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AN EVALUATION OF HYDROCLONE OPERATION FOR THE REMOVAL OF MICRON-SIZED PARTICLES FROM VISCOUS LIQUIDS

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ABSTRACT

The performance of a 1-cm-diam, Dorr-Oliver hydroclone with slurries containing about 5 wt % solids in water-glycerin solutions was studied to evaluate the effects of fluid viscosity. Micron-sized particles of low-density solids (kaolin) were removed from solutions with viscosities ranging from 1 to 13 cP. Pressure drop across the hydroclone increased with increasing feed rate and viscosity. Gross and centrifugal efficiencies were found to increase with flow rate and decrease with viscosity. The particle diameter, corresponding to a point efficiency of 50%, decreased as the inlet Reynolds number increased.

INTRODUCTION

Hydroclones have found many uses in the physical removal of solids from liquids or the concentration of solids, indicating a potential use of hydroclones as devices for removing solids from coal liquids, either alone or in series, with filtration equipment. The separation and concentration of micron-sized ash-char-catalyst solids from viscous liquid streams that result from hydroliquefaction and pyrolysis of coal is a crucial technical problem in the development and application of these processes. From a survey of the supporting research and development of separations technology for coal liquefaction processes (1), hydroclones have been used in a few pilot plants. These studies report limited amount of data, and no relationship was determined between efficiency and the operating parameters.

The basic advantages of a hydroclone over other solid-liquid separation techniques are simplicity, economy, and the possibility of operation at temperatures up to 450°C. Hydroclones are simple devices with no moving parts or mechanical seals. They require minimum maintenance, compared to a centrifuge or a continuous filter. The required energy of separation is the fluid pressure drop which can be supplied by a standard pump. The hydroclone size required for a given application is defined by the particle size to be separated. Small diameter hydroclones are generally more efficient for removing smaller (e.g., micron-sized) particles. The smallest hydroclone available commercially has a 1-cm major diameter; hydroclones with smaller diameters have not improved separation efficiencies significantly (2). For commercial applications, such as in coal liquefaction processing, a type TMC Dorrclone is available with 1-cm-diam hydroclones in manifolds containing 60, 162, and 300 units. The hydroclones are arranged in parallel; thus for a 100-psi pressure differential, the TMC-300 unit has a maximum capacity of about 15,000 bbl/day.

Previous studies or applications with 0.4- to 4.0-cm-diam hydroclones included (a) the recovery of catalysts from fluidized catalytic cracker distillation bottoms in petroleum refineries (3), (b) the removal of precipitated fission and corrosion products from uranyl sulfate solutions in an aqueous homogeneous nuclear reactor (2), (c) the separation of starch from gluten, and (d) the removal of fine particles from green liquor in the caustic soda forming steps of sulfate kraft mills (4).

The general performance of a hydroclone depends upon the physical dimensions of the unit, the feed capacity, and the physical properties of the feed. Performance criteria are usually defined by hydroclone efficiency, pressure drop, and the ratio of underflow to overflow rates. The literature has numerous papers concerning hydroclones which fall into two basic categories, those dealing with theory and design and those related to industrial applications. The most complete bibliography is contained in a book entitled, The Hydroclone (5).

The performance of hydroclones with relatively viscous liquids and micron-sized particles, such as those produced in coal hydroliquefaction processes, has not been studied adequately. From a previous study (6) using a 1-cm-diam hydroclone which removed micron-sized particles from solutions with viscosities as high as 85 cP, the author concluded (7) that liquid viscosities greater than 10 cP had deleterious effects on the pressure drop and efficiency; thus useful separations were not attained. Therefore, the main objective of this study was to experimentally measure the performance of a 1-cm-diam hydroclone as a function of applied pressure drop and liquid viscosities up to about 15 cP for solids with low density and small particle diameter. The relationship between pressure drop (inlet-to-overflow) and flow rate at varying viscosities was determined, and a correlation was developed to describe particle size classification as a function of the physical properties of the solid particles and liquid medium.

MATERIALS AND METHODS

A schematic diagram of the system used to study hydroclones is shown in Fig. 1. Slurry from a 20-ℓ stirred tank was recirculated by a Moyno slurry pump through a 1-cm Dorr-Oliver Doxie Type A hydroclone and returned to the feed tank. Pressure gauges were located as close to the hydroclone inlet and outlets as possible.

