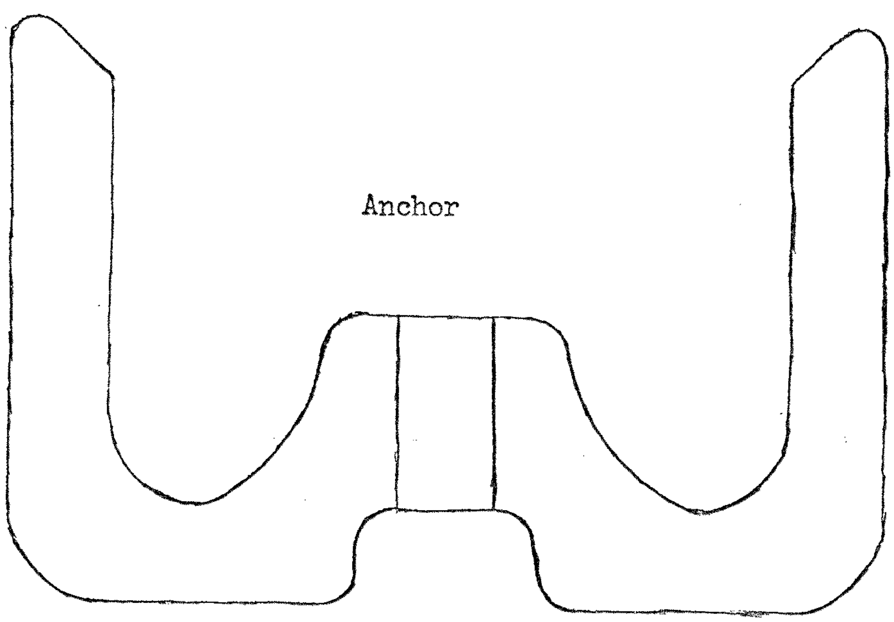
Disc and Vane Turbine



Propeller



Paddle



Anchor

TABLE NO. 2

IMPELLER DIMENSIONS

Impeller Types	Diameter Inches	Width Inches
Anchor	9.0	6.0
Paddles	4.0	1.0
	4.0	2.0
	6.0	1.0
	6.0	2.0
	8.0	1.0
	8.0	2.0
Propellers	4.1	---
	5.2	---
	6.0	---
Turbines (disc & vane)	4.0	0.75
	5.0	1.00
	6.0	1.25

Impeller	Position
Anchor	5 inch clearance
Paddle	7 inch center height
Propeller	10 inch clearance
Turbine	7 inch center height

The clearance is measured from the vessel's dished bottom to the impeller's bottom. The center height is measured from the vessel's dished bottom to the middle of the impeller's width. These impeller positions were experimentally shown to minimize discrepancies in wall temperature measurements among the three thermocouple locations.

Time was initially spent to become familiar with the equipment. During this period heat transfer data was obtained using water as the batch fluid. The experimental results for the water runs are given in Table No. 3 . Water is a well known Newtonian fluid whose properties have been well documented in the literature.[(23)] The pertinent data for water and its method of calculation are given in Appendix No. 1 .

The normal operating procedure for suspensions was to fill the vessel three quarters full of water. Then solids were added to the water using agitation until the desired solids content was obtained. Then premeasured quantities of water and solids were added until the desired volume of the vessel was filled. A ruler was attached to the vessel wall to facilitate the filling operation. The suspension uniformity was periodically checked by sampling the batch and drying the sample in a 250°F oven.

TABLE NO. 3

EXPERIMENTAL MEASUREMENTS FOR WATER

Run Number	Batch Temp.,°C No. 1	Batch Temp.,°C No. 2	Wall Temp. °C No. 1	Wall Temp. °C No. 2	Avg. Temp.,°C	RPM	Scale lbs.
			ANCHOR 9"				
155-1H	73.5	84.5	78.5	88.5	79.0	166	5.85
155-4C	43.6	38.5	41.4	36.5	41.1	166	5.85
156-2H	83.5	92.0	91.0	97.5	87.8	48	0.50
156-4C	44.0	39.5	39.5	35.1	41.8	48	0.50
157-1H	73.5	85.0	80.4	89.8	79.3	113	2.80
157-4C	46.4	41.0	43.1	38.0	43.6	113	2.80
			TURBINE 6 x 1.25"				
127-1H	69.8	84.3	76.0	90.2	77.1	285	3.90
127-3C	59.8	50.8	56.5	46.8	55.3	285	3.90
149-1H	67.0	80.5	73.5	85.4	73.8	330	5.52
149-3C	53.0	45.8	49.4	43.0	49.4	330	5.52
150-2H	80.5	90.0	85.7	93.5	85.3	246	3.10
150-3C	50.5	44.5	47.5	41.5	47.5	246	3.10
151-2H	78.0	88.0	86.5	94.1	83.0	106	0.50
151-3C	49.0	43.5	43.6	38.5	46.3	106	0.50
			TURBINE 5 x 1"				
128-2H	73.5	87.0	79.0	90.5	80.3	500	4.98
128-4C	60.5	52.5	57.0	49.1	56.5	500	4.98
129-1H	79.8	87.8	87.5	93.8	83.8	110	0.12
129-4C	61.0	54.3	53.8	47.0	57.7	110	0.17
130-1H	79.6	86.9	83.8	90.8	83.3	270	1.29
130-3C	47.4	42.5	43.5	39.2	45.0	270	1.30
131-1H	50.4	67.4	58.0	75.0	58.9	400	3.08
131-3C	67.3	58.3	63.0	54.4	62.8	400	3.10
132-1H	48.8	65.0	55.6	71.5	56.9	400	3.14
132-3C	72.0	62.2	66.6	57.5	67.1	400	3.12
133-2H	85.4	94.6	89.0	97.8	90.0	500	5.00
133-3C	75.0	63.5	69.0	59.4	69.3	500	5.00
			TURBINE 4 x 0.75"				
158-1H	70.4	82.7	77.0	87.4	76.6	645	3.10
158-4C	45.0	39.5	42.0	37.0	42.3	645	3.10
159-2H	78.5	87.0	85.2	92.5	82.8	300	0.60
159-4C	45.0	40.0	40.9	36.1	42.5	300	0.60

TABLE NO. 3 (contd.)

EXPERIMENTAL MEASUREMENTS FOR WATER

Run Number	Batch Temp., °C No. 1	Batch Temp., °C No. 2	Wall Temp., °C No. 1	Wall Temp., °C No. 2	Avg. Temp., °C	RPM	Scale lbs.
			TURBINE 4 x 0.75"				
160-1H	71.0	83.0	78.5	88.5	77.0	505	1.88
160-3C	55.0	47.9	51.1	44.5	51.5	505	1.88
			PADDLE 6 x 2"				
141-1H	65.5	79.5	73.0	84.2	72.5	401	6.33
141-4C	43.6	38.0	40.9	36.0	40.8	401	6.33
142-2H	82.0	91.0	87.0	94.2	86.5	301	3.50
142-4C	46.5	40.5	43.3	37.9	43.5	301	3.50
143-2H	81.6	89.4	87.5	93.9	85.5	200	1.57
143-3C	48.0	42.1	44.5	39.0	45.1	200	1.57
144-1H	75.9	83.9	84.4	91.5	79.9	93	0.40
144-3C	49.0	43.2	42.2	38.1	46.1	93	0.40
			PADDLE 6 x 1"				
137-1H	62.0	74.0	68.4	79.5	68.0	528	4.32
137-4C	42.5	37.5	39.9	35.1	40.0	528	4.32
138-1H	62.0	75.5	69.5	81.5	68.8	448	3.10
138-3C	53.5	46.5	49.0	42.6	50.0	448	3.10
139-2H	85.5	92.6	90.5	96.0	89.1	347	1.80
139-4C	40.1	35.8	36.5	33.0	38.0	347	1.80
140-1H	74.0	85.0	85.4	93.5	79.5	164	0.44
140-3C	47.5	42.5	42.4	37.9	45.0	164	0.44
			PADDLE 4 x 2"				
145-1H	72.0	86.0	80.0	91.0	79.0	595	2.90
145-3C	46.0	40.4	42.8	37.6	43.2	595	2.90
146-1H	63.0	72.6	74.1	82.0	67.8	194	0.60
146-4C	41.5	37.5	36.6	33.4	39.5	194	0.60
147-1H	71.4	83.8	81.0	90.0	77.6	331	0.80
147-3C	46.6	41.5	42.0	37.1	44.1	331	0.80
148-2H	77.1	87.0	83.6	92.0	82.0	494	1.95
			PADDLE 4 x 1"				
152-1H	74.0	85.5	83.5	91.0	79.8	651	1.38
152-3C	46.9	41.5	42.5	37.9	44.2	651	1.38
153-2H	84.0	91.5	91.1	97.8	87.8	364	0.47
153-3C	47.6	42.2	41.6	37.0	37.0	44.9	0.47

TABLE NO. 3 (contd.)

EXPERIMENTAL MEASUREMENTS FOR WATER

Run Number	Batch Temp.,°C No. 1	Batch Temp.,°C No. 2	Wall Temp.,°C No. 1	Wall Temp.,°C No. 2	Avg. Temp.,°C	RPM	Scale lbs.
			PADDLE 4 x 1"				
154-2H	73.5	85.5	82.0	91.9	79.5	494	0.80
154-3C	47.0	41.6	41.5	37.0	44.3	494	0.80
			PROPELLER 5.2"				
123-2H	79.0	87.1	85.8	93.0	83.1	319	0.35
123-4C	47.5	41.6	41.8	35.8	44.6	318	0.35
124-2H	68.7	76.8	78.6	85.0	72.7	332	0.24
124-3C	58.5	50.8	52.4	44.4	54.6	332	0.26
125-1H	70.0	81.8	75.8	86.8	75.9	545	0.94
125-4C	62.0	52.0	56.0	46.0	57.0	545	0.94
126-3C	46.1	40.0	42.5	36.0	43.1	765	2.00
			PROPELLER 4.1"				
134-1H	64.0	78.5	75.0	86.9	71.3	650	0.50
134-3C	56.4	49.5	50.0	43.9	53.0	650	0.50
135-2H	73.5	82.0	83.5	90.6	77.8	395	0.20
135-3C	56.0	49.0	48.0	42.5	52.5	395	0.20
136-1H	66.0	79.5	78.0	87.5	72.8	523	0.30
136-3C	53.0	46.5	46.5	41.0	49.8	523	0.30

Figure No. 7 . shows how steam and water entered and discharged from the jacket. Steam was admitted to the sealed jacket during the heating cycle until the batch temperature reached approximately 90°C. The steam was then discontinued and the top drain valve was opened. Cooling water, controlled through a rotometer, was then admitted through the top and bottom inlets for the cooling cycle. Temperature measurements were continually monitored throughout the heating and cooling cycle. After the cooling cycle the jacket was drained in preparation for the next heating cycle.

Where possible, three to four runs were made with the same impeller but at different revolutions. Mixing power limited some runs at the upper RPM and inadequate mixing, resulting in solids settling, limited some lower mixing speeds. A Smiths Hand Tachometer was used to measure rotational speed. Water was added when needed to compensate for evaporation.

During the heating cycle the wall temperature was higher than the batch temperature and during the cooling cycle the opposite was true. The temperature recorder curves for each run were examined. A two minute time interval, selected where the wall and batch temperatures formed the smoothest line, was used from both the heating and cooling cycle. A straight line was drawn through these points and these were used to determine the change in batch temperature at a given temperature drop between the batch and wall. This information was then used to calculate the heat transfer coefficient. The experimental data for all suspensions studied is given in Table Nos. 4 . to 8 .

F I G U R E N O. 7

HEAT TRANSFER VESSEL DIAGRAM

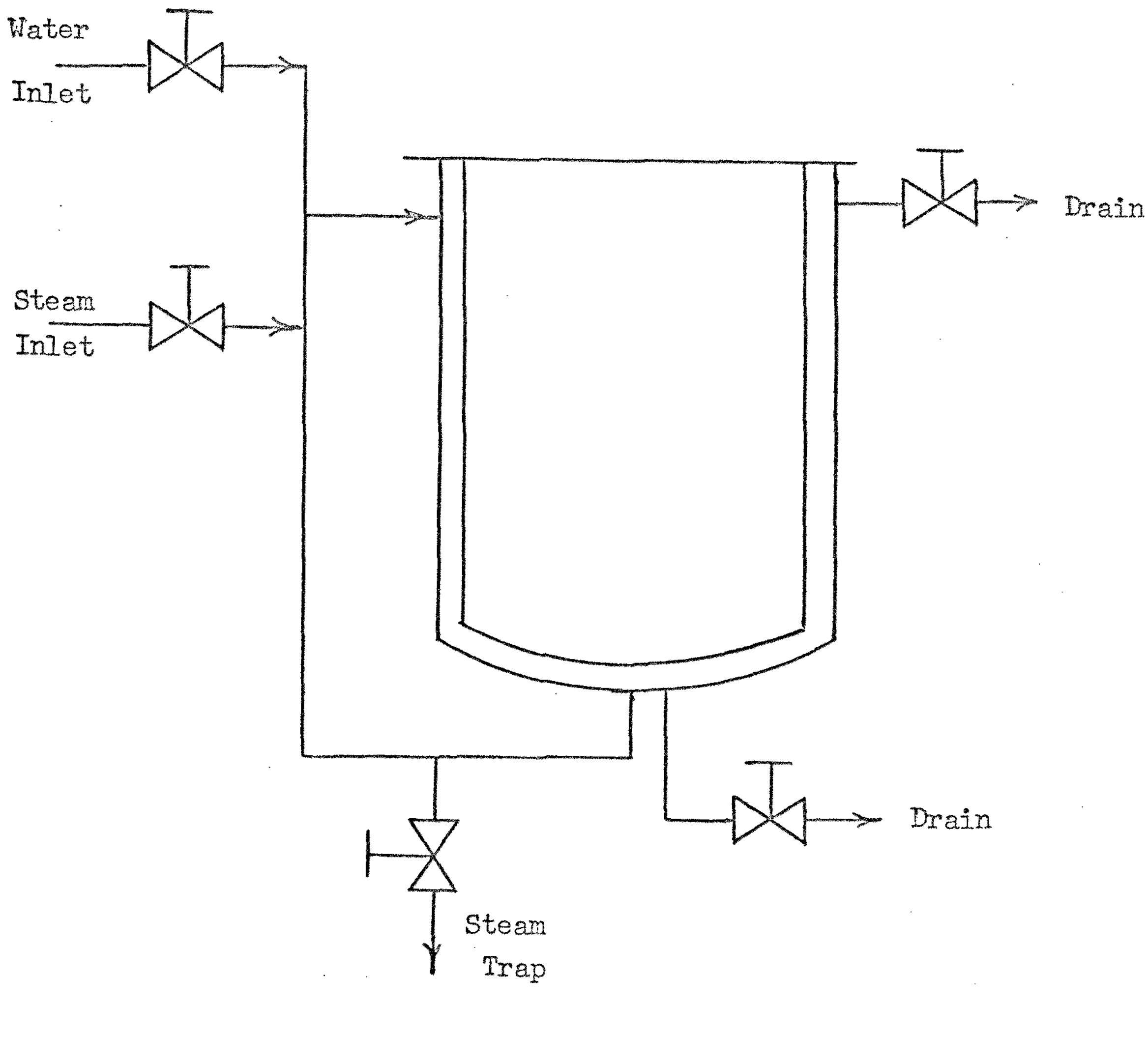


TABLE NO. 4

EXPERIMENTAL MEASUREMENTS FOR 33.2wt.% Fe_2O_3 SUSPENSIONS

Run Number	Batch Temp. No. 1	Batch Temp. No. 2	Wall Temp. No. 1	Wall Temp. No.2	Avg. Temp.°C	App Visc.cp.	RPM	Scale lbs.
				ANCHOR 9"				
44-1H	75.0	82.4	88.5	94.6	78.7	370	165	7.80
44-3C	47.3	42.3	36.9	33.5	44.8	340	165	7.80
				TURBINE 6 x 1.25"				
45-1H	77.5	85.6	92.1	96.5	81.6	202	342	7.95
45-3C	48.4	43.0	36.6	33.0	45.7	185	342	7.95
46-1H	66.0	74.0	90.4	94.0	70.0	235	277	5.12
46-3C	42.4	39.0	28.9	27.1	40.7	220	277	5.12
				TURBINE 5 x 1"				
32-1H	71.0	83.0	88.6	94.9	77.0	140	527	7.67
32-3C	43.0	38.3	34.8	31.2	40.7	128	527	7.67
33-1H	70.5	79.1	89.4	95.0	74.8	155	460	5.98
33-3C	43.0	39.0	33.0	29.5	41.0	142	460	5.98
				PADDLE 8 x 1"				
40-1H	69.7	79.2	90.5	94.5	74.5	200	351	7.73
40-3C	51.0	45.5	36.6	33.0	48.3	185	351	7.73
41-1H	63.1	73.0	89.5	93.5	68.0	217	299	5.51
41-3C	47.4	43.0	32.5	29.9	45.2	207	299	5.51
				PADDLE 6 x 2"				
37-1H	67.6	77.5	86.6	92.5	72.0	180	380	7.80
37-3C	45.6	41.0	35.5	32.0	43.2	168	380	7.80
38-1H	57.5	68.5	87.0	90.5	63.0	205	325	5.73
38-3C	46.5	42.0	31.4	29.0	44.3	195	325	5.73
				PADDLE 6 x 1"				
35-1H	70.1	80.0	88.5	94.6	75.0	130	575	7.61
35-3C	45.0	40.5	35.0	31.5	42.8	120	575	7.61
36-1H	69.9	78.5	91.4	95.5	74.2	147	492	5.61
36-3C	47.5	43.0	34.9	32.5	45.2	137	492	5.61
				PADDLE 4 x 2"				
39-1H	65.6	75.5	90.0	94.5	70.5	114	654	4.74
39-3C	51.0	46.0	36.5	33.5	48.5	109	654	4.74
				PROPELLER 6"				
42-1H	67.4	76.0	86.5	91.8	71.7	115	648	3.65
42-3C	49.0	44.1	37.6	34.5	46.6	107	648	3.65
43-1H	78.1	86.0	95.0	98.5	82.1	135	560	2.75
43-3C	47.1	43.0	34.6	32.1	45.1	122	560	2.75

TABLE NO. 5

EXPERIMENTAL MEASUREMENTS FOR 24.0 wt.% Fe_2O_3 SUSPENSIONS

Run Number	Batch Temp. No. 1	Batch Temp. No. 2	Wall Temp. No. 1	Wall Temp. No. 2	Avg. Temp.°C	App. Visc.cp.	RPM	Scale lbs.
				ANCHOR 9"				
83-1H	74.0	86.0	87.4	95.6	80.0	120	164	6.86
83-3C	50.2	44.0	44.0	38.5	47.1	120	"	6.86
84-1H	61.0	70.0	84.0	91.2	65.5	195	90	1.85
84-3C	46.6	42.3	35.0	32.4	44.5	195	"	1.85
				TURBINE 6 x 1.25"				
47-1H	81.0	87.0	87.0	93.5	84.0	63	351	7.50
47-3C	47.4	41.5	40.5	35.6	44.5	63	"	7.50
48-1H	62.5	72.5	83.4	89.5	67.5	98	210	2.65
48-3C	46.0	42.0	36.1	33.0	44.0	98	"	2.65
49-1H	75.5	83.0	86.4	91.1	79.3	71	305	5.73
49-3C	47.0	41.5	39.0	34.7	44.3	71	"	5.73
50-1H	73.5	81.5	87.0	93.0	77.5	81	259	4.13
50-3C	46.1	41.0	37.6	33.5	43.5	81	"	4.13
				TURBINE 5 x 1"				
79-1H	77.2	86.5	87.0	92.7	81.9	45	524	6.68
79-3C	49.0	43.0	42.4	37.1	46.0	45	"	6.68
80-1H	73.7	82.4	89.7	94.8	78.1	72	299	2.30
80-3C	47.7	43.1	36.5	32.9	45.4	72	"	2.30
81-1H	76.2	83.7	88.5	93.0	80.0	60	375	3.40
81-3C	43.0	38.2	34.5	31.3	40.6	60	"	3.40
82-1H	71.8	80.0	83.8	90.0	75.9	50	455	5.00
82-3C	46.0	40.5	39.0	34.0	43.3	50	"	5.00
				TURBINE 4 x 0.75				
51-1H	73.5	82.4	87.6	92.6	78.0	38	646	3.79
51-3C	51.0	45.0	42.0	36.6	48.0	38	"	3.79
52-1H	66.5	75.9	85.3	92.5	71.2	53	435	1.67
52-3C	48.5	44.0	38.5	35.0	46.3	53	"	1.67
53-1H	70.5	80.7	88.0	89.8	75.6	46	500	2.22
53-3C	49.9	44.2	39.0	34.9	47.1	46	"	2.22
54-3C	57.5	51.6	48.1	42.0	54.6	41	585	3.00
55-1H	70.1	79.4	86.0	92.2	74.8	42	569	2.88
55-3C	45.5	40.3	36.9	33.0	42.9	42	"	2.88

TABLE NO. 5 (contd.)