Feed slurries with approximately 5 wt % kaolin particles in water-glycerin solutions were used with viscosities ranging from 1 to 13 cP. The kaolin particles are less than 10 μm in diameter

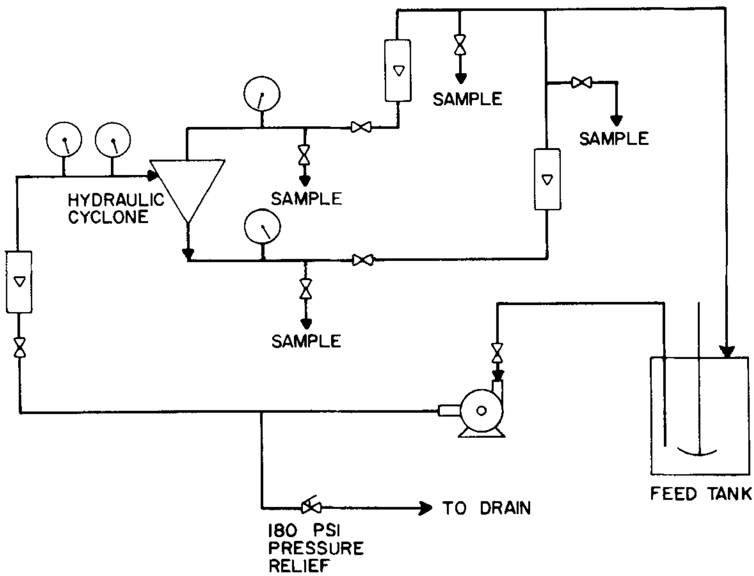

FIGURE 1. System to study hydroclone performance.

with approximately 70 wt % of the particles less than 5 μm. Liquid viscosities were determined with a Brooksfield viscometer. The kaolin solids density of 2.40 g/cm^3 was determined with a 50-cm^3 pynometer.

To begin an experiment, solutions were prepared with the desired viscosity and solids concentration and then stirred until the solids were suspended. Next the pump was started with the flow rate and pressure drop controlled by the pump throttle. At a desired pressure drop, inlet, overflow, and overflow pressures were recorded. Underflow and overflow rates were measured with a graduated cylinder and stop watch. Samples were taken of the overflow and underflow to determine the solids concentrations and particle size distributions. To measure solids concentration, 10-cm^3 liquid aliquots were evaporated for about 4 hr on a hot plate at 400°C and then dried in an oven at 500°C. A photolemetric technique was used to measure the particle size distributions.

Experiments were conducted to determine a relationship between pressure drop and both flow rate and viscosity. Data for the runs consist of pressure drop, feed liquid viscosity, overflow and underflow rate, and solids concentration in both the overflow and underflow streams. A series of tests were run at varying liquid feed viscosities; each series was conducted at several different pressure drops. The data for the series of tests are tabulated elsewhere (7). A summary of the test conditions are given in Table 1.

EXPERIMENTAL RESULTS AND PERFORMANCE CORRELATIONS

The operating variables of interest in this study are solid density, liquid medium viscosity, and particle size. Specifically, the hydroclone performance was evaluated as a function of a small solid-liquid density difference, a relatively high liquid viscosity, and micron-sized particles. Performance calculations were computed (7) using the operating data collected for the different test runs. The feed flow rate is the sum of the underflow and overflow rates. The solids concentration of the feed

TABLE 1

Summary of Test Conditions

Average Viscosities Investigated (cP)	Pressure Drop Range (psi)
1.0	13.6 - 97.7
3.8	12.7 - 64.7
4.3	12.8 - 66.6
7.0	12.0 - 65.0
10.7	34.0 - 65.3
11.8	11.2 - 59.7
12.8	12.0 - 35.2

was calculated from the solid concentrations and flow rates of the overflow and underflow streams.

Particle size distributions were determined for the kaolin slurries with average viscosities of 1.0, 4.3, 10.7, 11.8, and 12.8 cP. The particle size distributions for the overflow and underflow streams were measured, and the particle size distribution in the feed was calculated from these data on the outlet streams. Figure 2 shows typical size distributions for the slurry feed, overflow, and underflow streams of a kaolin-aqueous solution with a liquid viscosity of 1 cP. The slurry feed contains 40 wt % particles less than 3 μm in diameter. The overflow and underflow streams contained respective 98 and 13 wt % particles less than 3 μm in diameter when the pressure drop was 87.3 psi. For this particular run, 80% of the feed solids exited the underflow.

The effect of viscosity on the particle size distribution curves is shown in Figs. 3 and 4. Figure 3 shows the overflow particle size distribution curves for three runs at an average pressure drop of 28.1 psi for liquid viscosities of 1, 4.4, and 11.4 cP. As viscosity increases, the curve shifts to the right, indicating that larger size particles are not being separated as effectively. The particle diameters corresponding to less than 50 wt % removed in the 1, 4.4, and 11.4 cP viscosity runs are 1.88, 2.04, and 3.20 μm, respectively. Figure 4 also shows the shift of the overflow particle size distribution curves with increasing viscosity at a higher average pressure drop, 66.0 psi. The corresponding particle diameters where less than 50 wt % are removed at fluid viscosities of 1, 4.2, and 10.1 cP are 1.39, 2.20, and 3.30 μm, respectively. The increase in pressure drop (and flow rate) produced a steeper size-distribution curve for the 1-cP run. However, the increase in pressure drop did not improve the separation for the higher viscosities.

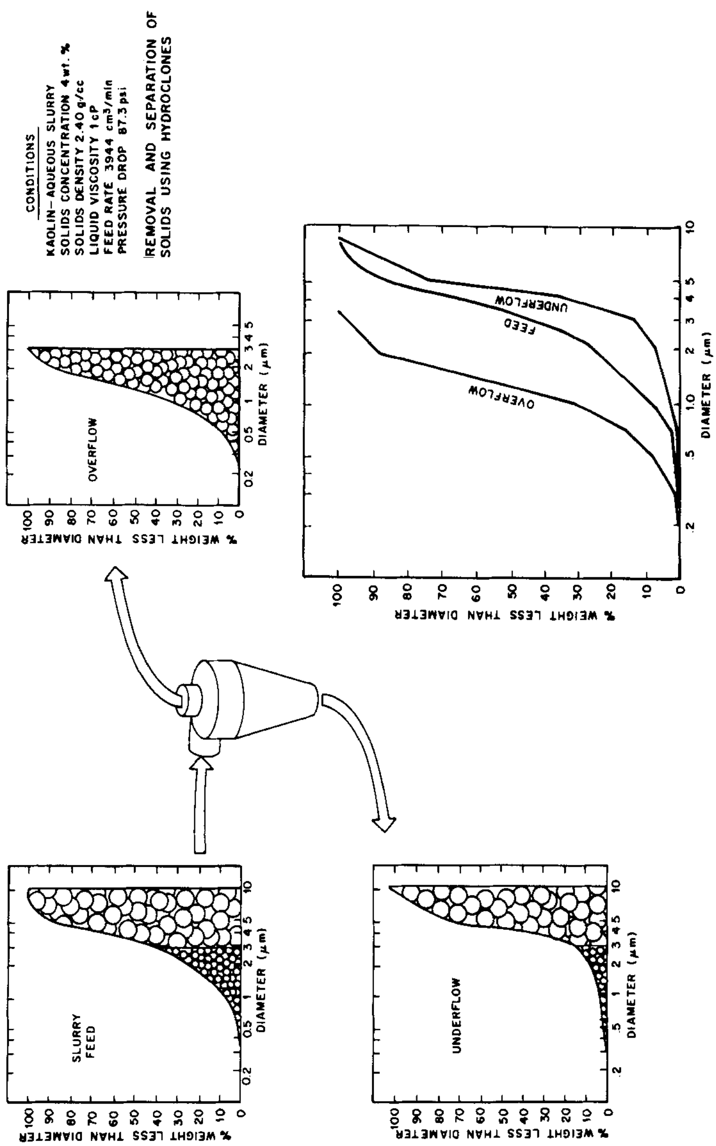

FIGURE 2. Typical size distribution curves for kaolin-aqueous solution.

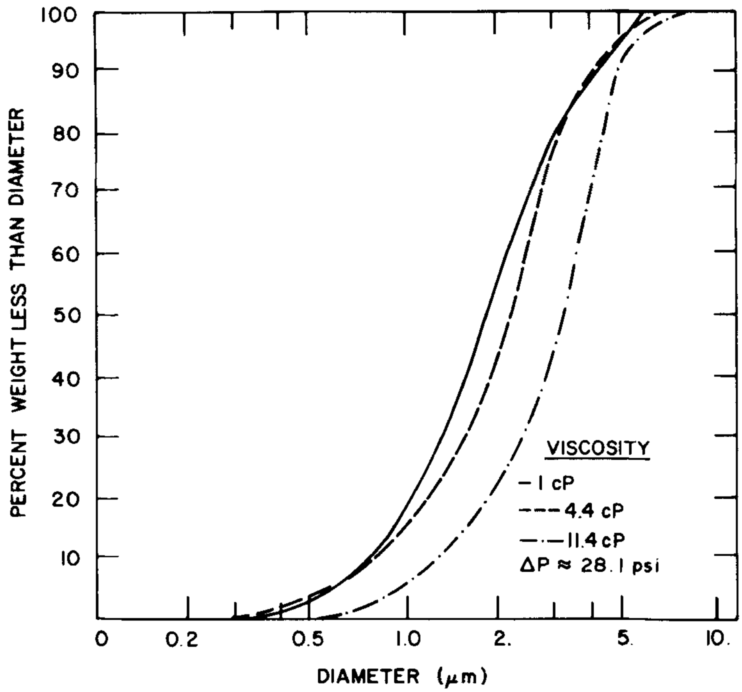

FIGURE 3. The effect of viscosity on the overflow particle size distribution curve for $\Delta P \cong 28.1$ psi.