EXPERIMENTAL MEASUREMENTS FOR 24.0 wt.% Fe_2O_3 SUSPENSIONS

Run Number	Batch Temp. No. 1	Batch Temp. No. 2	Wall Temp. No. 1	Wall Temp. No. 2	Avg. Temp.°C	App. Visc.cp.	RPM	Scale lbs.
				PADDLE 8 x 2"				
72-1H	72.5	85.4	87.0	94.9	79.0	94	221	6.97
72-3C	49.0	43.5	41.5	37.0	46.3	94	"	6.97
73-1H	65.0	76.0	88.1	93.5	70.5	140	135	2.43
73-3C	48.0	43.9	36.8	33.0	46.0	140	"	2.43
				PADDLE 8 x 1"				
69-1H	73.0	85.5	87.0	95.3	79.3	63	349	6.85
69-3C	48.6	43.0	41.0	36.5	45.8	63	"	6.85
70-1H	63.5	69.5	85.4	92.5	66.5	92	225	2.90
70-3C	46.9	42.2	35.0	32.0	44.6	92	"	2.90
71-1H	70.8	82.5	88.5	95.5	76.7	75	284	4.53
71-3C	45.0	40.0	35.9	32.5	42.3	75	"	4.53
				PADDLE 6 x 2"				
66-1H	73.4	85.0	86.0	94.2	79.2	60	381	6.97
66-3C	54.4	47.6	46.1	40.0	51.0	60	"	6.97
67-1H	68.0	76.5	90.0	95.5	72.3	92	223	2.35
67-3C	45.7	41.6	34.5	31.5	43.7	92	"	2.35
68-1H	74.5	82.0	87.5	92.5	78.3	72	300	4.25
68-3C	44.5	40.1	36.5	33.1	42.3	72	"	4.25
				PADDLE 6 x 1"				
62-1H	73.0	85.5	86.0	94.5	79.3	40	602	7.13
62-3C	57.0	47.6	47.0	41.0	52.2	40	"	7.13
63-1H	72.0	82.5	92.0	97.2	77.3	65	337	2.23
63-3C	47.0	42.4	34.0	31.0	44.7	65	"	2.23
64-1H	62.5	74.4	84.4	91.4	68.5	54	416	3.44
64-3C	49.0	43.8	38.6	34.7	46.4	54	"	3.44
65-1H	78.3	85.0	90.1	94.6	81.7	46	510	5.10
65-3C	46.0	41.0	38.1	34.0	43.5	46	"	5.10
				PADDLE 4 X 2"				
58-1H	73.5	82.0	86.6	92.5	77.8	73.5	652	4.25
58-3C	52.9	47.0	44.6	40.1	50.0	73.5	"	4.25
59-1H	65.3	73.5	85.6	90.5	69.4	49.0	465	2.13
59-3C	47.6	43.5	37.5	34.2	45.6	49.0	"	2.13

TABLE NO. 5 (contd)

EXPERIMENTAL MEASUREMENTS FOR 24.0 wt.% Fe_2O_3 SUSPENSIONS

Run Number	Batch Temp. No. 1	Batch Temp. No. 2	Wall Temp. No. 1	Wall Temp. No. 2	Avg. Temp. °C	App. Visc. cp.	RPM	Scale lbs.
				PADDLE 4 x 2"				
60-1H	69.6	78.0	88.0	93.5	73.8	45	519	2.66
60-3C	58.1	52.4	46.4	41.0	55.3	45	"	2.66
61-1H	68.9	80.0	84.0	92.0	74.5	41	584	3.32
61-3C	52.1	46.6	41.7	37.1	49.4	41	"	3.32
				PADDLE 4 x 1"				
56-1H	67.4	78.5	89.9	95.5	73.0	38	645	1.88
56-3C	52.5	48.0	40.5	37.5	50.3	38	"	1.88
57-1H	63.0	73.5	89.5	94.6	68.3	43	550	1.37
57-3C	42.0	39.0	31.5	29.9	40.5	43	"	1.37
				PROPELLER 6"				
75-1H	62.0	75.0	78.6	87.2	68.5	38	646	3.04
75-3C	48.2	42.5	40.5	36.5	45.4	38	"	3.04
76-1H	64.6	74.5	89.3	93.6	69.6	60	375	1.10
76-3C	49.0	44.4	34.5	31.0	46.7	60	"	1.10
77-1H	69.5	78.0	86.5	92.0	73.8	48	478	1.58
77-3C	61.7	54.4	46.5	41.7	58.1	48	"	1.58
78-1H	63.0	73.1	82.6	89.3	68.1	44	556	2.22
78-3C	45.8	40.7	37.1	33.3	43.3	44	"	2.22

TABLE NO. 6

EXPERIMENTAL MEASUREMENTS FOR 13.1 wt.% Fe_2O_3 SUSPENSIONS

Run Number	Batch Temp. No. 1	Batch Temp. No. 2	Wall Temp. No. 1	Wall Temp. No. 2	Avg. Temp.°C	App. Visc.cp.	RPM	Scale lbs.
				ANCHOR 9"				
85-1H	67.0	80.0	76.0	86.7	73.5	17.0	162	5.96
85-3C	53.0	46.0	47.5	41.2	49.5	18.2	"	5.96
86-1H	72.0	82.3	89.0	94.5	77.2	28.8	65	1.02
86-3C	52.0	46.5	43.0	38.5	49.3	31.5	"	1.02
87-1H	63.7	78.5	77.5	87.5	71.1	21.0	116	3.22
87-3C	47.2	41.5	41.0	36.0	44.4	22.8	"	3.22
				TURBINE 6 x 1.25"				
109-1H	70.5	83.0	78.0	88.0	76.8	11.0	334	6.20
109-3C	49.3	43.0	45.1	39.6	46.2	12.1	"	6.20
110-1H	76.7	85.3	88.0	94.5	81.0	18.6	136	1.12
110-3C	53.0	47.3	45.3	40.3	50.2	20.2	"	1.12
111-1H	77.3	86.7	84.5	92.0	82.0	13.5	239	3.22
111-3C	49.1	43.1	44.0	38.3	46.1	14.7	"	3.22
				TURBINE 4 x 0.75"				
112-1H	74.3	86.5	82.3	91.8	80.4	7.3	653	3.48
112-3C	43.6	38.3	39.8	35.3	41.0	8.4	"	3.48
113-1H	78.5	86.5	90.2	96.2	82.5	11.2	308	0.80
113-3C	57.0	50.4	46.0	40.3	53.7	12.2	"	0.80
114-1H	78.5	87.0	87.7	94.4	82.8	9.5	414	1.40
114-3C	46.2	41.0	40.1	36.3	43.6	11.0	"	1.40
115-1H	70.3	80.0	79.7	87.0	74.6	8.4	535	2.37
115-3C	50.0	44.0	44.0	39.0	47.0	9.2	"	2.37
				PADDLE 8 x 2"				
106-1H	65.8	74.5	72.0	80.5	70.2	14.8	204	5.40
106-3C	51.4	45.0	46.1	40.5	48.2	15.8	"	5.40
107-1H	79.0	86.5	91.0	96.0	82.8	23.5	88	1.00
107-3C	51.5	46.0	42.0	38.0	48.8	26.0	"	1.00
108-1H	77.2	87.3	86.5	94.0	82.0	17.5	149	2.90
108-3C	51.3	45.3	44.0	39.5	48.3	19.0	"	2.90
				PADDLE 8 x 1"				
102-1H	67.8	76.5	73.1	81.0	72.2	10.8	361	6.60
102-3C	44.5	39.0	40.0	35.5	41.8	11.8	"	6.60
103-1H	75.6	83.5	90.4	94.5	79.6	19.0	130	0.90
103-3C	51.5	46.5	40.0	36.0	49.0	21.8	"	0.90

TABLE NO. 6 (contd.)

EXPERIMENTAL MEASUREMENTS FOR 13.1 wt.% Fe_2O_3 SUSPENSIONS

Run Number	Batch Temp. No. 1	Batch Temp. No. 2	Wall Temp. No. 1	Wall Temp. No. 2	Avg. Temp.°C	App. Visc.cp.	RPM	Scale lbs.
				PADDLE 8 x 1"				
104-1H	66.7	74.0	75.7	81.0	70.4	14.8	209	2.25
104-3C	52.0	45.8	44.1	39.0	48.9	15.7	"	2.25
105-1H	71.0	82.0	80.0	89.0	76.5	12.2	282	4.00
105-3C	54.3	47.5	49.0	43.2	50.9	13.2	"	4.00
				PADDLE 6 x 2"				
99-1H	75.2	83.8	81.0	89.0	79.5	10.1	378	6.16
99-3C	65.5	55.6	58.5	50.1	60.5	10.8	"	6.16
100-1H	77.0	85.0	92.5	98.5	81.0	18.0	144	0.90
100-3C	48.0	43.3	37.5	34.3	45.7	20.0	"	0.90
101-1H	67.5	77.0	78.0	86.0	72.3	12.8	265	3.00
101-3C	48.5	43.0	42.0	37.0	45.8	13.8	"	3.00
				PADDLE 6 x 1"				
95-1H	67.8	78.0	74.8	84.5	72.9	7.8	605	6.67
95-3C	52.5	45.3	47.5	41.5	48.9	8.4	"	6.67
96-1H	72.4	81.5	85.6	92.3	77.0	12.7	262	1.22
96-3C	45.8	41.0	37.5	33.5	43.4	14.2	"	1.22
97-1H	70.8	82.5	83.3	90.2	76.7	10.3	375	2.52
97-3C	49.1	43.1	43.5	38.0	46.1	11.4	"	2.52
98-1H	63.0	76.0	73.0	84.5	69.5	9.1	474	4.08
98-3C	45.7	40.0	41.0	36.0	42.9	10.0	"	4.08
				PADDLE 4 x 2"				
91-1H	78.2	87.9	85.5	93.5	83.1	7.4	650	3.86
91-3C	49.5	43.3	44.2	39.0	46.4	8.3	"	3.86
92-1H	67.0	78.0	82.5	89.5	72.5	10.7	354	1.20
92-3C	46.0	41.5	38.5	34.5	43.8	11.9	"	1.20
93-1H	67.3	78.8	80.4	88.5	73.1	9.3	450	1.85
93-3C	46.9	41.7	41.0	36.6	44.3	10.2	"	1.85
94-1H	79.0	87.4	86.5	93.5	83.2	8.0	550	2.80
94-3C	45.8	40.5	40.5	35.6	43.2	9.2	"	2.80
				PADDLE 4 x 1"				
88-1H	68.4	80.4	82.6	92.0	74.4	7.8	644	1.68
88-3C	56.0	49.0	47.0	41.0	52.5	8.2	"	1.68
89-1H	61.3	72.5	80.8	88.8	66.9	9.7	450	0.80
89-3C	48.6	43.5	38.7	35.0	46.1	10.3	"	0.80

TABLE NO. 6 (contd.)

EXPERIMENTAL MEASUREMENTS FOR 13.1 wt.% Fe_2O_3 SUSPENSIONS

Run Number	Batch Temp. No. 1	Batch Temp. No. 2	Wall Temp. No.1	Wall Temp. No. 2	Avg. Temp.°C	App. Visc.cp.	RPM	Scale lbs.
				PADDLE 4 x 1"				
90-1H	79.5	89.0	92.0	97.7	84.3	8.1	546	1.14
90-3C	48.6	43.3	40.0	36.0	46.0	9.0	"	1.14
				PROPELLER 6"				
116-1H	79.0	90.5	87.2	95.3	84.8	7.4	629	2.93
116-3C	47.6	41.6	43.5	38.0	44.6	8.4	"	2.93
117=1H	77.2	85.0	89.6	94.0	81.1	11.8	292	0.68
117-3C	45.3	40.8	37.8	34.2	43.1	13.0	"	0.68
118-1H	66.7	81.0	81.0	90.5	73.9	10.0	407	1.12
118-3C	51.8	45.4	45.6	40.0	48.6	10.8	"	1.12
119-1H	70.3	80.8	79.7	87.3	75.5	8.5	508	1.82
119-3C	45.8	40.6	41.1	36.0	43.2	9.5	"	1.82
				PROPELLER 4.1"				
120-1H	60.2	71.2	79.0	85.0	65.7	7.7	643	0.50
120-3C	49.3	43.8	40.1	35.7	46.6	8.4	"	0.50

TABLE NO. 7

EXPERIMENTAL MEASUREMENTS FOR 24.4 wt.% KAOLIN SUSPENSIONS

Run Number	Batch Temp. No. 1	Batch Temp. No. 2	Wall Temp. No. 1	Wall Temp. No. 2	Avg. Temp. °C	App. Visc.cp.	RPM	Scale lbs.
				ANCHOR 9"				
06-1H	51.5	62.0	87.5	91.3	56.8	580	180	7.51
06-4C	44.8	41.5	32.5	32.3	43.2	580	180	7.51
				TURBINE 5 x 1"				
01-1H	49.3	58.8	73.6	80.5	54.1	215	573	7.86
01-5C	51.2	47.1	39.0	35.9	49.2	215	573	7.86
02-2H	59.8	70.6	88.6	93.4	65.2	215	567	7.85
02-6C	53.5	48.6	37.6	34.8	51.1	215	567	7.85
				PADDLE 6 x 2"				
05-2H	72.7	77.8	95.6	100.0	75.3	300	397	7.57
05-6C	46.9	44.2	31.8	29.6	45.6	300	397	7.57
				PROPELLER 6"				
04-4H	68.8	74.6	93.8	96.4	71.7	180	700	3.80
04-7C	48.7	45.0	33.7	31.5	46.9	180	700	3.80

TABLE NO. 8

EXPERIMENTAL MEASUREMENTS FOR 18.4 wt.% KAOLIN SUSPENSIONS

Run Number	Batch Temp. No. 1	Batch Temp. No. 2	Wall Temp. No. 1	Wall Temp. No. 2	Avg. Temp.°C	App. Visc.cp.	RPM	Scale lbs.
				ANCHOR 9"				
08-1H	40.7	51.0	61.2	75.4	45.8	167	135	4.35
08-7C	54.4	49.0	42.6	38.4	51.7	166	135	4.35
				TURBINE 6 x 1.25"				
12-2H	76.5	85.2	91.0	96.8	80.9	67	371	7.80
12-4C	51.9	46.0	42.6	37.9	49.0	71	371	7.80
13-2H	74.8	83.8	93.0	97.5	79.3	78	308	5.30
13-5C	49.8	45.0	38.7	34.9	47.4	84	308	5.30
14-2H	66.6	75.0	93.7	96.5	70.8	98	241	3.23
14-5C	52.3	48.0	34.2	32.2	50.2	104	241	3.23
				TURBINE 4 x 0.75"				
15-1H	67.8	76.0	88.2	92.4	71.9	44	620	3.15
15-6C	47.8	43.8	37.1	33.6	45.8	47	620	3.15
				TURBINE 5 x 1"				
09-1H	77.3	85.6	90.6	95.4	81.5	46	575	7.75
09-3C	54.5	48.0	45.8	40.7	51.3	49	575	7.75
10-2H	69.8	79.7	87.1	93.2	74.8	53	500	5.93
10-7C	46.0	41.4	37.0	33.8	43.7	56	500	5.93
11-3H	69.0	77.7	90.2	94.4	73.4	62	416	4.03
11-5C	71.0	63.2	52.6	47.5	67.1	63	416	4.03
12-2H	76.5	85.2	91.0	96.8	80.9	67	371	7.80
12-4C	51.9	46.0	42.6	37.9	49.0	71	371	7.80
				PADDLE 8 x 1"				
25-2H	71.0	83.3	92.3	97.0	77.2	66	385	7.65
25-5C	49.2	42.8	37.3	33.8	45.8	70	385	7.65
26-3H	72.8	81.2	94.8	98.2	77.0	80	305	4.82
26-4C	56.6	51.3	39.6	37.0	54.0	83	305	4.82
				PADDLE 6 x 2"				
16-2H	73.5	80.5	89.3	92.8	77.0	62	410	7.45
16-6C	48.9	43.6	39.0	34.7	46.3	66	410	7.45
17-2H	75.4	83.8	92.5	97.8	79.6	72	341	5.30
17-4C	51.4	46.3	40.0	36.7	48.9	77	341	5.30
18-2H	61.5	72.0	92.0	95.0	66.8	88	276	3.36
18-6C	48.6	44.7	32.8	31.0	46.7	92	276	3.36

TABLE NO. 8 (contd.)

EXPERIMENTAL MEASUREMENTS FOR 18.4 wt.% KAOLIN SUSPENSIONS

Run Number	Batch Temp. No. 1	No. 2	Wall Temp. No. 1	No. 2	Avg. Temp.°C	App. Visc.cp.	RPM	Scale lbs.
				PADDLE 6 x 1"				
19-2H	68.3	81.5	87.2	92.8	74.9	44	620	7.40
19-7C	43.4	39.0	36.4	32.9	41.2	47	620	7.40
20-1H	69.3	78.0	87.2	92.5	73.7	49	548	5.80
20-6C	51.0	45.7	40.0	35.8	48.4	52	548	5.80
21-2H	77.7	86.0	94.4	99.5	81.9	54	482	4.39
21-5C	49.6	44.6	36.8	34.0	47.1	57	482	4.39
22-1H	61.8	72.5	92.6	95.8	67.2	64	402	3.08
22-6C	46.9	41.1	29.8	27.7	44.0	67	402	3.08
				PADDLE 4 x 2"				
23-1H	80.6	87.5	95.6	99.0	84.1	42	642	3.86
23-4C	43.4	38.5	31.6	29.6	40.9	46	642	3.86
24-2H	70.4	77.8	93.5	95.8	74.1	50	531	2.58
24-4C	47.1	42.4	31.5	30.2	44.8	53	531	2.58
				PROPELLER 6"				
27-2H	76.0	84.8	94.5	98.9	80.4	42	657	2.73
27-4C	51.3	46.2	39.5	36.0	46.8	44	657	2.73
28-2H	72.0	81.4	94.0	98.2	76.7	48	549	1.91
28-5C	49.5	45.2	37.5	34.8	47.4	52	549	1.91
29-2H	64.6	74.2	87.9	93.3	69.4	46	604	2.34
29-6C	42.9	39.0	33.6	30.5	41.0	48	604	2.34
				PROPELLER 5.2"				
31-2H	77.5	83.8	97.8	99.8	80.7	42	654	1.65
31-5C	39.0	36.2	30.3	28.6	37.6	45	654	1.65

Calculations

A correction in the heat balance was made to compensate for the heat due to mixing. This quantity can be readily calculated knowing the torque from the dynamometer and the mixer speed. This quantity must be subtracted during heating and added during cooling.

The heat input to the batch is equal to:

$$Q = WC_b\,dT_b/dt \pm Q_{p'} \qquad (23)$$

where W is the batch weight, C_b the batch specific heat, and dT_b is the change in batch temperature over some time interval dt. $Q_{p'}$ is the heat due to mixing.

Knowing Q, the heat transfer coefficient, H, can be calculated as follows:

$$H = Q/A\,\Delta T_{\omega-b} \qquad (24)$$

Where A is the heat transfer area, and ΔT is the temperature driving force measured at the vessel surface and average batch temperature.

The wall temperature measured in these studies was recessed (.04 inches) within the wall. This extra resistance between the wall surface and the thermocouple can be approximated by knowing the wall thickness to the thermocouple and the thermal conductivity of the wall.

This approximation shown by Hagedorn and Salamone (9) results in the following:

$$H = H'\left[1 + H(L/K_\omega)\right] \qquad (25)$$

or $$H = H'\,(1 + 0.0001774H')$$

where $$H' = Q/A\,\Delta T_{\omega'-b}$$

ΔT_{w-b} being the average difference in the temperature measured in the wall and the batch temperature.

The desired dimensionless groups were then calculated. The Nusselt, Reynolds, Prandtl, and Power numbers were calculated as follows:

$$N_{Nu} = HD_t/K_s \qquad (26)$$

$$N_{Re} = \frac{D_a{}^2 N}{\mu_a} \qquad (27)$$

$$N_{Pr} = C_b \, \mu_a/K_s \qquad (28)$$

$$N_{Po} = 32.2 \; P/\rho \, N^3 D_a^5 \qquad (29)$$

where H is the film heat transfer coefficient

D_t is the tank diameter

K_s is the suspension's thermal conductivity

ρ is the suspension's density

C_b is the suspension's specific heat

N is the mixer revolutions

D_a is the impeller diameter

P is the mixing power

μ_a is the apparent viscosity determined at a shear rate equal to 11.5N. Sample calculations can be found in Appendix No. I. All calculations were performed using a Wang 380 desk computer with tape programing. The calculated results for all five suspensions and water are given in Tables No. 9 to 14.

TABLE NO. 9

CALCULATED MEASUREMENTS FOR WATER

Run Numbers	Density lb./ft.^{3}	k Btu / hr.ft.°F	Power ft.lb./sec.	H Btu / °F hr.ft.^{2}	N_{Nu}	N_{Re}	N_{Pr}	N_{Po}	N_V
				ANCHOR 9"					
155-1H	60.7	0.395	27.6	1332	3944	389746	2.2	2.9	1.05
155-4C	61.8	0.367	27.6	1117	3565	246903	3.8	2.9	0.95
156-2H	60.4	0.403	0.7	659	1915	124461	2.0	3.0	1.07
156-4C	61.8	0.367	0.7	569	1817	71566	3.8	2.9	0.89
157-1H	60.7	0.395	9.0	1038	3073	266096	2.2	3.0	1.07
157-4C	61.9	0.364	9.0	892	2869	158847	4.1	3.0	0.93
				TURBINE 6 x 1.25"					
127-1H	60.8	0.393	31.6	1302	3873	290523	2.3	5.0	1.08
127-3C	61.6	0.374	31.6	1376	4305	215726	3.3	4.9	0.94
149-1H	60.9	0.390	51.8	1282	3842	322985	2.4	5.3	1.08
149-3C	61.7	0.369	51.8	1222	3877	227606	3.7	5.2	0.93
150-2H	60.5	0.401	21.7	1169	3415	275816	2.0	5.4	1.05
150-3C	61.8	0.367	21.7	1064	3390	164393	3.8	5.3	0.93
151-2H	60.6	0.399	1.5	694	2036	115875	2.1	4.7	1.08
151-3C	61.8	0.366	1.5	523	1674	69353	3.9	4.6	0.89
				TURBINE 5 x 1"					
128-2H	60.7	0.396	70.8	1691	4993	367696	2.2	5.2	1.06
128-4C	61.5	0.375	70.8	1268	3954	267879	3.2	5.1	0.94
129-1H	60.5	0.399	0.4	579	1696	84233	2.1	2.6	1.07
129-4C	61.5	0.376	0.5	451	1404	59954	3.1	3.6	0.88

TABLE NO. 9 (contd.)

CALCULATED MEASUREMENTS FOR WATER

Run Numbers	Density lb./ft.^{3}	k Btu / hr.ft.°F	Power ft.lb./sec.	H Btu / °F hr.ft.^{2}	N_{Nu}	N_{Re}	N_{Pr}	N_{Po}	N_V
				TURBINE 5 x 1"					
130-1H	60.6	0.399	9.9	940	2759	205555	2.1	4.6	1.05
130-3C	60.8	0.393	10.0	940	2799	190558	2.3	4.6	0.92
131-1H	61.5	0.377	35.1	1202	3729	222151	3.1	4.9	1.12
131-3C	61.3	0.381	35.3	1201	3690	234846	2.9	5.0	0.93
132-1H	61.5	0.376	35.7	1326	4132	215541	3.2	5.0	1.12
132-3C	61.2	0.385	35.5	1028	3127	249372	2.7	5.0	1.06
133-2H	60.3	0.405	71.1	1492	4311	409760	1.9	5.2	1.04
133-3C	61.1	0.386	71.1	1238	3748	320625	2.6	5.2	0.93
				TURBINE 4 x 0.75"					
158-1H	60.8	0.393	56.9	1162	3461	289872	2.3	5.9	1.09
158-4C	61.9	0.363	56.9	1071	3458	174538	4.2	5.8	0.94
159-2H	60.6	0.398	5.1	706	2075	145050	2.1	5.3	1.07
159-4C	61.9	0.63	5.1	628	2027	81544	4.2	5.2	0.91
160-1H	60.8	0.393	27.0	965	2872	228198	2.3	5.9	1.07
160-3C	61.7	0.371	27.0	1031	3254	159726	3.5	5.8	0.95
				PADDLE 6 x 2"					
141-1H	61.0	0.389	72.2	478	1438	386328	2.4	4.1	1.10
141-4C	61.9	0.361	72.2	1314	4257	238311	4.3	4.0	1.05
142-2H	60.4	0.402	30.0	1175	3422	342181	2.0	4.0	1.05
142-4C	61.9	0.364	30.0	1107	3563	187758	4.1	4.0	0.94

TABLE NO. 9 (contd.)

CALCULATED MEASUREMENTS FOR WATER

Run Numbers	Density lb./ft.^{3}	k $\frac{Btu}{hr.ft.°F}$	Power ft.lb./sec.	H $\frac{Btu}{°F\ hr.ft.^2}$	N_{Nu}	N_{Re}	N_{Pr}	N_{Po}	N_V
				PADDLE 6 x 2"					
143-2H	60.5	0.401	8.9	766	2236	224842	2.0	4.1	1.07
143-3C	61.8	0.365	8.9	935	2997	128168	4.0	4.0	0.93
144-1H	60.7	0.396	1.1	489	1447	98082	2.2	4.8	1.12
144-3C	61.8	0.366	1.1	479	1534	60690	3.9	4.7	0.88
				PADDLE 6 x 1"					
137-1H	61.2	0.385	64.9	1064	3231	479730	2.6	1.6	1.06
137-4C	62.0	0.361	64.9	1074	3486	309221	4.4	1.6	0.94
138-1H	61.1	0.386	39.5	1056	3203	411122	2.6	1.6	1.11
138-3C	61.7	0.369	39.5	867	2748	312047	3.6	1.6	0.92
139-2H	60.3	0.404	17.8	874	2532	405508	1.9	1.6	1.05
139-4C	62.0	0.359	17.8	682	2226	195585	4.6	1.5	0.94
140-1H	60.7	0.396	2.1	549	1624	172128	2.2	1.7	1.12
140-3C	61.8	0.365	2.1	509	1634	105005	4.0	1.7	0.89
				PADDLE 4 x 2"					
145-1H	60.7	0.395	49.1	1149	3403	275395	2.2	6.5	1.08
145-3C	61.9	0.363	49.1	989	3184	163754	4.1	6.4	0.93
146-1H	61.2	0.385	3.3	500	1520	77974	2.6	12.6	1.15
146-4C	62.0	0.360	3.3	435	1413	49931	4.5	12.4	0.88
147-1H	60.8	0.394	7.5	806	2395	150659	2.3	5.8	1.11
147-3C	61.9	0.364	7.5	674	2168	92471	4.1	5.7	0.90
148-2H	60.6	0.398	27.4	892	2624	236805	2.1	6.4	1.08

TABLE NO. 9 (contd.)

CALCULATED MEASUREMENTS FOR WATER

Run Numbers	Density lb./ft.^{3}	k Btu / hr.ft.°F	Power ft.lb./sec.	H Btu / °F hr.ft.^{2}	N_{Nu}	N_{Re}	N_{Pr}	N_{Po}	N_V
				PADDLE 4 x 1"					
152-1H	60.7	0.396	25.6	784	2319	303998	2.2	2.6	1.09
152-3C	61.9	0.364	25.6	686	2204	182347	4.0	2.5	0.91
153-2H	60.4	0.403	4.9	556	1616	186074	2.0	2.8	1.07
153-3C	61.8	0.365	4.9	474	1522	103214	4.0	2.8	0.90
154-2H	60.7	0.396	11.2	829	2454	230004	2.2	2.6	1.10
154-3C	61.8	0.364	11.2	531	1705	138608	4.0	2.6	0.90
				PROPELLER 5.2"					
123-2H	60.6	0.399	3.2	644	1891	261838	2.1	0.7	1.08
123-4C	61.9	0.365	3.2	507	1627	152097	4.0	0.7	0.89
124-2H	61.0	0.390	2.3	663	1991	240548	2.4	0.5	1.14
124-3C	61.6	0.374	2.3	625	1959	186905	3.3	0.5	0.89
125-1H	60.9	0.392	14.6	1170	3490	411301	2.3	0.7	1.07
125-4C	61.5	0.376	14.6	864	2691	318156	3.2	0.7	0.91
126-3C	61.9	0.363	43.5	833	2685	355527	4.1	0.7	0.91
				PROPELLER 4.1"					
134-1H	61.0	0.388	9.2	763	2302	287767	2.5	0.8	1.14
134-3C	61.6	0.372	9.2	574	1805	221655	3.4	0.8	0.89
135-2H	60.8	0.394	2.2	447	1329	189606	2.3	0.9	1.12
135-3C	61.7	0.372	2.2	475	1495	133739	3.4	0.9	0.87
136-1H	61.0	0.390	4.5	682	2050	236031	2.4	0.8	1.14
136-3C	61.7	0.369	4.5	537	1704	169411	3.6	0.8	0.92

TABLE NO. 10

CALCULATED RESULTS FOR 33.2 wt.% Fe_2O_3 SUSPENSIONS

Run Number	Density lb./ft.^{3}	k $\frac{Btu}{hr.\ ft.°F}$	Power ft.lb./sec.	H $\frac{Btu}{°F\ hr.ft.^2}$	N_{Nu}	N_{Re}	N_{Pr}	N_{Po}	N_V
				ANCHOR 9"					
44-1H	83.1	0.384	36.6	271	828	517	1698	2.87	0.97
44-3C	84.5	0.356	36.6	260	857	572	1670	2.83	1.05
				TURBINE 6 x 1.25"					
45-1H	83.0	0.386	77.4	299	909	871	922	5.19	0.94
45-3C	84.5	0.357	77.4	235	770	968	907	5.09	1.03
46-1H	83.6	0.377	40.4	167	518	610	1097	5.06	0.92
46-3C	84.6	0.353	40.4	124	412	660	1090	4.99	1.06
				TURBINE 5 x 1"					
32-1H	83.2	0.382	115.0	389	1190	1349	645	5.23	0.93
32-3C	84.6	0.353	115.0	297	984	1500	634	5.14	1.04
33-1H	83.3	0.381	78.3	230	709	1065	717	5.34	0.92
33-3C	84.6	0.354	78.3	194	643	1180	703	5.26	1.03
				PADDLE 8 x 1"					
40-1H	83.3	0.380	77.2	246	758	1612	925	1.13	0.94
40-3C	84.4	0.360	77.2	193	628	1765	902	1.12	1.06
41-1H	83.7	0.375	46.9	351	1094	1270	1017	1.11	0.91
41-3C	84.5	0.357	46.9	146	480	1345	1016	1.10	1.04
				PADDLE 6 x 2"					
37-1H	83.5	0.378	84.3	273	846	1092	837	4.10	0.95
37-3C	84.5	0.355	84.3	229	755	1185	828	4.05	1.04
38-1H	83.9	0.371	53.0	198	626	824	970	4.10	0.93
38-3C	84.5	0.356	53.0	149	491	873	959	4.06	1.05

TABLE NO. 10 (contd.)

CALCULATED RESULTS FOR 33.2 wt.% Fe_2O_3 SUSPENSIONS

Run Number	Density lb./ft.^{3}	k $\frac{Btu}{hr.\ ft.\ °F}$	Power ft.lb./sec.	h $\frac{Btu}{°F\ hr.ft.^2}$	N_{Nu}	N_{Re}	N_{Pr}	N_{Po}	N_V
				PADDLE 6 x 1"					
35-1H	83.3	0.381	124.5	281	864	2285	601	1.75	0.94
35-3C	84.6	0.355	124.5	227	749	2512	592	1.72	1.03
36-1H	83.4	0.380	78.5	207	639	1729	681	1.76	0.93
36-3C	84.5	0.357	78.5	184	603	1881	672	1.74	1.04
				PADDLE 4 x 2"					
39-1H	83.5	0.377	88.2	212	658	1320	532	6.38	0.92
39-3C	84.4	0.360	88.2	174	568	1395	531	6.31	1.04
				PROPELLER 6"					
42-1H	83.5	0.378	67.3	230	712	2916	535	0.66	0.94
42-3C	84.5	0.358	67.3	221	722	3171	524	0.65	1.02
43-1H	83.0	0.386	43.8	252	765	2133	616	0.67	0.93
43-3C	84.5	0.357	43.8	164	537	2404	599	0.66	1.02

TABLE NO. 11

CALCULATED RESULTS FOR 24.0 wt.% Fe_2O_3 SUSPENSIONS

Run Number	Density lb./ft.^{3}	k Btu/hr. ft. °F	Power ft.lb./sec.	H Btu/°F hr.ft.^{2}	N_{Nu}	N_{Re}	N_{Pr}	N_{Po}	N_V
				ANCHOR 9"					
83-1H	75.4	0.389	32.0	507	1527	1436	600	2.82	1.00
83-3C	76.7	0.362	32.0	520	1682	1461	643	2.78	1.00
84-1H	76.0	0.377	4.7	167	519	489	1005	2.51	1.00
84-3C	76.7	0.360	4.7	185	603	494	1052	2.48	1.00
				TURBINE 6 x 1.25"					
47-1H	75.2	0.392	74.9	459	1372	2596	313	5.13	1.00
47-3C	76.7	0.360	74.9	449	1463	2650	340	5.02	1.00
48-1H	75.9	0.379	15.8	246	763	1008	503	5.01	1.00
48-3C	76.7	0.359	15.8	197	642	1019	529	4.96	1.00
49-1H	75.4	0.388	49.7	375	1131	2008	356	5.17	1.00
49-3C	76.7	0.359	49.7	356	1160	2043	383	5.08	1.00
50-1H	75.5	0.387	30.4	301	912	1496	407	5.16	1.00
50-3C	76.8	0.359	30.4	302	985	1521	438	5.08	1.00
				TURBINE 5 x 1"					
79-1H	75.3	0.390	99.6	566	1696	3774	224	5.09	1.00
79-3C	76.7	0.361	99.6	471	1528	3844	242	5.00	1.00
80-1H	75.5	0.387	19.6	288	872	1349	362	5.37	1.00
80-3C	76.7	0.360	19.6	200	650	1371	388	5.29	1.00

TABLE NO. 11 (contd.)