Hydroclone Performance Parameters

A plot of inlet-to-overflow pressure drop, ΔP (psi), as a function of feed flow rate, Q_f (cm^3/min), at various viscosities is shown in Fig. 5. As expected, pressure drop increases with increasing flow rate. Figure 5 shows a least-squares fit of 60 data points for the kaolin-glycerol runs, excluding those at 1 cP, which can be described by the following equation:

$$\Delta P = 4.25 \times 10^{-6} Q_f^{2.00}. \tag{1}$$

The coefficient of determination, r^2, is 0.99. This equation and the data at 1 cP agree well with a relationship in the literature (5) which states that the pressure drop is proportional to the

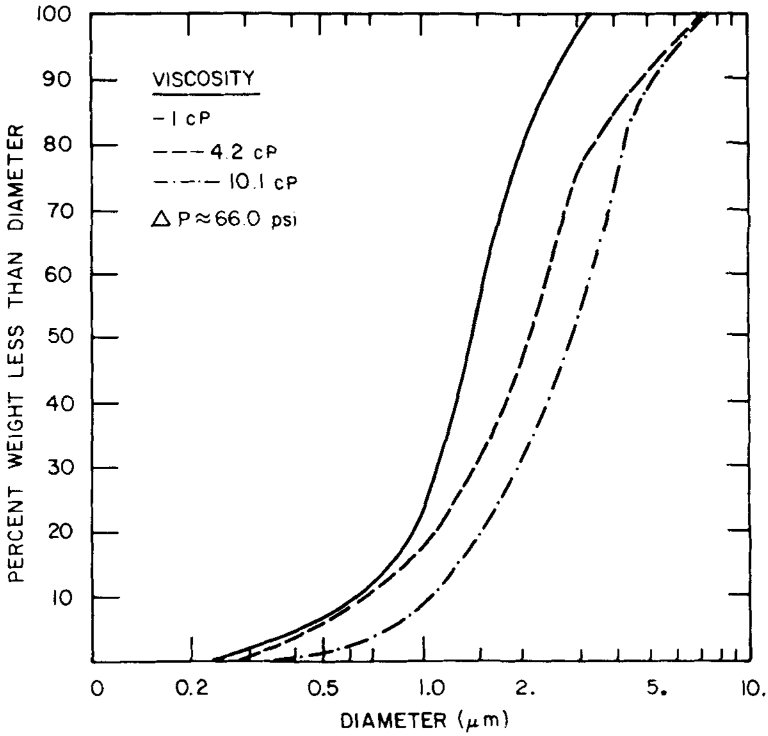

FIGURE 4. The effect of viscosity on the overflow particle size distribution curve for $\Delta P \cong 66.0$ psi.

square of the feed rate. Increasing viscosity did not seem to effect the experiments significantly, whereas previous data (6) using slurries with viscosities up to 85 cP indicated that the slope decreases with increasing viscosity.

An important parameter which describes hydroclone performance is volume split, S, which is defined as the ratio of the underflow-to-overflow rate. For the 1-cm Dorr-Oliver hydroclone used in this study, the natural feed split (free discharge conditions, i.e., no back pressure on the exiting streams) is 60% to the overflow and 40% to the underflow (8); S = 0.67. The normal operating condition for a hydroclone is S < 1, or the overlfow

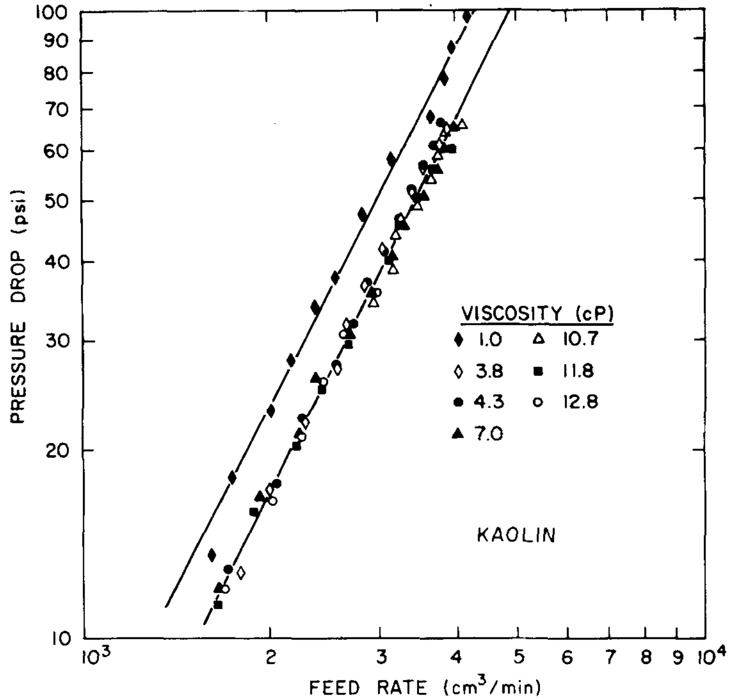

FIGURE 5. Pressure drop as a function of feed rate.

rate to be greater than the underflow rate. The work done with small diameter hydroclones (5) has shown conditions where the volume split has decreased, remained constant, or decreased with an increase in flow rate. Generally, with small diameter hydroclones, when S > 0.5, the split was independent of feed rate, and when S < 0.5, the split decreased with an increase in feed rate. The results of this study give values of S greater than the split given by the vendor (S = 0.67). For the majority of test runs, the volume split increased with an increase in feed rate.