CALCULATED RESULTS FOR 24.0 wt.% Fe_2O_3 SUSPENSIONS

Run Number	Density lb./ft.^{3}	k $\frac{\text{Btu}}{\text{hr. ft. °F}}$	Power ft.lb./sec.	H $\frac{\text{Btu}}{\text{°F hr.ft.}^2}$	N_{Nu}	N_{Re}	N_{Pr}	N_{Po}	N_V
			TURBINE 5 x 1"						
81-1H	75.4	0.389	36.3	328	988	2028	300	5.05	1.00
81-3C	76.8	0.356	36.3	295	970	2067	326	4.96	1.00
82-1H	75.6	0.386	64.7	352	1070	2960	252	5.04	1.00
82-3C	76.8	0.359	64.7	393	1285	3007	270	4.96	1.00
			TURBINE 4 x 0.75"						
51-1H	75.5	0.387	69.7	346	1046	3535	191	5.79	1.00
51-3C	76.6	0.362	69.7	330	1066	3589	203	5.70	1.00
52-1H	75.8	0.382	20.7	248	762	1713	267	5.60	1.00
52-3C	76.7	0.361	20.7	221	718	1733	285	5.54	1.00
53-1H	75.6	0.385	31.6	365	1109	2263	232	5.65	1.00
53-3C	76.7	0.362	31.6	266	860	2295	247	5.57	1.00
54-3C	76.4	0.368	49.9	295	938	3004	216	5.52	1.00
55-1H	75.6	0.385	46.6	305	928	2822	212	5.66	1.00
55-3C	76.8	0.358	46.6	311	1017	2865	227	5.57	1.00
			PADDLE 8 x 2"						
72-1H	75.4	0.388	43.8	523	1579	1956	471	2.83	1.00
72-3C	76.7	0.361	43.8	377	1223	1988	505	2.79	1.00
73-1H	75.8	0.381	9.3	254	780	806	714	2.63	1.00
73-3C	76.6	0.361	9.3	171	557	815	753	2.61	1.00

TABLE NO. 11 (contd.)

CALCULATED RESULTS FOR 24.0 wt.% Fe_2O_3 SUSPENSIONS

Run Number	Density lb./ft.^{3}	k Btu/hr. ft.°F	Power ft.lb./sec.	H Btu/°F hr.ft.^{2}	N_{Nu}	N_{Re}	N_{Pr}	N_{Po}	N_V
			PADDLE 8 x 1"						
69-1H	75.4	0.388	68.0	509	1536	4609	316	1.12	1.00
69-3C	76.7	0.361	68.0	383	1244	4687	339	1.10	1.00
70-1H	76.0	0.378	18.6	122	379	2050	473	1.13	1.00
70-3C	76.7	0.360	18.6	198	644	2070	496	1.12	1.00
71-1H	75.5	0.386	36.6	362	1099	3155	378	1.11	1.00
71-3C	76.8	0.358	36.6	285	932	3208	406	1.10	1.00
			PADDLE 6 x 2"						
66-1H	75.4	0.388	75.6	516	1556	2969	301	4.03	1.00
66-3C	76.5	0.365	75.6	414	1329	3013	319	3.97	1.00
67-1H	75.7	0.383	14.9	164	517	1138	468	3.95	1.00
67-3C	76.7	0.359	14.9	177	578	1153	497	3.90	1.00
68-1H	75.5	0.387	36.3	300	907	1949	362	3.96	1.00
68-3C	76.8	0.358	36.3	277	908	1983	390	3.89	1.00
			PADDLE 6 x 1"						
62-1H	75.4	0.388	122.1	552	1665	7034	201	1.65	1.00
62-3C	76.5	0.366	122.1	576	1845	7135	212	1.63	1.00
63-1H	75.5	0.387	21.4	285	862	2427	327	1.65	1.00
63-3C	76.7	0.360	21.4	175	569	2466	350	1.62	1.00
64-1H	75.9	0.379	40.7	287	887	3625	276	1.66	1.00
64-3C	76.7	0.361	40.7	251	814	3662	290	1.64	1.00

TABLE NO. 11 (contd.)

CALCULATED RESULTS FOR 24.0 wt.% Fe_2O_3 SUSPENSIONS

Run Number	Density lb./ft.^{3}	k $\frac{\text{Btu}}{\text{hr. ft.°F}}$	Power ft.lb./sec.	H $\frac{\text{Btu}}{\text{°F hr.ft.}^2}$	N_{Nu}	N_{Re}	N_{Pr}	N_{Po}	N_V
				PADDLE 6 x 1"					
65-1H	75.3	0.390	74.0	293	878	5175	229	1.65	1.00
65-3C	76.8	0.359	74.0	321	1049	5276	249	1.62	1.00
				PADDLE 4 x 2"					
58-1H	75.5	0.387	78.8	339	1027	3616	188	6.37	1.00
58-3C	76.6	0.364	78.8	374	1204	3667	200	6.28	1.00
59-1H	75.9	0.380	28.2	204	628	1983	250	6.25	1.00
59-3C	76.7	0.360	28.2	197	640	2005	264	6.18	1.00
60-1H	75.7	0.384	39.3	230	703	2404	228	6.28	1.00
60-3C	76.4	0.368	39.3	231	736	2427	237	6.22	1.00
61-1H	75.6	0.384	55.2	390	1190	2968	208	6.19	1.00
61-3C	76.6	0.364	55.2	261	841	3005	219	6.12	1.00
				PADDLE 4 x 1"					
56-1H	75.7	0.383	34.5	263	804	3540	193	2.87	1.00
56-3C	76.6	0.364	34.5	186	599	3580	202	2.84	1.00
57-1H	75.9	0.379	21.4	205	632	2674	210	2.87	1.00
57-3C	76.8	0.356	21.4	141	465	2707	234	2.84	1.00
				PROPELLER 6"					
75-1H	75.9	0.379	55.9	433	1336	7999	195	0.61	1.00
75-3C	76.7	0.360	55.9	402	1305	8085	205	0.60	1.00
76-1H	75.9	0.380	11.7	210	647	2939	307	0.65	1.00
76-3C	76.7	0.361	11.7	152	492	2970	322	0.65	1.00

TABLE NO. 11 (contd.)

CALCULATED RESULTS FOR 24.0 wt.% Fe_2O_3 SUSPENSIONS

Run Number	Density $lb./ft.^3$	k $\frac{Btu}{hr.\ ft.\ °F}$	Power ft.lb./sec.	H $\frac{Btu}{°F\ hr.ft.^2}$	N_{Nu}	N_{Re}	N_{Pr}	N_{Po}	N_V
			PROPELLER 6"						
77-1H	75.7	0.384	21.5	256	783	4672	243	0.58	1.00
77-3C	76.3	0.371	21.5	245	775	4711	251	0.57	1.00
78-1H	75.9	0.379	35.1	264	815	5947	226	0.60	1.00
78-3C	76.8	0.359	35.1	300	980	6014	238	0.59	1.00

TABLE NO. 12

CALCULATED RESULTS FOR 13.1 wt.% Fe_2O_3 SUSPENSIONS

Run Number	Density lb./ft.^{3}	k Btu / hr. ft.°F	Power ft.lb./sec.	H Btu / °F hr.ft.^{2}	N_{Nu}	N_{Re}	N_{Pr}	N_{Po}	N_V
				ANCHOR 9"					
85-1H	68.2	0.387	27.5	855	2586	9066	95.1	2.78	1.03
85-3C	69.0	0.366	27.5	690	2205	8572	107.4	2.74	0.98
86-1H	68.0	0.390	1.9	340	1021	2141	159.8	2.96	1.09
86-3C	69.0	0.366	1.9	310	992	1986	186.0	2.92	0.98
87-1H	68.3	0.385	10.6	654	1989	6068	122.6	2.92	1.05
87-3C	69.2	0.362	10.6	479	1551	4909	136.2	2.89	0.97
				TURBINE 6 x 1.25"					
109-1H	68.1	0.390	58.9	1055	3169	12814	61.1	5.17	1.02
109-3C	69.1	0.363	58.9	864	2785	11832	72.0	5.09	0.98
110-1H	67.9	0.393	4.3	408	1216	3077	102.4	5.65	1.06
110-3C	69.0	0.367	4.3	375	1199	2881	119.0	5.55	0.96
111-1H	67.8	0.394	21.9	768	2281	7438	74.1	5.27	1.04
111-3C	69.1	0.363	21.9	608	1960	6963	87.4	5.17	0.98
				TURBINE 4 x 0.75"					
112-1H	67.9	0.393	64.4	956	2850	16656	40.2	5.83	1.04
112-3C	69.3	0.359	64.4	809	2639	14765	50.6	5.72	0.99
113-1H	67.8	0.394	7.0	361	1072	5136	61.4	5.98	1.04
113-3C	68.9	0.370	7.0	299	948	4792	71.3	5.89	0.94

TABLE NO. 12 (contd.)

CALCULATED RESULTS FOR 13.1 wt.% Fe_2O_3 SUSPENSIONS

Run Number	Density lb./ft.^{3}	k Btu / hr. ft. °F	Power ft.lb./sec.	H Btu / °F hr.ft.^{2}	N_{Nu}	N_{Re}	N_{Pr}	N_{Po}	N_V
				TURBINE 4 x 0.75"					
114-1H	67.8	0.395	16.5	505	1497	8139	52.1	5.80	1.06
114-3C	69.2	0.361	16.5	474	1537	7175	65.8	5.68	0.98
115-1H	68.2	0.388	36.1	570	1894	11959	46.9	5.85	1.02
115-3C	69.1	0.364	36.1	544	1749	11072	54.6	5.76	0.98
				PADDLE 8 x 2"					
106-1H	68.3	0.384	31.3	723	2204	10392	83.4	2.85	1.02
106-3C	69.1	0.365	31.3	661	2119	9840	93.5	2.82	0.99
107-1H	67.8	0.395	2.5	336	997	2801	128.9	2.85	1.07
107-3C	69.1	0.366	2.5	301	963	2579	153.7	2.80	0.96
108-1H	67.8	0.394	12.3	634	1883	6371	96.1	2.89	1.03
108-3C	69.1	0.365	12.3	449	1439	5975	112.4	2.84	0.96
				PADDLE 8 x 1"					
102-1H	68.3	0.386	67.8	923	2801	25173	60.6	0.51	1.03
102-3C	69.2	0.360	67.8	699	2278	23373	70.9	0.50	0.98
103-1H	67.9	0.392	3.3	292	873	5129	104.9	8.61	1.07
103-3C	69.1	0.366	3.3	215	690	4544	128.8	8.47	0.99
104-1H	68.3	0.384	13.4	446	1360	10645	83.4	0.45	1.02
104-3C	69.1	0.366	13.4	411	1315	10141	92.8	0.45	0.98
105-1H	68.1	0.389	32.0	696	2092	17361	67.8	0.62	1.02
105-3C	69.0	0.367	32.0	721	2298	16263	77.6	0.61	0.99

TABLE NO. 12 (contd.)

CALCULATED RESULTS FOR 13.1 wt.% Fe_2O_3 SUSPENSIONS

Run Number	Density lb./ft.^{3}	k Btu / hr. ft. °F	Power ft.lb./sec.	H Btu / °F hr.ft.^{2}	N_{Nu}	N_{Re}	N_{Pr}	N_{Po}	N_V
				PADDLE 6 x 2"					
99-1H	67.9	0.392	66.2	797	2381	15765	55.8	4.01	1.01
99-3C	68.7	0.376	66.2	820	2555	14906	62.2	3.97	0.98
100-1H	67.9	0.393	3.7	391	1163	3366	99.1	4.05	1.07
100-3C	69.1	0.363	3.7	228	736	3086	119.1	3.97	0.95
101-1H	68.2	0.386	22.6	478	1451	8761	71.8	3.96	1.03
101-3C	69.1	0.363	22.6	431	1390	8232	82.1	3.91	0.98
				PADDLE 6 x 1"					
95-1H	68.2	0.386	114.8	765	2317	32798	43.7	1.69	1.03
95-3C	69.1	0.366	114.8	858	2745	30827	49.6	1.67	0.99
96-1H	68.1	0.390	9.1	366	1101	8705	70.5	1.65	1.06
96-3C	69.2	0.361	9.1	290	943	7917	85.0	1.63	0.98
97-1H	68.1	0.389	26.9	576	1733	15364	57.2	1.67	1.05
97-3C	69.1	0.363	26.9	559	1803	14099	67.8	1.64	0.99
98-1H	68.4	0.383	55.0	711	2170	22077	51.3	1.68	1.03
98-3C	69.2	0.360	55.0	666	2163	20341	59.9	1.66	0.99
				PADDLE 4 x 2"					
91-1H	67.8	0.395	71.4	764	2264	16402	40.6	6.49	1.06
91-3C	69.1	0.364	71.4	657	2116	14913	49.3	6.36	0.98
92-1H	68.2	0.386	12.1	395	1200	6220	60.0	6.75	1.05
92-3C	69.2	0.361	12.1	297	964	5670	71.2	6.66	0.97

TABLE NO. 12 (contd.)

CALCULATED RESULTS FOR 13.1 wt.% Fe_2O_3 SUSPENSIONS

Run Number	Density lb./ft.^{3}	k $\frac{Btu}{hr.\ ft.\ °F}$	Power ft.lb./sec.	H $\frac{Btu}{°F\ hr.ft.^2}$	N_{Nu}	N_{Re}	N_{Pr}	N_{Po}	N_V
				PADDLE 4 x 2"					
93-1H	68.2	0.386	23.7	496	1504	9094	52.1	6.44	1.03
93-3C	69.2	0.362	23.7	465	1506	8408	60.9	6.35	0.97
94-1H	67.8	0.395	43.8	617	1827	12837	43.8	6.57	1.03
94-3C	69.2	0.361	43.8	517	1678	11399	55.1	6.43	0.98
				PADDLE 4 x 1"					
88-1H	68.2	0.388	30.8	455	1374	15907	42.4	2.86	1.08
88-3C	68.9	0.369	30.8	402	1275	14914	48.1	2.83	0.98
89-1H	68.5	0.381	10.2	299	919	8750	55.0	2.78	1.08
89-3C	69.1	0.363	10.2	264	851	8321	61.3	2.75	0.98
90-1H	67.7	0.396	17.7	438	1294	12576	44.3	2.72	1.08
90-3C	69.1	0.363	17.7	321	1034	11555	53.5	2.66	0.96
				PROPELLER 6"					
116-1H	67.7	0.396	52.4	919	2712	35677	40.4	0.69	1.03
116-3C	69.1	0.362	52.4	806	2607	32113	50.1	0.68	0.99
117-1H	67.9	0.393	5.6	352	1047	10413	64.9	0.74	1.05
117-3C	69.2	0.361	5.6	306	993	9639	77.9	0.73	0.93
118-1H	68.2	0.387	13.0	601	1817	17205	55.9	0.63	1.05
118-3C	69.1	0.365	13.0	548	1757	16136	63.9	0.62	0.98
119-1H	68.1	0.388	26.3	657	1980	25241	47.3	0.66	1.01
119-3C	69.2	0.361	26.3	558	1810	22946	56.9	0.65	0.98

TABLE NO. 12 (contd.)

CALCULATED RESULTS FOR 13.1 wt.% Fe_2O_3 SUSPENSIONS

Run Number	Density lb./ft.^{3}	k $\frac{Btu}{hr. ft. °F}$	Power ft.lb./sec.	H $\frac{Btu}{°F\ hr.ft.^2}$	N_{Nu}	N_{Re}	N_{Pr}	N_{Po}	N_V
				PROPELLER 4.1"					
120-1H	68.5	0.380	9.1	335	1034	15761	43.8	0.85	1.03
120-3C	69.1	0.364	9.1	305	981	14577	49.9	0.84	0.99

TABLE NO. 13

CALCULATED RESULTS FOR 24.4 wt.% KAOLIN SUSPENSIONS

Run Number	Density lb./ft.^{3}	k Btu / hr. ft. °F	Power ft.lb./sec.	H Btu / °F hr.ft.^{2}	N_{Nu}	N_{Re}	N_{Pr}	N_{Po}	N_V
				ANCHOR 9"					
06-1H	72.4	0.338	38.5	145	502	313	3371	2.67	1.00
06-4C	72.8	0.328	38.5	124	444	315	3476	2.65	1.00
				TURBINE 5 x 1"					
01-1H	72.5	0.336	128.1	186	648	832	1257	5.20	1.00
01-5C	72.7	0.333	128.1	212	747	834	1271	5.19	1.00
02-2H	72.2	0.345	126.6	189	642	819	1227	5.33	1.00
02-6C	72.6	0.334	126.6	153	537	824	1266	5.30	1.00
				PADDLE 6 x 2"					
05-2H	71.8	0.352	85.5	101	335	588	1675	4.24	1.00
05-6C	72.8	0.330	85.5	83	297	597	1788	4.18	1.00
				PROPELLER 6"					
04-4H	71.9	0.350	75.7	125	420	1734	1013	0.68	1.00
04-7C	72.7	0.331	75.7	119	422	1754	1069	0.67	1.00

TABLE NO. 14

CALCULATED RESULTS FOR 18.4 wt.% KAOLIN SUSPENSIONS

Run Numbers	Density lb./ft.^{3}	k $\frac{\text{Btu}}{\text{hr. ft.}^\circ\text{F}}$	Power ft.lb./sec.	H $\frac{\text{Btu}}{^\circ\text{F hr.ft.}^2}$	N_{Nu}	N_{Re}	N_{Pr}	N_{Po}	N_V
				ANCHOR 9"					
08-1H	69.7	0.340	16.7	209	722	783	1026	2.85	1.04
08-7C	69.6	0.345	16.7	222	754	790	1001	2.86	0.98
				TURBINE 6 x 1.25"					
12-2H	68.5	0.368	82.3	307	979	2350	380	5.24	1.03
12-4C	69.6	0.342	82.3	320	1094	2245	434	5.15	0.98
13-2H	68.6	0.366	46.4	259	828	1666	447	5.16	1.03
13-5C	69.7	0.341	46.4	209	718	1590	510	5.08	0.98
14-2H	68.9	0.360	22.1	156	509	1048	568	5.11	1.05
14-5C	69.6	0.343	22.1	115	392	1000	620	5.06	0.97
				TURBINE 5 x 1"					
09-1H	68.5	0.368	127.0	330	1051	3670	262	5.37	1.02
09-3C	69.6	0.344	127.0	389	1325	3514	297	5.29	0.98
10-2H	68.8	0.363	84.4	296	955	2802	303	5.43	1.03
10-7C	69.7	0.342	84.4	256	878	2698	338	5.36	0.98
11-3H	68.8	0.362	47.7	209	677	1994	356	5.32	1.04
11-5C	69.1	0.357	47.7	210	691	1976	365	5.31	0.97
				TURBINE 4 x 0.75"					
15-1H	68.9	0.360	55.5	202	658	2599	256	6.02	1.04
15-6C	69.7	0.340	55.5	176	608	2501	286	5.95	0.98

TABLE NO. 14 (contd.)