Since a large number of variables are involved in the operation of a hydroclone, the experimental results of some investigations have been expressed in terms of dimensionless groups, in particular, Reynolds number. Reynolds number can be thought of as the ratio of inertial to viscous forces. Therefore, the dimensionless numbers can be expressed as follows:

$$N_{Re} = \frac{4D_c Q_f \rho}{\pi D_f^2 \mu} , \tag{2}$$

or

$$N_{Re\ inlet} = \frac{4Q_f \rho}{\pi D_f \mu} , \tag{3}$$

where

ρ = the liquid density (g/cm^3),

D_f = the feed port diameter (0.325 cm), and

D_c = the main hydroclone diameter (1.00 cm).

Therefore, for the hydroclone used in this study,

$$N_{Re} = 3.08\ N_{Re\ inlet}. \tag{4}$$

The optimum operating condition (5) for a 1-cm-diam hydroclone using water should correspond to an inlet N_{Re} in the range of $\sim 10^4$ to 5×10^4. In this study, inlet N_{Re} ranged from 828 to 2.7×10^4; for the 1-cP runs the inlet Reynolds numbers were greater than 10^4.

Hydrogen Efficiency

Hydroclone efficiency is defined in several different ways in the literature (5). Gross efficiency, G, is the ratio of the solids discharge rate at the underflow to the solids feed rate. Since liquid is continuously removed with the underflow solids, two liquid and two solid flow rates are involved in any useful definition of efficiency. Therefore, the hydroclone efficiency more commonly used is the centrifugal efficiency, E, which is defined as follows:

$$E = \frac{G - Rf}{1 - Rf} , \tag{5}$$

where Rf = ratio of the underflow rate to the feed rate. For example, if all solids entering the hydroclone leave at the underflow, G = 1. If all the liquid leaves at the overflow, Rf = 0 and the centrifugal efficiency equals unity. Centrifugal efficiency is also called the separation number (9). The values G and E are not referenced to a particle size distribution but describe the bulk stream separation.

The results of this study show that both gross and centrifugal efficiencies increase with increasing feed rate; however, increasing viscosity decreases the hydroclone efficiency. The effect of viscosity on gross and centrifugal efficiencies is shown in Fig. 6 at a feed rate of 2500 cm^3/min. The efficiency values in Fig. 6 are interpolated from correlations of efficiency as a function of feed rate (7). Both gross and centrifugal efficiencies decrease with increasing viscosity. The equations for the curves shown in Fig. 6 are as follows:

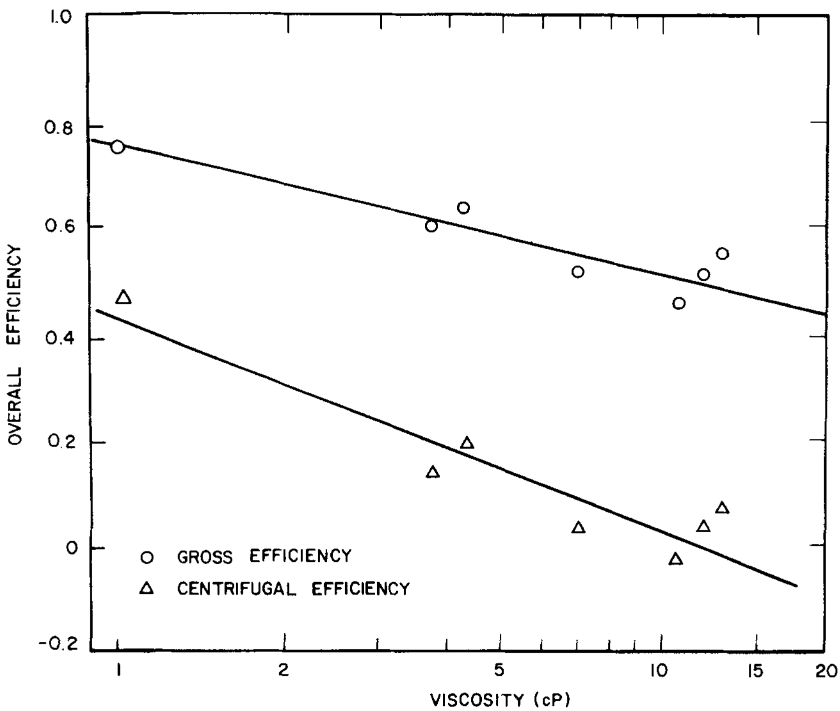

FIGURE 6. Effect of viscosity on gross and centrifugal efficiency at a feed rate of 2500 cm^3/min.

$$G = 0.751 - 0.102\ \ell n \mu,\ r^2 = 0.85, \qquad (6)$$

$$E = 0.427 - 0.175\ \ell n \mu,\ r^2 = 0.88. \qquad (7)$$

The least-squares fit of the data in Fig. 6 indicates that the fraction of solids and the fraction of liquid that go to the underflow are essentially equal (gross efficiency equal 0.5) at a viscosity of 10 to 11 cP. As shown in Fig. 6, this viscosity corresponds to a centrifugal efficiency of zero.

The effect of Reynolds number on both gross and centrifugal efficiencies was determined. Gross efficiency increases with increasing Reynolds number, as follows:

$$G = 0.143\ N_{Re}^{0.153},\ r^2 = 0.81. \qquad (8)$$

The Reynolds number that corresponds to a maximum gross efficiency (G = 1) is 3.3×10^5. As shown in Fig. 7, centrifugal efficiency also increases with increasing Reynolds number and with decreasing viscosity. The least-squares equation for the data in Fig. 7 is:

$$E = 1.38 \times 10^{-6}\ N_{Re}^{1.179},\ r^2 = 0.64. \qquad (9)$$

The Reynolds number that corresponds to a maximum centrifugal efficiency (E = 1) is 9.3×10^4. The runs at 1 cP have the highest Reynolds numbers and centrifugal efficiencies.

Since all of the solids in the feed material were not the same size, efficiency must be referenced to a size distribution. The point efficiency, E', expresses the centrifugal efficiency for a given particle size or fraction of a given particle size interval which is removed from the feed stream through the underflow. Point efficiencies were calculated from the size distribution curves, and particle diameters corresponding to point efficiencies of 50%, d_{50}, were determined by interpolation (7). Although particle size distributions and subsequent point efficiency curves were determined for the kaolin slurries with average viscosities of 1.0, 4.3, 10.7, 11.8, and 12.8 cP, only a few d_{50} values could

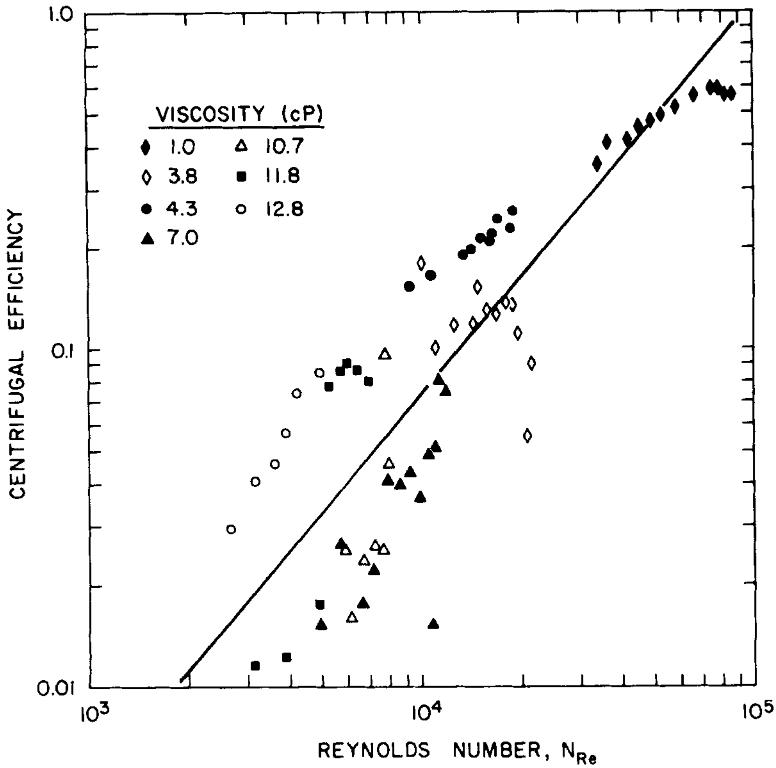

FIGURE 7. Centrifugal efficiency as a function of Reynolds number.

be evaluated. The particle size analyses for the overflow and underflow streams were nearly identical for many of the runs; therefore, the point efficiency data were too scattered to be useful. There are two possible explanations for the similarity of the overflow and underflow size distribution curves. First, if the size distributions are accurate, essentially no separation occurred according to specific particle size ranges. The gross efficiency calculations indicated that G approached 0.5 at viscosities >10 cP. Therefore, the bulk solids are splitting nearly evenly between the overflow and underflow streams. The second possibility is that the particle size distributions are not accurate and, therefore, do not show the actual separation by particle size when used to determine point efficiencies.

The d_{50} values ranged from 1.3 to 3.8 μm. The literature (10) states that a plot of d_{50} vs $(N_{Re\ inlet})(\sigma-\rho)/\rho$ (see Fig. 8) should give a straight line, where σ is the solid density (g/cm^3). The number of d_{50} values are small and there is much scatter, however, a least-squares linear line is drawn through all the d_{50} values and also two separate dashed lines are drawn for $(N_{Re\ inlet})\ (\sigma-\rho)/\rho$ values less than and greater than 10^4. The following correlations were determined from least-squares fit of the data:

Overall $$d_{50} = 9.5[(N_{Re\ inlet})(\frac{\sigma-\rho}{\rho})]^{-0.16},\ r^2 = 0.38, \quad (9)$$

$(N_{Re\ inlet})(\frac{\sigma-\rho}{\rho}) < 10^4$ $$d_{50} = 585\ [(N_{Re\ inlet})(\frac{\sigma-\rho}{\rho})]^{-0.68},\quad r^2 = 0.73 \quad (10)$$

$(N_{Re\ inlet})(\frac{\sigma-\rho}{\rho}) > 10^4$ $$d_{50} = 154\ [(N_{Re\ inlet})\ \frac{\sigma-\rho}{\rho}]^{-0.43},\quad r^2 = 0.32. \quad (11)$$

The least-squares fit of all the experimental d_{50} values in Fig. 8 does not indicate a negative slope of one-half which is found in the literature (5). By separating the d_{50} values in Fig. 8 into two regimes, the experimental relationships are closer to those found in the literature. There are not enough d_{50} data to give an acceptable correlation.