CALCULATED RESULTS FOR 18.4 wt.% KAOLIN SUSPENSIONS

Run Number	Density lb./ft.^{3}	k Btu / hr. ft.°F	Power ft.lb./sec.	H Btu / °F hr.ft.^{2}	N_{Nu}	N_{Re}	N_{Pr}	N_{Po}	N_V
				PADDLE 8 x 1"					
25-2H	68.7	0.365	83.8	320	1030	4363	374	1.19	1.04
25-5C	69.7	0.340	83.8	294	1012	4257	426	1.11	0.98
26-3H	68.7	0.365	41.8	196	629	2902	455	1.13	1.04
26-4C	69.5	0.346	41.8	155	523	2807	500	1.12	0.97
				PADDLE 6 x 2"					
16-2H	68.7	0.365	86.9	226	726	2810	355	4.09	1.03
16-6C	69.7	0.340	86.9	264	910	2687	403	4.03	0.98
17-2H	68.6	0.367	51.4	247	790	2009	410	4.21	1.03
17-4C	69.6	0.342	51.4	225	770	1922	466	4.14	0.98
18-2H	69.1	0.356	26.4	178	586	1337	516	4.04	1.06
18-6C	69.7	0.341	26.4	120	412	1298	561	4.01	0.97
				PADDLE 6 x 1"					
19-2H	68.8	0.363	130.5	374	1204	5995	253	1.77	1.03
19-7C	69.8	0.336	130.5	322	1120	5705	291	1.75	0.99
20-1H	68.8	0.362	90.4	245	792	4769	282	1.78	1.03
20-6C	69.7	0.342	90.4	237	811	4596	313	1.76	0.98
21-2H	68.5	0.368	60.2	251	800	3810	303	1.75	1.03
21-5C	69.7	0.341	60.2	197	678	3623	350	1.72	0.98
22-1H	69.1	0.357	35.2	185	605	2673	376	1.74	1.06
22-6C	69.8	0.338	35.2	174	602	2583	414	1.73	0.97

TABLE NO. 14 (contd.)

CALCULATED RESULTS FOR 18.4 wt.% KAOLIN SUSPENSIONS

Run Number	Density lb./ft.^{3}	k Btu/(hr. ft. °F)	Power ft.lb./sec.	H Btu/(°F hr.ft.^{2})	N_{Nu}	N_{Re}	N_{Pr}	N_{Po}	N_V
				PADDLE 4 x 2"					
23-1H	68.4	0.370	70.5	237	750	2876	236	6.59	1.03
23-4C	69.8	0.336	70.5	224	784	2697	283	6.48	0.98
24-2H	68.8	0.362	39.0	163	526	2001	289	6.40	1.04
24-4C	69.8	0.339	39.0	160	556	1917	327	6.31	0.97
				PROPELLER 6"					
27-2H	68.5	0.367	51.0	247	788	6721	235	0.58	1.04
27-4C	69.7	0.342	51.0	214	733	6420	269	0.57	0.98
28-2H	68.7	0.364	29.8	221	712	4805	278	0.58	1.04
28-5C	69.7	0.341	29.8	176	604	4605	314	0.58	0.98
29-2H	69.0	0.359	40.2	206	674	5670	264	0.59	1.04
29-6C	69.8	0.336	40.2	202	705	5435	298	0.58	0.98
				PROPELLER 5.2"					
31-2H	68.5	0.367	30.7	157	500	5006	236	0.73	1.04
31-5C	69.9	0.333	30.7	157	553	4700	283	0.71	0.99

DISCUSSION OF RESULTS

Viscosity

The viscosity data for each of the five suspensions is shown in Figure Nos. 1 to 5. Most Newtonian and non-Newtonian materials will show a decrease in viscosity with increasing temperature. This was found to be true of the more dilute kaolin and iron-oxide suspensions. Although, the amount of viscosity dependency with temperature was found to be relatively small. As the solids content for both suspension types was increased to approximately 24 wt.% the viscosity was found to be virtually independent of temperature. The most concentrated of the iron oxide suspensions, 33.2 wt.%, actually showed a slight increase in viscosity as the temperature was increased. The degree of pseudoplastic behavior appeared to be independent of temperature.

The degree of pseudoplastic behavior, as measured by the flow behavior index was shown to be at least partially dependent on the suspensions's solids content.[14] The most dramatic increase in pseudoplasticity was realized in going from 13.1 wt.% to 24.0 wt.% solids in the iron oxide system, where the flow behavior index decreased from 0.42 to 0.15, respectively. No decrease in the flow behavior index was found in going from 24.0 wt.% to 33.2 wt.% iron oxide solids. The flow behavior index decreased slightly in the kaolin system when the solids content was increased from 18.4 wt.% to 24.4 wt.%, where the index decreased from 0.16 to 0.15, respectively. Thus the degree of pseudoplasticity for four of the five suspensions was quite similar, being in the range of 0.15 to 0.16.

Experimental Error

Hagedorn[9] has presented a discussion of the magnitude of error. Since operating practices were nearly the same his estimates remain applicable. The amount of error inherent in determining the vessel's area, batch weight, batch temperature, and rheological determinations was small compared to that associated with measuring the wall temperature. At a given instant, the wall temperatures were somewhat different due to uneven heat transfer over the vessel wall. This resulted in an estimated experimental error of about $\pm$ 20%.

Correlation of Data

The heat transfer data for suspensions was correlated using an existing semi-empirical equation. The equation used had previously been developed by Hagedorn and Salamone:

$$N_{Nu} = C(N_{Re})^{1.30/(n+1)}(N_{Pr})^{0.28}\ (N_V)^{0.30/n^{0.75}}\ (D_t/D_a)^{-0.50}\ (W_a/D_a)^{0.50}n^a \qquad (20)$$

The constants C and a suggested by Hagedorn are given in Table No. 15 for anchor, paddle, propeller and turbine type impellers. The Reynold and Prandtl numbers are calculated using a shear rate equal to 11.5N to determine viscosity.

Hagedorn suggested the use of a more theoretical dimensional equation also developed by him. However, the more empirical of the two correlations gave better agreement with the more pseudoplastic system studied by Hagedorn, 15% error versus 19% error for the more theoretical correlation. Thus the more empirical of the two correlations was used in this study.

An evaluation of the preliminary water runs was made. The experimentally determined Nusselt numbers for water are compared graphically with those predicted by the Hagedorn and Salamone correlation in Figure No. 8 Points lying on the 45° line would indicate perfect agreement. The amount of error was calculated as follows:

$$\%\ \text{Error} = \left| \frac{N_{Nu}\ \text{exp.} - N_{NuH}}{N_{Nu}\ \text{exp.}} \right| \times 100 \tag{30}$$

with the average error being defined as:

$$\text{ave. Error} = \frac{\sum \%\ \text{Error}}{\text{No.}} \tag{31}$$

where N_{Nu} exp. is the experimentally determined Nusselt number

N_{NuH} is the Nusselt number predicted by the Hagedorn correlation

No.is the number of data points.

The precent errors for the water runs are shown in Table No.15 for each type of impeller. Figure No. 8 shows a fairly uniform scatter about the 45° line. The tabulated results show an overall error of 9.5%. This result agrees well with the 10% error obtained by Hagedorn for his water runs.

The Hagedorn and Salamone correlation was then used to predict Nusselt numbers using the necessary data experimentally determined for suspensions. These calculated Nusselt numbers were graphically compared with the experimentally determined numbers. Figure Nos. 9 to 12show the amount of agreement or disagreement between the calculated and experimentally determined Nusselt numbers. These are plotted according to the four major types of impellers, anchor, paddles, propellers and turbines at each solids content studied. Points lying on the 45° line would

TABLE NO. 15

Hagadorn and Salamone Semi Empirical Correlation

$$N_{Nu} = C\ (N_{Re})^{1.30/n+1)}\ (N_{Pr})^{0.28}\ (N_{v})^{(0.30/n^{0.75})}\ (D_t/D_a)^{-0.50}\ (W_a/D_a)^{0.50}\ n_a$$

Impeller Type	Correlation Constants C	a	Average Errors for Water
Anchor	0.74	1.43	4.6%
Paddle	2.00	1.96	11.2%
Propeller	0.86	2.51	9.1%
Turbine	3.09	2.06	8.8%

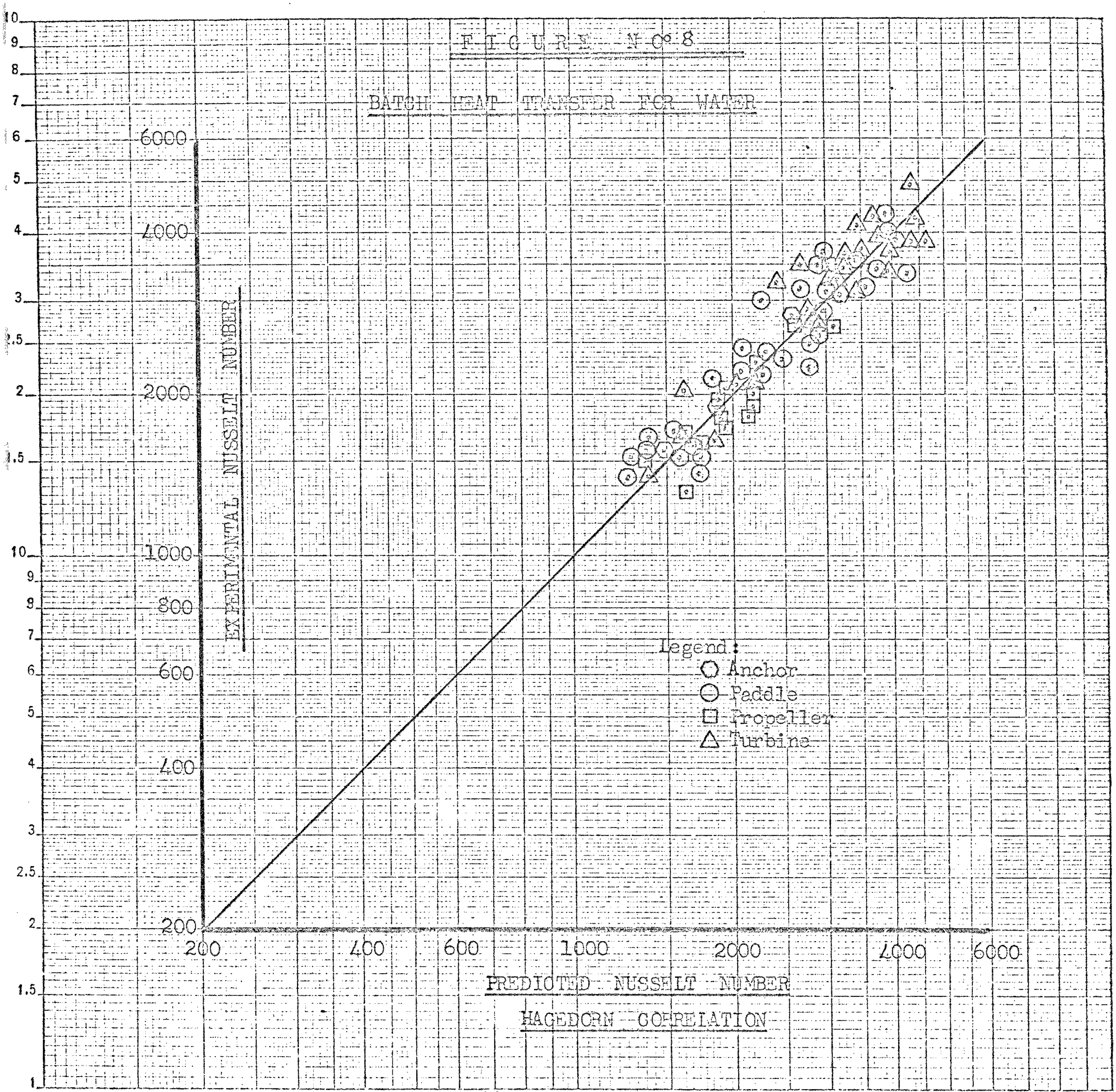


FIGURE N° 8
BATCH HEAT TRANSFER FOR WATER
EXPERIMENTAL NUSSELT NUMBER
PREDICTED NUSSELT NUMBER
HAGEDORN CORRELATION
6000
4000
2000
1000
800
600
400
200
200
400
600
1000
2000
4000
6000
Legend:
Anchor
Paddle
Propeller
Turbine

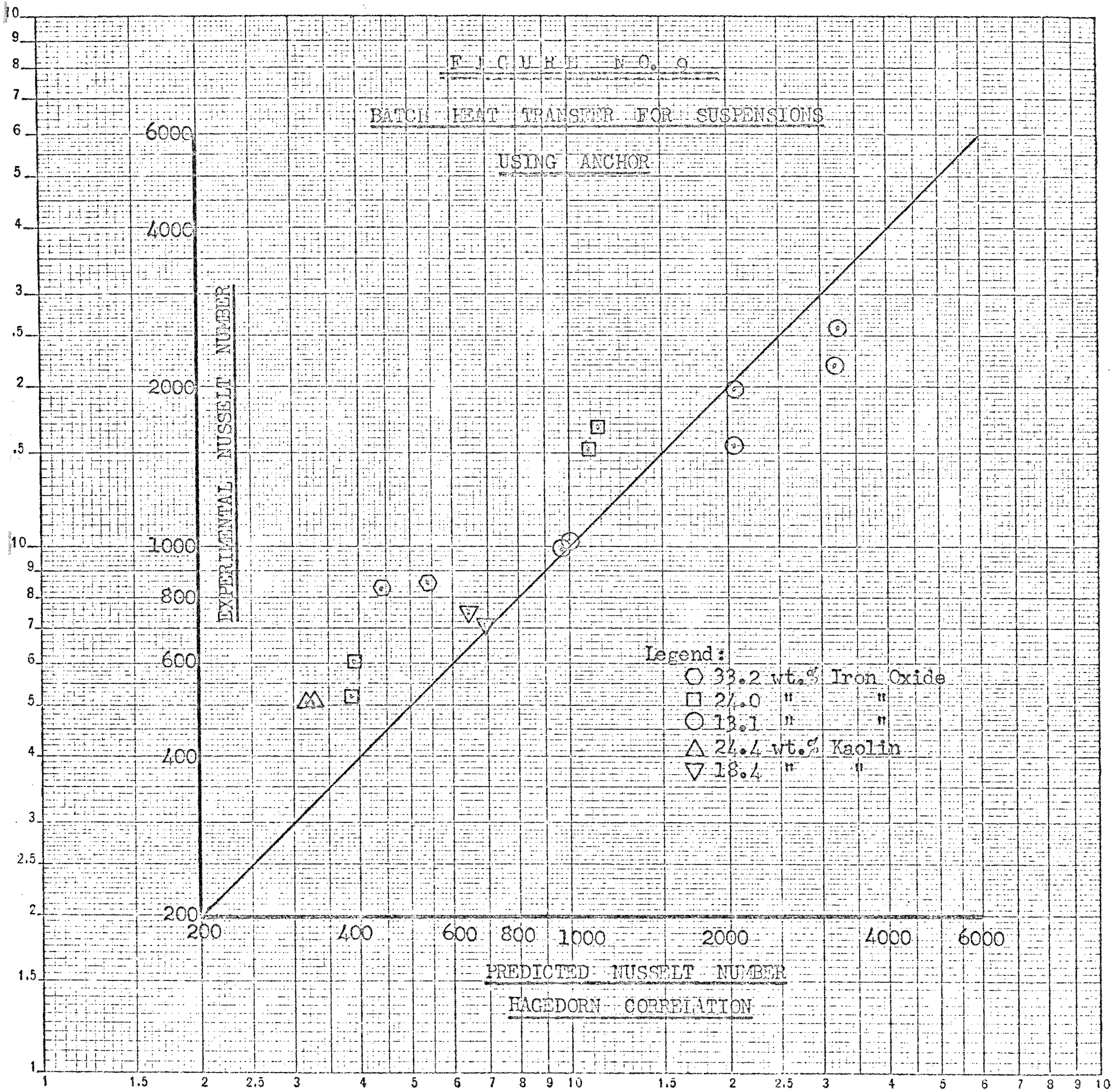


FIGURE NO. 9
BATCH HEAT TRANSFER FOR SUSPENSIONS
USING ANCHOR
EXPERIMENTAL NUSSELT NUMBER
6000
4000
2000
1000
800
600
400
200
200
400
600
800
1000
2000
4000
6000
PREDICTED NUSSELT NUMBER
HAGEDORN CORRELATION
Legend:
○ 33.2 wt.% Iron Oxide
□ 24.0 " "
○ 13.1 " "
△ 24.4 wt.% Kaolin
▽ 18.4 " "