A reduced efficiency relationship (point efficiency as a function of a reduced particle diameter, d/d_{50}) for the kaolin-aqueous slurries (1 cP) is shown in Fig. 9. The following empirical equation (10) has been deduced to describe hydroclone performance:

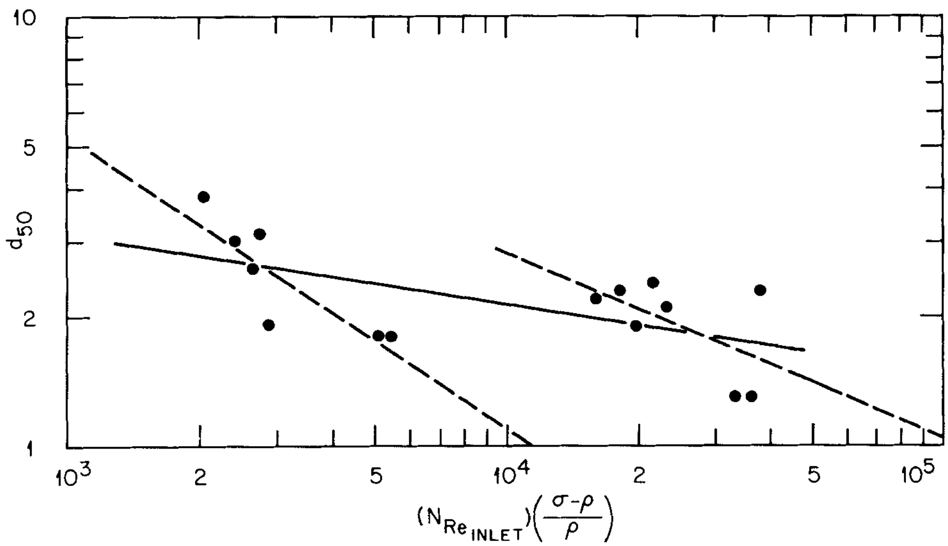

FIGURE 8. Effect of $(N_{Re\ inlet})(\sigma-\rho)/\rho$ on d_{50} values.

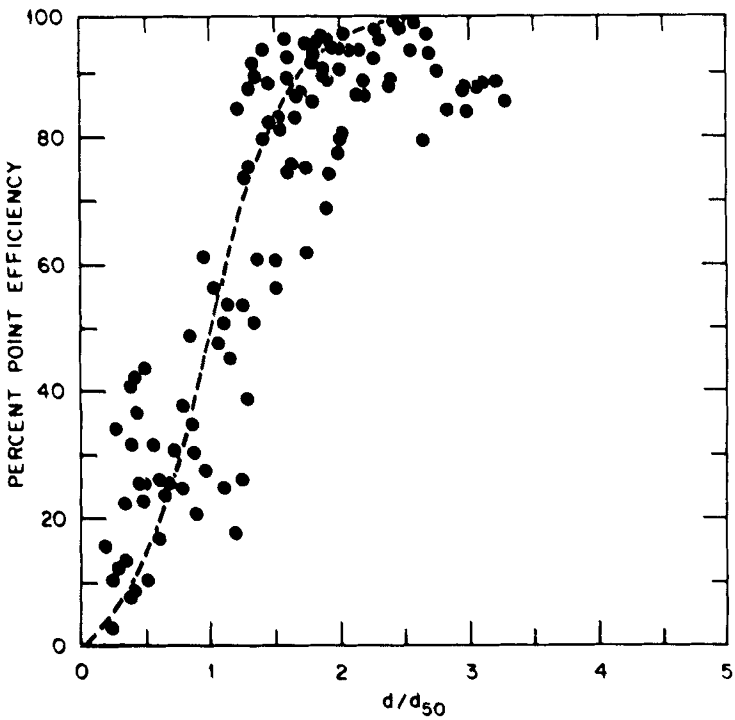

FIGURE 9. Reduced efficiency data showing literature correlation for β = 3.0.

$$E' = \frac{\exp(\beta\, d/d_{50}) - 1}{\exp(\beta d/d_{50}) + \exp\beta - 2}, \tag{12}$$

where

d = the particle diameter (μm), and

β = a constant.

The constant β was found to depend on the slurry feed (10) with β = 2.5 for silica ore and 2.0 for copper ore. The "s"-shaped curve shown in Fig. 9 was calculated from Eq. (12) and correlates reasonably well with the kaolin-water data using β = 3.0.

Particle removal data obtained from Dorr-Oliver for the hydroclone used in this study are given in Fig. 10 as a function of feed rate and pressure drop. The Dorr-Oliver d_{95} values indicate the particle diameters in microns at which 95% of the solids were discharged to the underflow stream. As seen in Fig. 9, $d_{95}/d_{50} \cong 2$ for Eq. (12) (β = 3.0). By comparing the experimental values with the Dorr-Oliver correlation at the same pressure drop (see Fig. 10), the particle removal efficiencies observed in experiments with 1-cP slurries appear comparable to the manufacturer's specifications.

The same 1-cm-diam Dorr-Oliver "Doxie" hydroclone was used for all experiments. Upon completion of the performance experiments, measurements of the hydroclone internal dimensions were repeated to determine the effect of the abrasive solid particles in the slurry feed. The main hydroclone diameter and overflow port diameter did not increase in size; however, the underflow port diameter increased by 11%.

CONCLUSIONS

This evaluation of a 1-cm-diam hydroclone studied its performance at the limits of operation by combining the parameters of high liquid viscosity, micron-sized particles, and small solid-liquid density difference (which simulated the properties of coal-derived liquids). As mentioned in the literature and

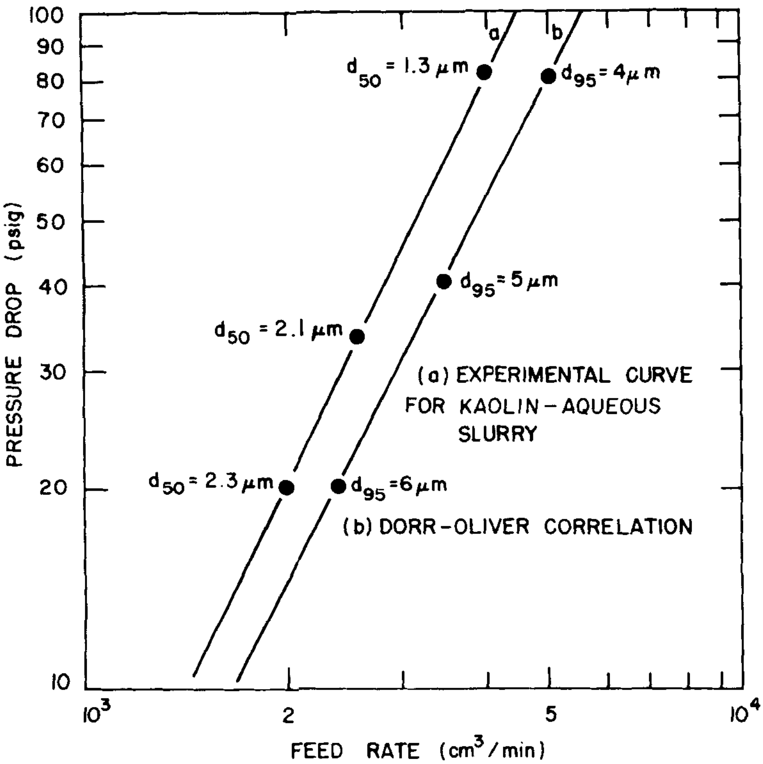

FIGURE 10. Comparison of experimental and manufacturer particle removal data.

concluded in this study, the performance criteria of pressure drop and hydroclone efficiency are greatly influenced by the parameters of interest. Pressure drop increased with increasing viscosity and feed rate; however, the maximum ΔP which could be attained decreased with increasing viscosity. The maximum feed rates for liquid viscosities of 1 cP and 12.8 cP are approximately 4000 and 3000 cm^3/min, respectively. Table 2 compares pressure drop, Reynolds number, and efficiencies for kaolin at the above conditions. This comparison shows the pronounced effect of

TABLE 2

Comparison of Calculated Results for Kaolin Particles

Maximum feed rate (cm^3/min)	Liquid viscosity (cP)	Pressure drop (psi)	Reynolds number N_{Re}	Gross efficiency G	Centrifugal efficiency E
4000	1	68.0	80,400	0.805	0.838
3000	12.8	38.3	4,710	0.522	0.030

viscosity on efficiency. Notice, however, that the maximum feed rate and lowest viscosity for a kaolin slurry resulted in a maximum gross efficiency of 80.5% and centrifugal efficiency of 83.3%.

Viscosity has a noticeable effect on the particle size distribution curves, as shown in Figs. 3 and 4. As viscosity increases, the smaller sized particles are not separated from the bulk fluid to the underflow stream. At the most favorable conditions (high feed rate and 1 cP viscosity), a d_{50} value of 1.3 μm is predicted from Fig. 10 which corresponds to a d_{95} value of about 3 μm. Therefore, at higher viscosities it can be assumed that the d_{50} value (and d_{95}) would only increase. At optimum operating conditions using kaolin-water slurries (feed capacity of 4000 cm^3/min), 95% of the particles larger than 3 μm in diameter can be separated to the underflow stream using the 1-cm-diam hydroclone.

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