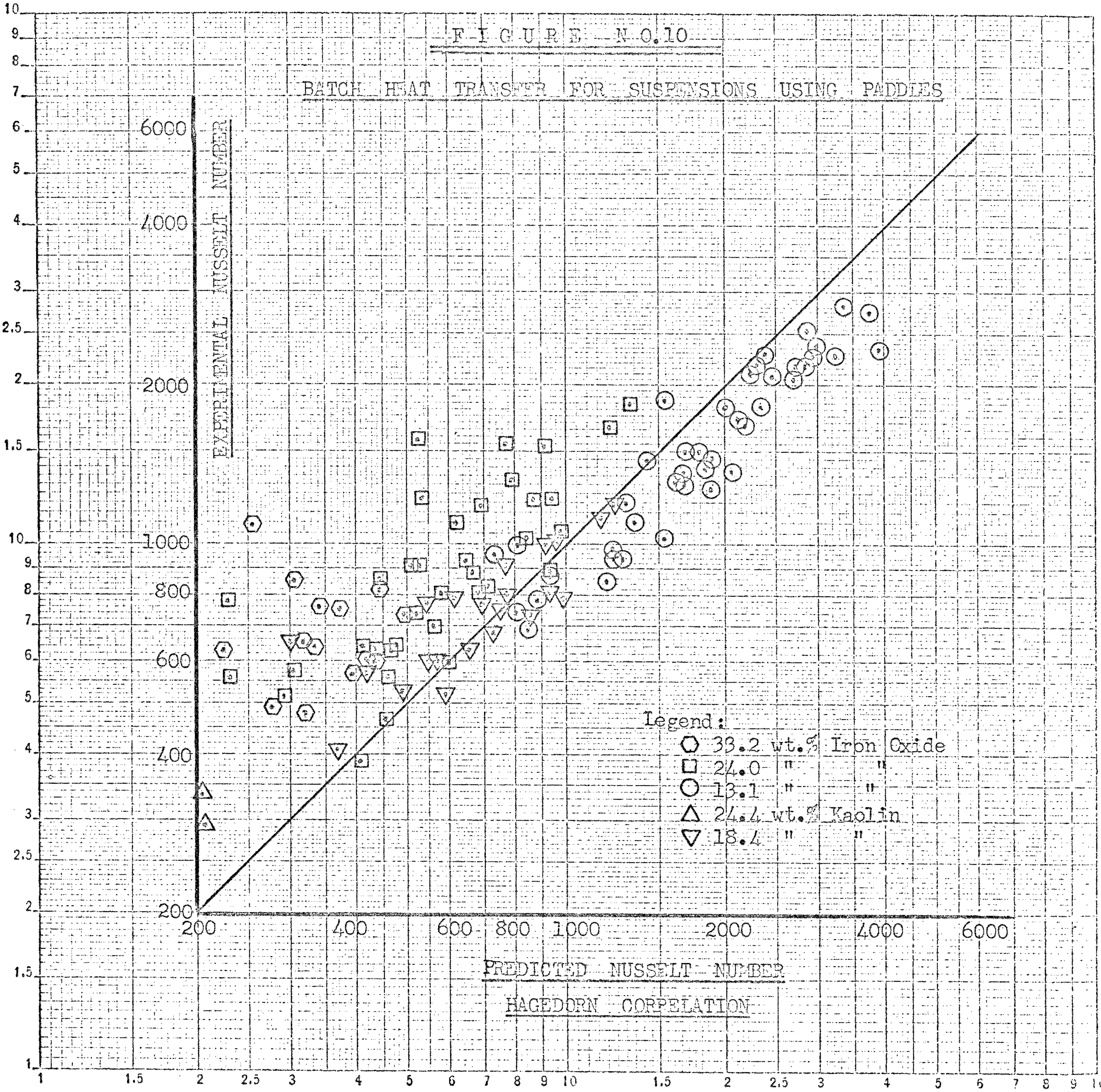


FIGURE NO.10
BATCH HEAT TRANSFER FOR SUSPENSIONS USING PADDLES
EXPERIMENTAL NUSSELT NUMBER
6000
4000
2000
1000
800
600
400
200
200
400
600
800
1000
2000
4000
6000
PREDICTED NUSSELT NUMBER
HAGEDORN CORRELATION
Legend:
33.2 wt.% Iron Oxide
24.0 " "
13.1 " "
24.4 wt.% Kaolin
18.4 " "

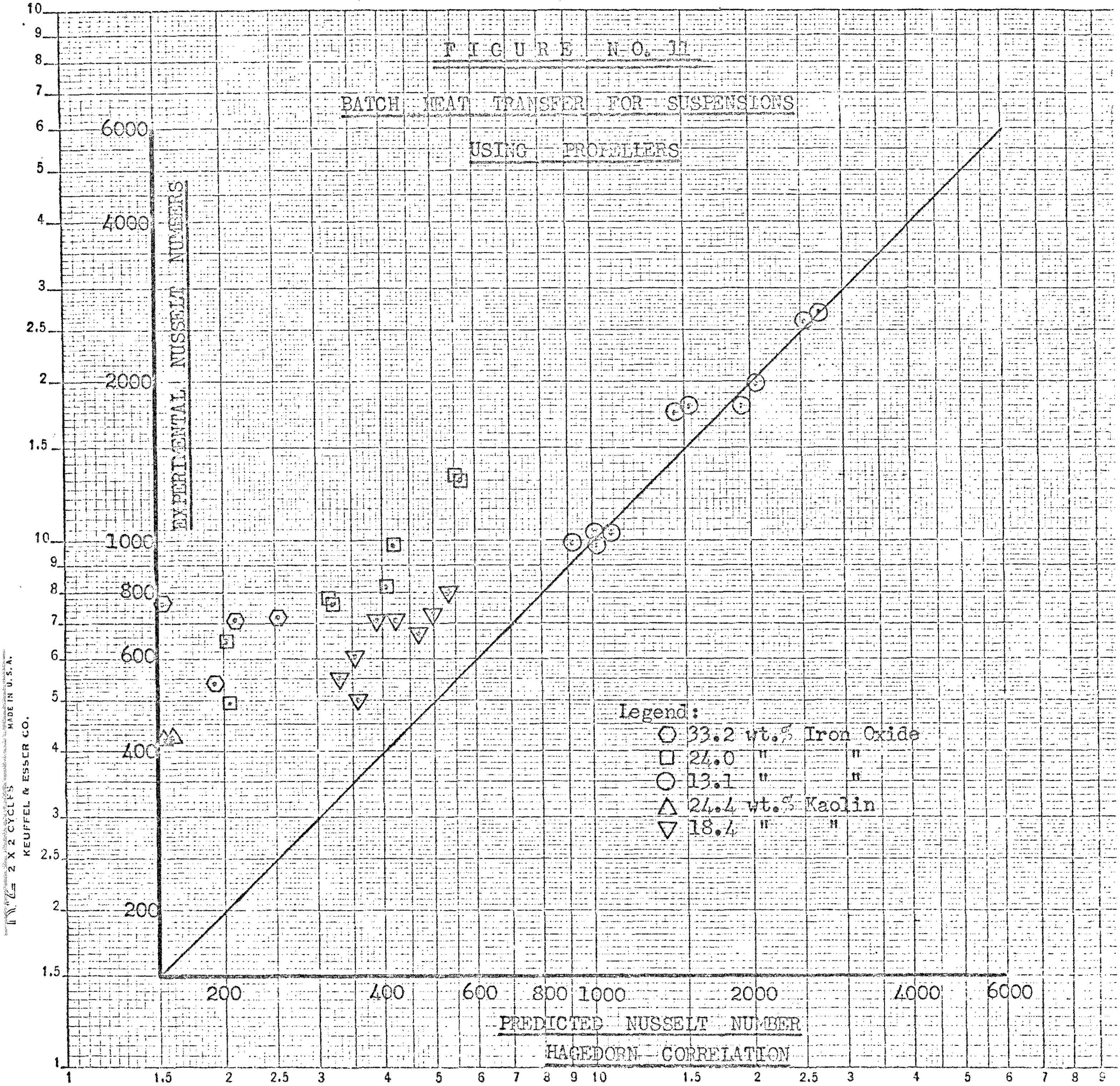


FIGURE N.O. 11
BATCH HEAT TRANSFER FOR SUSPENSIONS
USING PROPELLERS
EXPERIMENTAL NUSSELT NUMBERS
PREDICTED NUSSELT NUMBER
HAGEDORN CORRELATION
6000
4000
2000
1000
800
600
400
200
200
400
600
800
1000
2000
4000
6000
Legend:
33.2 wt.% Iron Oxide
24.0 " "
13.1 " "
24.4 wt.% Kaolin
18.4 " "
2 X 2 CYCLES
KEUFFEL & ESSER CO.
MADE IN U.S.A.

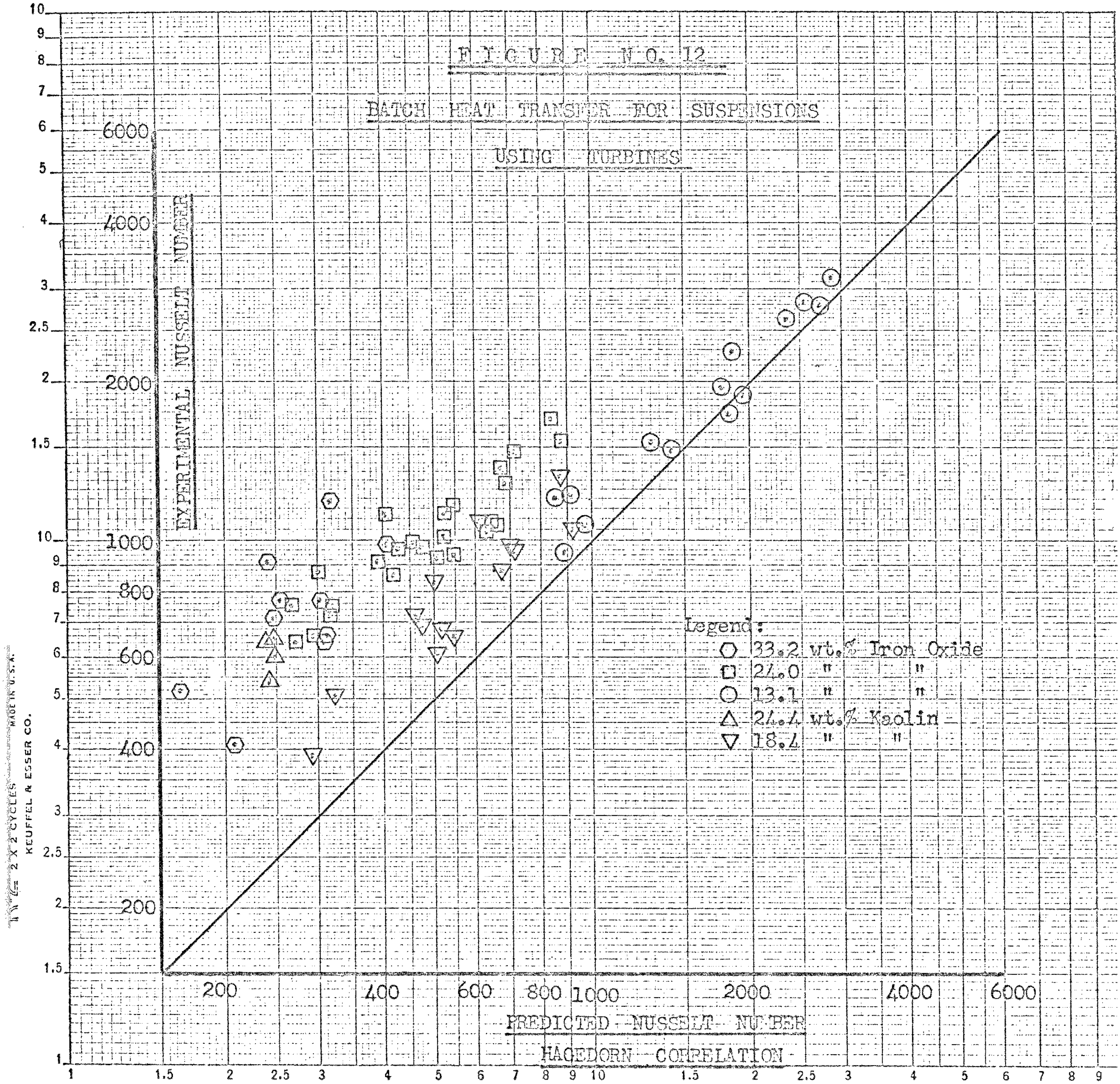


FIGURE NO. 12
BATCH HEAT TRANSFER FOR SUSPENSIONS
USING TURBINES
EXPERIMENTAL NUSSELT NUMBER
PREDICTED NUSSELT NUMBER
HAGEDORN CORRELATION
Legend:
33.2 wt.% Iron Oxide
24.0 " "
13.1 " "
24.4 wt.% Kaolin
18.4 " "
6000
4000
2000
1000
800
600
400
200
200
400
600
800
1000
2000
4000
6000
KEUFFEL & ESSER CO.
2 X 2 CYCLES
MADE IN U.S.A.

indicate perfect agreement between the experimental and calculated Nusselt numbers.

Most cases show a substantial error between the two methods for determining Nusselt numbers. Table No.16 shows the percent error between the two results which was calculated as previously described.

The best agreement was obtained with the more dilute suspensions. However the overall errors obtained are in considerable disagreement with the 10.8% obtained by Hagedorn and Salamone. Examination of Figure Nos. 9 to 12 shows that a given suspension will in general, result in nearly all of the experimental Nusselt numbers being either greater or less than those obtained via the correlation for a given impeller. That is a given suspension will have Nusselt numbers all above or all below the 45° line with little scatter on either side of the line.

Therefore, the method used to determine the amount of the deviation and whether the deviation was positive or negative was as follows:

$$\%\ \text{Deviation} = \left[(N_{Nu}\ \text{exp.} - N_{NuH}) \Big/ N_{Nu}\ \text{exp.}\right] \times 100 \qquad (32)$$

The average deviation is thus:

$$\text{Avg. Deviation} = \frac{\sum \%\ \text{Deviations}}{\text{No.}} \qquad (33)$$

Where No. is the number of data points. These results are given in Table No. 17.

The method of determining the percent deviation is very similar to finding the percent error except in the former the absolute value is not taken and the sign is carried. The percent deviation shows a definite

TABLE NO.16

Comparing Experimental and Predicted Nusselt Numbers Using Hagedorn-Salamone Correlation

$$\text{Avg. \% Error} = \frac{\sum \left| N_{Nu\ H} - N_{Nu\ exp.} \right| / N_{Nu\ exp.}}{\text{No.}} \times 100$$

Percent Error

Impeller Type	Iron Oxide, wt. % 33.2	24.0	13.1	Kaolin, wt. % 24.4	18.4	Overall
Anchor	42.0	31.2.	18.2	36.6	14.5	26.3
Paddle	46.8	31.5	24.8	35.6	11.6	27.2
Propeller	70.0	58.5	6.5	62.7	36.7	38.7
Turbine	61.7	51.8	11.5	59.5	28.2	40.4

TABLE NO. 17

Percent Deviation For Suspensions From Hagedorn-Salamone Correlation

$$\% \text{ Deviation} = \frac{\sum (N_{Nu\ exp.} - N_{Nu\ H}) / N_{Nu\ exp.}}{No.} \times 100$$

Solid	Iron Oxide			Kaolin	
Wt. %	33.2	24.0	13.1	24.4	18.4
Flow Behavior Index	0.15	0.15	0.42	0.15	0.16
	Percent Deviation				
Anchor	42.0	31.3	-17.1	36.5	9.4
Paddle	46.8	30.7	-21.9	35.6	4.0
Propeller	70.0	58.5	3.3	62.7	36.7
Turbine	61.7	51.8	10.3	59.5	28.2
$\frac{1-\phi}{\phi}$	2.01	3.17	6.63	3.1	4.44

trend with percent solids. This is shown in Figure No.13 . The degree of the deviation increases with higher solids contents. All four impellers show the same trend but, in general, the curves are somewhat displaced.

Both the paddles and anchor show a negative deviation at the lowest solids content studied, 13.1%. Increasing the solids content results in increasing positive deviations with a leveling in the deviation at the higher solids, 24.0 - 33.2 wt.%. The propellers and turbines deviations are displaced upwards with 13.1 wt.% showing a slight positive deviation. However, as the solids content is increased for the propellers and turbines the deviations increase at approximately the same rate as for the anchor and paddles.

The deviation between the experimental and Hagedorn and Salamone correlation thus has been shown to be a function of solids content. Thus, it would be of significant value if the already existing correlation could be modified to apply it to suspensions. The Hagedorn-Salamone correlation considered here resulted from a semi-empirical dimensional analysis.

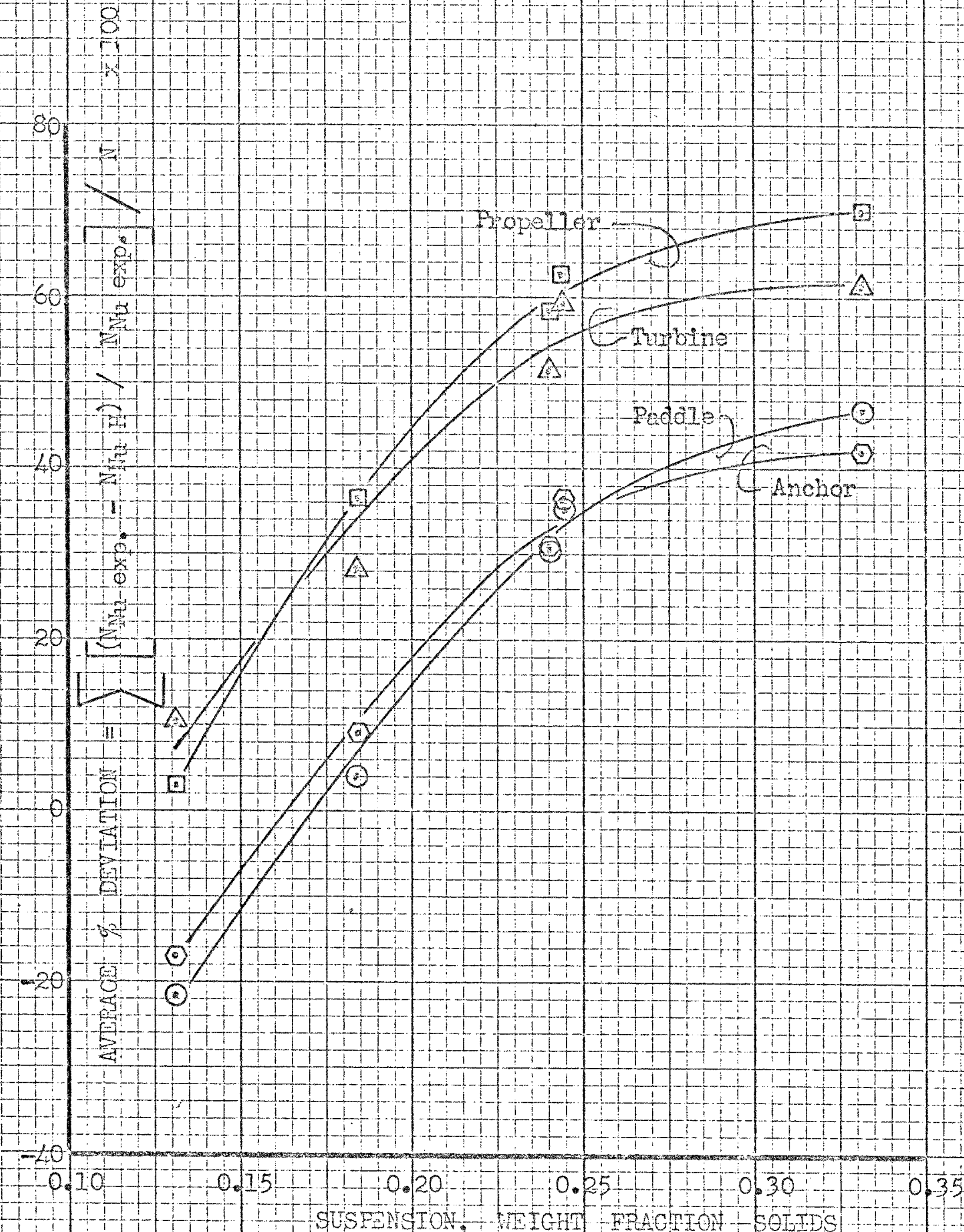
Several dimensionless relationships dependent on solids content were analyzed in an attempt to linearize the deviation. Linearization of the deviation as a function of solids content would greatly simplify any modifications made to the Hagedorn-Salamone correlation.

The most successful attempt at linearizing the deviation was obtained by plotting the deviation as a function of:

FIGURE NO. 13

AVERAGE DEVIATION OF EXPERIMENTAL RESULTS

FROM HAGEDORN - SALAMONE CORRELATION



$$(1 - \phi) / \phi$$

where ϕ is the weight fraction solids for a given suspension. Thus the function is weight fraction liquid divided by weight fraction solids.

A linear regression analysis was made using all of the data points for suspensions. The calculations were facilitated through a General Electric, Mark II time sharing computer. Figure No. 14 graphically shows the best fit regression line for each impeller. The Hagedorn-Salamone correlation can now be modified to give the Nusselt number for suspensions. Therefore, the final modified correlation for suspensions within the range of 13-33 weight percent solids is as follows:

$$N_{NuS} = N_{NuH} \Big/ \left[a' + b \ \frac{1 - \phi}{\phi} \right] \qquad (34)$$

where N_{NuS} = predicted Nusselt number for suspensions

N_{NuH} = predicted Nusselt for pseudoplastic liquids using Hagedorn correlation

ϕ = weight percent solids

The constants, a' and b for each type of impeller are given in Table No. 18 The percent errors were calculated as previously defined using the new modified correlation for suspensions. The data is presented in Table No. 18 Figure Nos. 15 to 18 graphically portray the agreement between the experimentally determined Nusselt numbers and those calculated from the modified correlation for suspensions. The overall average error for all the suspensions was slightly less than 13%.

The 13.1 wt.% iron oxide was the only suspension which had a flow behavior index within the range studied by Hagedorn. This suspension of the

FIGURE NO. 14

BEST FIT REGRESSION LINE FOR EACH IMPELLER

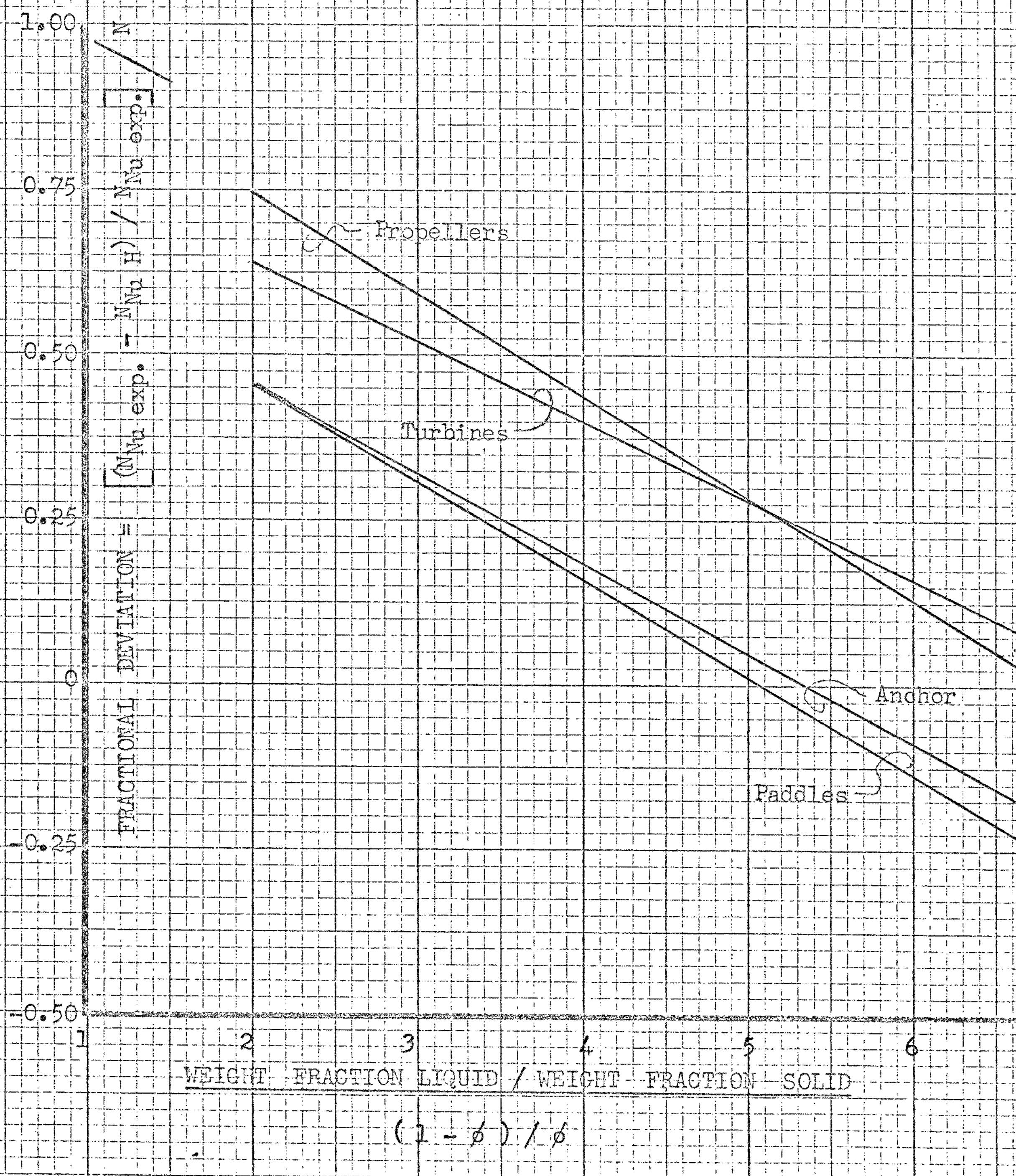


TABLE NO. 18

SUSPENSION CORRELATION

$$N_{Nu} = (N_{Nu\,H})^{*} \Big/ \left[a' + b \left(\frac{1-\phi}{\phi} \right) \right]$$

Impeller Type	Correlation Constants a'	b	Average Errors, % Iron Oxide, weight 33.2%	24.0%	13.1%	Kaolin, weight 24.4%	18.4%	Overall
Anchor	0.265	0.136	14.2	4.6	14.8	7.6	6.1	10.1
Paddles	0.234	0.150	22.9	20.8	11.3	8.0	15.3	16.3
Propellers	-0.058	0.154	30.7	7.7	6.8	11.2	8.4	11.1
Turbines	0.122	0.120	21.6	12.8	7.9	17.9	13.2	13.5

*Calculated from Hagedorn and Salamone Correlation

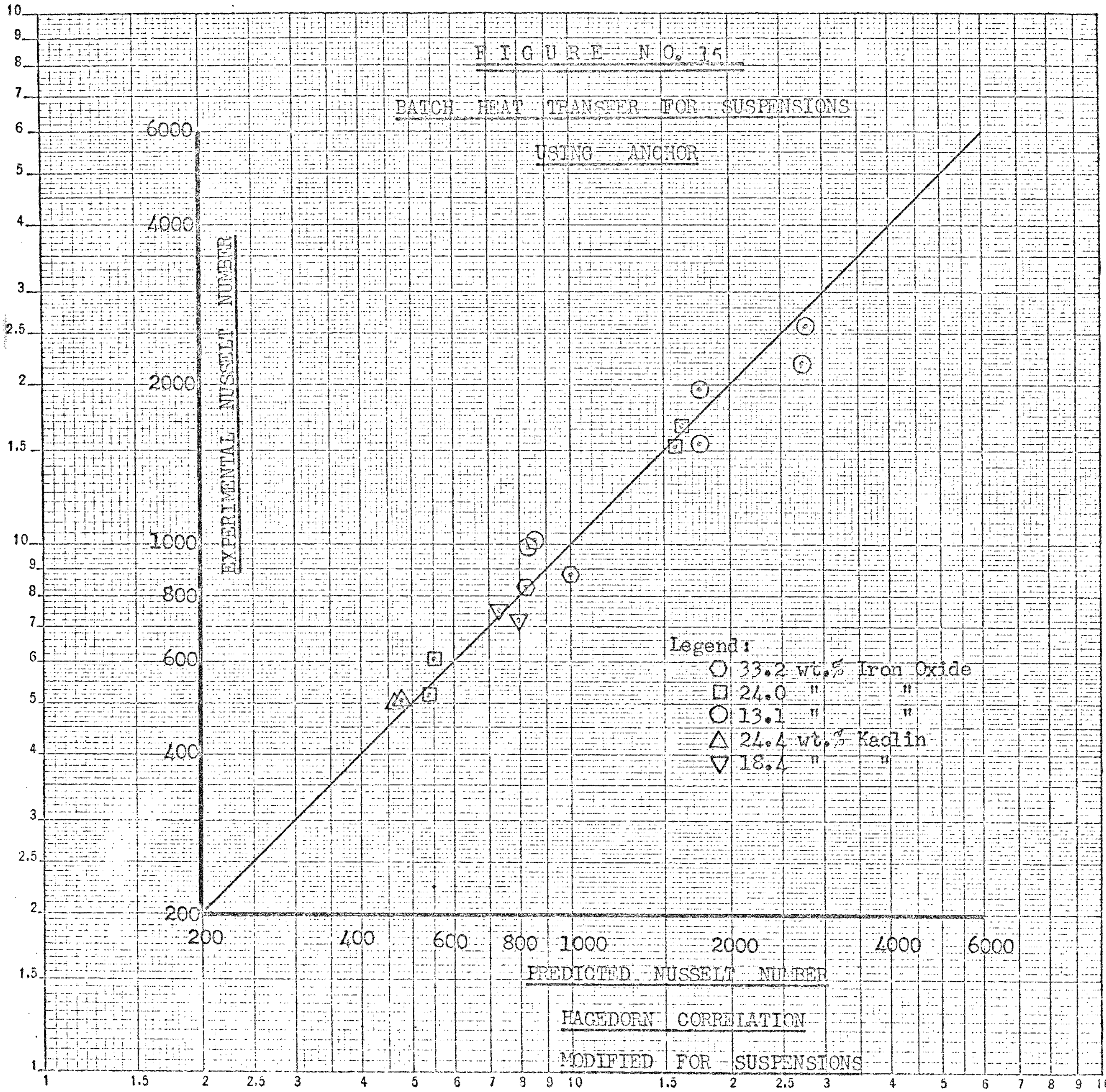


FIGURE NO. 15
BATCH HEAT TRANSFER FOR SUSPENSIONS
USING ANCHOR
EXPERIMENTAL NUSSELT NUMBER
6000
4000
2000
1000
800
600
400
200
200
400
600
800
1000
2000
4000
6000
PREDICTED NUSSELT NUMBER
HAGEDORN CORRELATION
MODIFIED FOR SUSPENSIONS
Legend:
33.2 wt.% Iron Oxide
24.0 " "
13.1 " "
24.4 wt.% Kaolin
18.4 " "

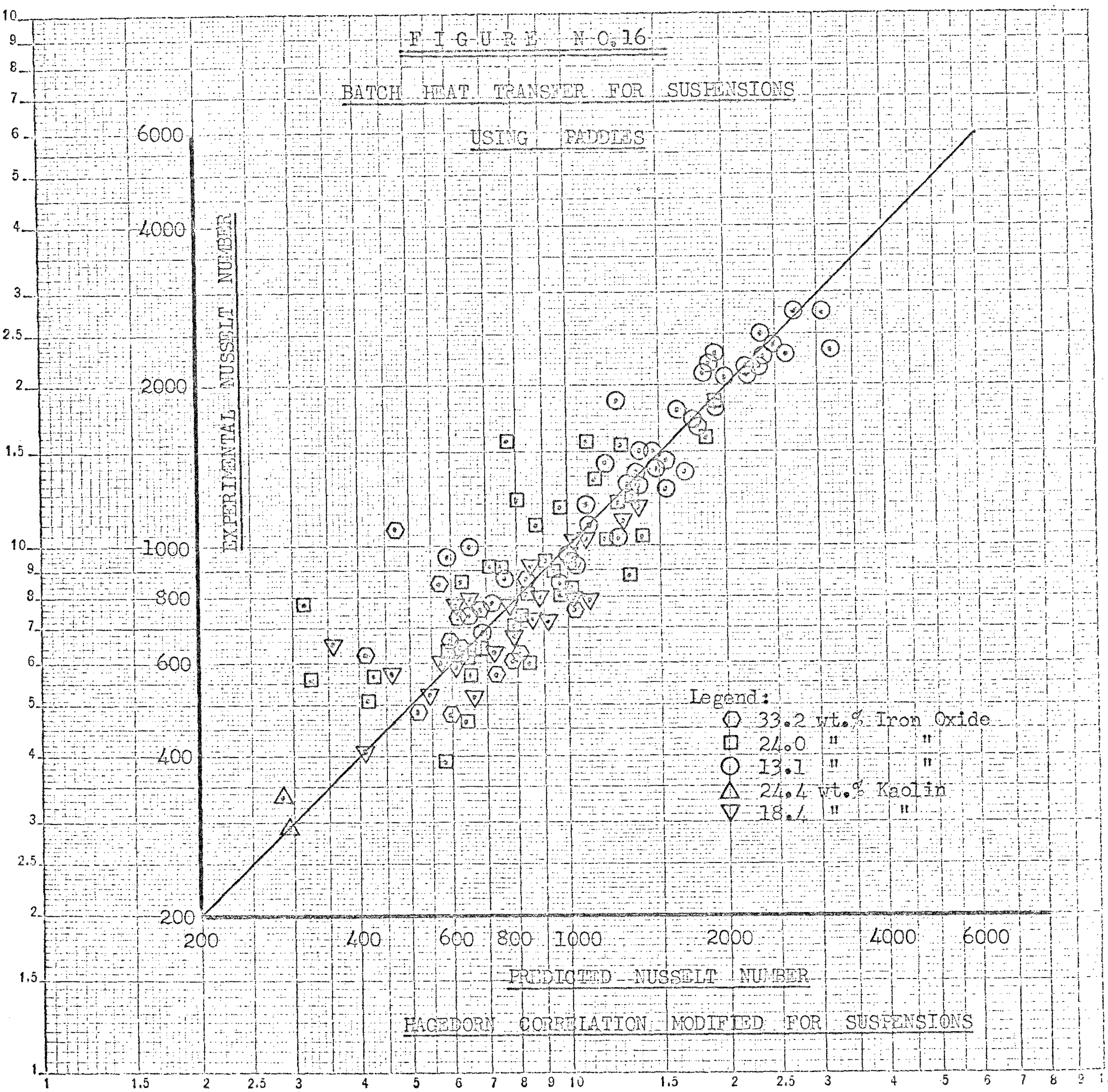


FIGURE NO. 16
BATCH HEAT TRANSFER FOR SUSPENSIONS
USING PADDLES
EXPERIMENTAL NUSSELT NUMBER
6000
4000
2000
1000
800
600
400
200
200
400
600
800
1000
2000
4000
6000
PREDICTED NUSSELT NUMBER
HAGEDORN CORRELATION MODIFIED FOR SUSPENSIONS
Legend:
33.2 wt.% Iron Oxide
24.0 " "
13.1 " "
24.4 wt.% Kaolin
18.4 " "

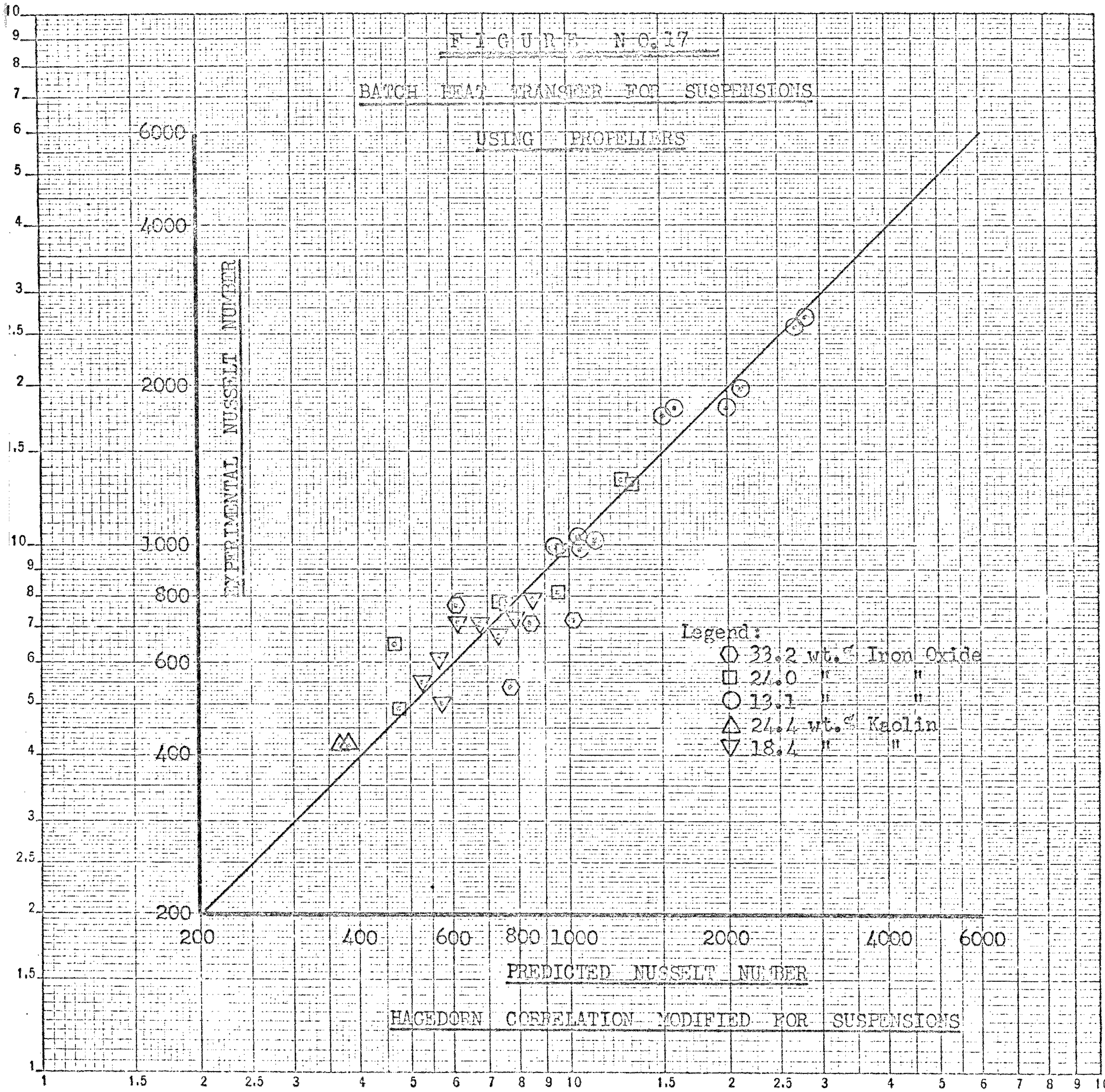


FIGURE NO. 17
BATCH HEAT TRANSFER FOR SUSPENSIONS
USING PROPELLERS
EXPERIMENTAL NUSSELT NUMBER
6000
4000
2000
1000
800
600
400
200
200
400
600
800
1000
2000
4000
6000
PREDICTED NUSSELT NUMBER
HAGEDORN CORRELATION MODIFIED FOR SUSPENSIONS
Legend:
33.2 wt.% Iron Oxide
24.0 " "
13.1 " "
24.4 wt.% Kaolin
18.4 " "

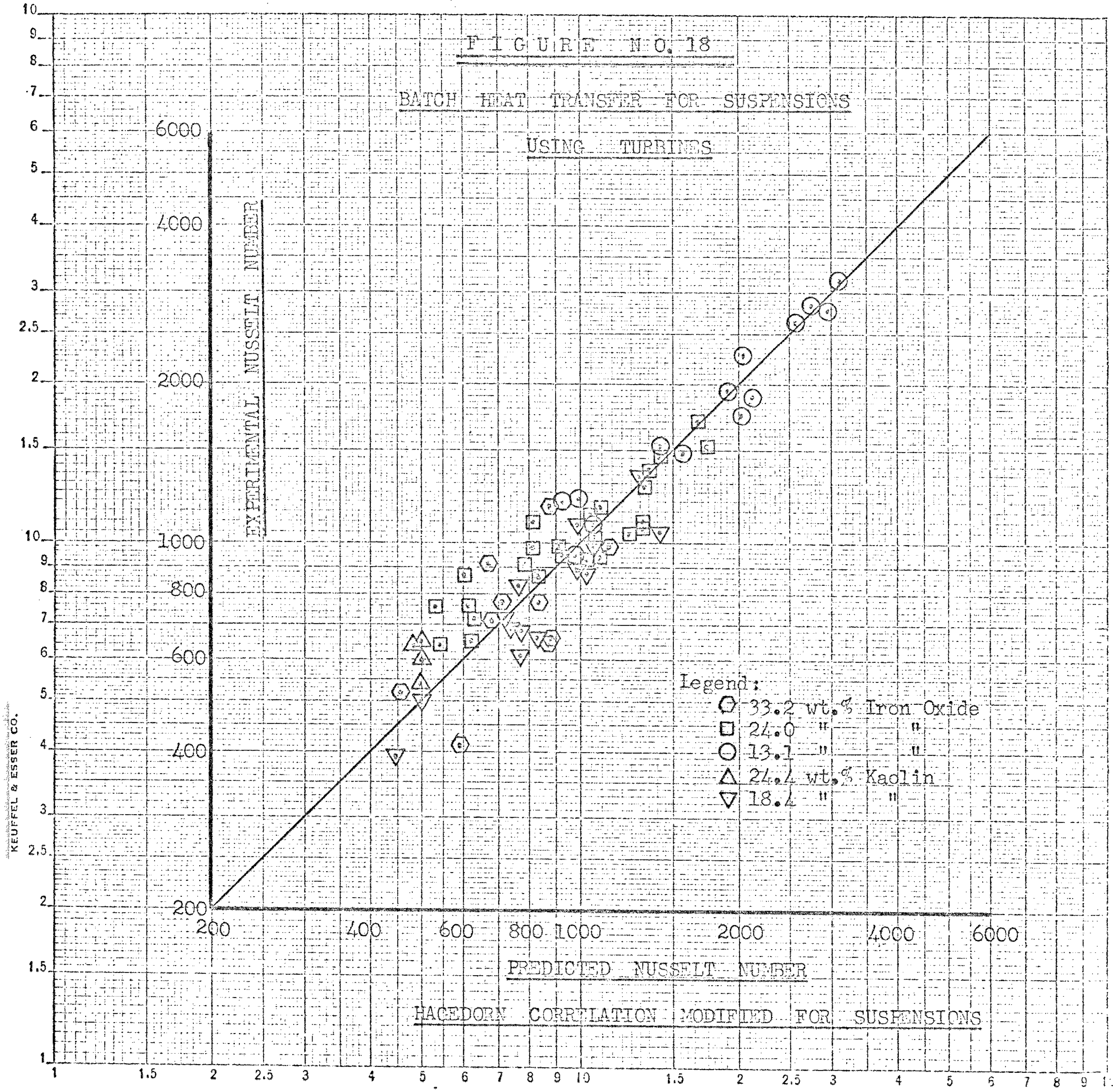


FIGURE NO. 18
BATCH HEAT TRANSFER FOR SUSPENSIONS
USING TURBINES
EXPERIMENTAL NUSSELT NUMBER
6000
4000
2000
1000
800
600
400
200
200
400
600
800
1000
2000
4000
6000
Legend:
33.2 wt.% Iron Oxide
24.0 " "
13.1 " "
24.4 wt.% Kaolin
18.4 " "
PREDICTED NUSSELT NUMBER
HAGEDORN CORRELATION MODIFIED FOR SUSPENSIONS
KEUFFEL & ESSER CO.

five studied had the best agreement with Hagedorn's correlation. The agreement was especially good for the propellers and turbines. Whereas, the anchor and paddle both gave experimental results about 20% below those predicted by Hagedorn's correlation.

Perry[17] states that suspensions of finely divided particles in a liquid may tend to reduce turbulence. The fluid will exert a drag force upon the particle whether or not the particle is moving faster or slower than the liquid. Stokes law shows that a particle falling under the influence of gravity through a liquid will attain a certain terminal velocity dependent upon the drag of the fluid. Thus the presents of solids may retard mixing patterns somewhat and a logical extension would be a reduction in the heat transfer coefficient.

Four of the five suspensions studied were more pseudoplastic than those studied by Hagedorn. Thus the Hagedorn correlation might not hold for pure liquids for the more pseudoplastic systems and this might have accounted for the substantially higher experimental Nusselt numbers.

However, the differences in the flow behavior indexes can not be held totally to blame for the discrepancies between the experimental and predicted results. Four of the five suspensions had almost identical flow behavior indexes (0.16 - 0.15). Yet, Figure No. 13 shows that the degree of deviation was substantially different for each suspension, and the amount of deviation can be seen to be a function of solids content.

Both the kaolin and iron oxide suspensions behaved similarly. The amount of deviation from the Hagedorn -Salamone correlation was about the same for both types of suspensions at the same solids content. Both types of solids were evaluated at about 24 wt.%. The kaolin was actually 24.4 wt.%. Table No.17 shows that the deviation for kaolin at 24.4 wt.% solids is consistently slightly higher for all impellers than that for 24.0 wt.% Fe_2O_3. Although, one would expect that the slightly higher solids, 24.4 versus 24.0, would result in a slightly higher deviation. There did not appear to be any significant difference between the two types of solids due to differences in physical properties.

Some investigators have tried to correlate the effect of particle size on heat transfer. However, some solids such as kaolin have highly active surfaces. This allows the particle to immobilize water molecules in its vicinity thus presenting an effective volume larger than the solid itself. Therefore, the effective volume must be known before any correlations with heat transfer can be attained.

The heat transfer data for suspensions was found to correlate with the dimensionless group $(1 - \emptyset) / \emptyset$ where $\emptyset$ = wt.% solids. The range of solids contents studied was 13 - 33 wt.%. Care should be taken in extrapolating the group to solids levels above or below those studied. It is quite apparent that at low solids levels the group value tends towards infinity.

CONCLUSIONS

1. Kaolin - water and iron oxide - water suspensions were found to be pseudoplastic and obeyed the power law equation.

2. The Hagedorn - Salamone semi empirical correlation was verified to predict Nusselt numbers for water with an average error of 9.5%.

3. A suspension with a flow behavior index (0.42) within the range studied by Hagedorn gave good agreement with the Hagedorn - Salamone correlation for propellers and turbines.

4. The same suspension as above with a flow behavior index of 0.42 gave experimental Nusselt numbers about 20% lower than those predicted by the Hagedorn - Salamone correlation for anchors and paddles.

5. Overall, suspensions were found to deviate from the Hagedorn - Salamone correlation as a function of weight percent solids.

6. It was shown that the Hagedorn - Salamone correlation could be modified to predict Nusselt numbers for suspensions within the range 13-33 wt.% solids and flow behavior indexes of 0.42 to 0.15. The modification was the introduction of a dimensionless group composed of weight fraction liquid divided by weight fraction solids. The final modified correlation was as follows:

$$N_{Nu} = \frac{C\, N_{Re}^{\,1.30/(n+1)}\, N_{Pr}^{\,0.28}\, (N_V)^{0.30/n^{0.75}}\, (D_t/D_a)^{-0.50}\, (W_a/D_a)^{0.50}\, n^{a}}{a' + b\left(\frac{1-\phi}{\phi}\right)}$$

where viscosities for N_{Re} and N_{Pr} are calculated at a shear rate equal to 11.5N. The constants vary with impeller type and the values are:

	C	a	a'	b
Anchor	0.74	1.43	0.265	0.136
Paddle	2.00	1.96	0.234	0.150
Propeller	0.86	2.51	-0.058	0.154
Turbine	3.09	2.06	0.122	0.120

The above correlation was used to predict batch side heat transfer coefficients with an overall error of 13%. However, before any rigorous conclusions can be drawn on the effect of weight percent solids, more data will have to be collected for more pseudoplastic pure liquids matching closer the range of suspensions studied.

RECOMMENDATIONS

1. Further work is needed to test the Hagedorn correlation using liquids (non-suspensions) with flow behavior indexes below 0.36.

2. The modified correlation developed for suspensions should be tested using materials with flow behavior indexes above 0.42.

3. The modified correlation developed for suspensions should be tested for other materials having physical properties outside of those investigated in this study, such as particle size, thermal conductivity, etc.

NOMENCLATURE

English Alphabet

A – Area for heat transfer

C – Specific heat

D – Diameter

h – Viscometer bob height

H – Batch film heat transfer coefficient

H' – Pseudo batch film heat transfer coefficient

k – Fluid consistency index

K – Thermal conductivity

L – Thickness

n – Flow behavior index

n" – Measure of non-Newtonian behavior

N – Revolutions per unit time

No. – Number of data points

P – Mixing power

Q – Heat flux

R – Viscometer bob radius

S – Dynamometer reading

T – Temperature

T' – Torque

v – Linear velocity

W – Impeller width

W' – Batch weight

X – Fractional portion of solids

Greek

Δ - For difference

μ - Viscosity

θ - Reciprocal of viscosity

π - 3.1416

ρ - Density

γ - Shear rate

τ - Shear stress

ϕ - Weight fraction solids

Subscripts

a - Agitator

b - Batch

e - Effective height

f - Fluid phase

h - Uncorrected for mixing power

p - Pipe

p' - Mixing power

r - Relative

s - Suspension

s' - Solid phase

t - Tank

w - Wall

Dimensionless Groups

N_{Nu} - Nusselt Number

N_{Po} - Power Number

N_{Pr} - Prandtl Number

N_{Re} - Reynolds Number

N_{V} - Viscosity Number

APPENDIX

Sample Calculations

I. Properties of water:

1. Viscosity

$$\theta = 0.021482 \left[(T - 8.435) + \sqrt{8078.4 + (T-8.435)^2}\right] - 1.20$$

where T = °C

$$\mu = 6.72 \times 10^{-4} / \theta \quad \text{lb./ft. sec.}$$

2. Thermal conductivity

$$K = 0.325 + .000888T \quad \text{Btu/hr. ft.}^2 \text{ (°F/ft.)}$$

where T = °C

3. Heat capacity

$$C_p = 1.003 \text{ Btu/lb.°F} \quad (0\text{–}100°C)$$

4. Density

$$\rho = 62.42 - 0.001645T - 0.000248T^2 \quad \text{lb./ft.}^3$$

where T = °C

II. Non-Newtonian viscosity, typical Brookfield determination.

Temperature = 40°C = 104°F

Spindle turning at 120 RPM = 2 RPS

Brookfield reading = 17.6% of scale

Spindle No. 2

γ = shear rate = $4\pi N/n''$

n'' determined by plotting log of torque versus log of spindle speed and taking slope of line.

$n'' = 0.16$

$= 4\pi(2)/0.161 = 156$ /sec.

Viscometer torque, $T' = 0.176$ (3368.5 dyne cm.)

= 593 dyne cm.

Shear stress, $\tau = T / 2\pi R^2 h_e$

R^2 = 0.513 cm. (radius of spindle)

h_e = 6.11 cm. (effective height)

τ = 593/2 $(.513)^2(6.11)$

τ = 59

The effective viscosity equals: $\mu_a = \tau / \gamma$

μ_a = 59/156 = .378 poise or 37.8 cp.

III. Calculations for Run No. 14-5C

1. The suspension viscosity at the conditions of Run 14-5C are found as follows:

   a. Average batch temperature = 50°C

   b. Mixing shear rate = 11.5N

      γ = 11.5 (4.0) = 48/sec.

   c. Interpolate the apparent viscosity from the ordinate using Figure No. . and the data above.

      μ_a = 104 cps.

2. Density:

   $\rho_{water} = 62.42 - 0.001645T - 0.000248T^2$ T = 50.0°C

   = 62.4 lb./ft.^{3}

   kaolin = 161 lb./ft.^{3}

   Assume 100 lbs. of slurry:

   at 18.4 wt.% solids (18.4 lb. clay + 81.6 lb. water)

   18.4 lb./(161 lb./ft.^{3}) = 0.114 ft.^{3} kaolin

   81.6 lb./(62.4 lb./ft.^{3}) = 1.307 ft.^{3} water

   1.421 ft.^{3} total

   ρ_{slurry} = 100 lb./1.421 ft.^{3} = 69.6 lb./ft.^{3}

3. Heat Capacity:

C (water) = 1.003 Btu/lb.°F

C (kaolin) = 0.224 Btu/lb.°F

C slurry = $1.003\ (1 - X_w) + 0.224\ X_w$

X_w = weight fraction kaolin

C slurry = 0.860 Btu/lb.°F

4. Thermal Conductivity:

$$K \text{ slurry} = \frac{K_f \quad 2K_f + K_s' - 2X_v\ (K_f - K_s')}{2K_f + K_s' + X_v\ (K_f - K_s')}$$

K_f = $0.325 + 0.000888T$ (for water) T = °C

X_v = 0.080 (volume fraction solids)

K_s' = 0.110

where K = Btu/hr. ft.^{2} (°F/ft.)

at 50°C

K_s = 0.343 Btu/hr. ft.^{2} (°F/ft.)

5. Mixing Power to the Batch:

$P = 2\pi\,(\text{Torque})N$

where torque equals dynamometer reading x dynamometer pulley radius

Pulley radius = 3.26 inches

N = 4 rps S = 3.23 lb.

P = 22.1 ft. lb./sec.

or the heat input to the batch equals 1.71 btu/min.

6. Batch Heating:

$Q_h = WC_p dT/dt$

where dT/dt equals the change in batch temperature with time:

$(52.3 - 48.0°C) \times 1.8°F/°C \ /2 \text{ mins.} = 3.87°F/\text{min.}$

W equals batch weight

$W = \rho \text{ slurry (volume)}$

$= 69.6 \text{ lb./ft.}^3 \times 1.52 \text{ ft.}^3 = 106 \text{ lbs.}$

C_p slurry = 0.860 Btu/lb.°F

$$Q_h = 106 \text{ lb.} \times 0.860 \frac{\text{Btu}}{\text{lb.°F}} \times \frac{3.87°F}{\text{min.}}$$

$= 352.8$ Btu/min.

7. Film Coefficient:

$H' = Q/A \Delta T_{w-b}$

where A = 6.2 ft.^{2} (heat transfer area)

ΔT is the average temperature drop between the wall thermocouple and the batch temperature.

	No. 1	No. 2
Batch Temp. °C	52.3	48.0
Wall Temp.	34.2	32.2
ΔT_{w-b}	18.1	15.8

Tavg. = $(18.1 + 15.8)°C/2 \times 1.8°F/°C$

$\Delta T_{w-b} = 30.5°F$

Q = heat transfered through wall + heat of mixing

= 352.8 + 1.7

= 354.5 Btu/min.

7. Film Coefficient: continued

$H' = (354.5 \text{ Btu/min.}) / (6.2 \text{ ft.}^2) \quad (30.5°F)$

$= 1.88 \text{ Btu/min. ft.}^2 °F$

or $113 \text{ Btu /hr. ft.}^2 °F$

Adjusting H' to compensate for the wall thickness between the thermocouple and the batch wall:

$H = H' \quad (1 + 0.0001774 \, H')$

$H = 115.0 \text{ Btu/hr. ft.}^2 °F$

8. Nusselt Number:

$N_{Nu} = D_t \, H/K$

$D_t = 1.17 \text{ ft. (vessel diameter)}$

$$N_{Nu} = \frac{1.17 \text{ ft.} \quad 114 \text{ Btu/hr. ft.}^2 °F}{0.343 \text{ Btu/hr. ft.}^2 (°F/\text{ft.})}$$

$= 392$

9. Reynolds Number:

$N_{Re} = D_a^2 \, N\rho/U_a$

$D_a = 0.50 \text{ (impeller diameter) ft.}$

$$N_{Re} = \frac{(0.50 \text{ ft.})^2 (4.0/\text{sec.})(69.6 \text{ lb./ft.}^3)}{0.0698 \text{ lb./ft. sec.}}$$

$N_{Re} = 1000$

10. Prandtl Number:

$N_{Pr} = C_p \, U_a/K$

$$= \frac{(0.86 \text{ Btu/lb.}°F)(0.0698 \text{ lb./ft. sec.})}{0.343 \text{ Btu/hr.ft.}^2 \ (°F/\text{ft.})} \times \frac{3600 \text{ sec.}}{\text{hr.}}$$

$= 620$

11. Power Number:

$$N_{Po} = 32.2\ P/\rho\ N^3\ D_a^5$$

$$= 32.2\ (22.1)\ /\ 69.6\ (4)^3 (0.50)^5$$

$$= 5.1$$

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