Miniature Hydroclones as Slurry Concentrators

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Miniature hydroclones were evaluated for use with thoria-urania slurries being considered as fuels for one type of homogeneous nuclear reactor. In addition to extensive room temperature data on concentrating performance, the results of tests with thoria slurries at a pressure of 2,000 lb./sq. in. and temperatures up to 550°F. are given. The data correlation presented allows prediction of the concentrating performance of a given clone provided that the properties and particle size distribution of the slurry feed are known.

The proposed homogeneous-slurry nuclear reactor, which is fueled with an aqueous thoria-urania suspension, requires devices capable of both concentrating and diluting the slurry fuel during start-up and shut-down. Hydroclones seemed particularly suitable for such purposes, being easily designed for high pressures and temperatures, simple and durable, and devoid of moving parts to complicate remote maintenance. In addition they have proved highly efficient in the removal of micron-size particles from the uranyl sulfate solutions that are employed in one type of aqueous homogeneous reactor (*11*). Therefore the concentrating behavior of miniature hydroclones was investigated as one part of an extensive feasibility study of the homogeneous slurry reactor (*14*, *15*).

Most previous investigations (*4* to *8*, *11*, *16*, *19*) have been concerned primarily with the classification action of hydroclones. The solids-separation ability of the hydroclones was described in terms of the particle diameter at which 50% of the particles enter the underflow. Since the thoria-urania slurry contains an appreciable quantity of submicron particles, use of the smallest miniature hydroclone practical (5 to 10 mm.) at reasonable pressure drops (20 to 40 lb./sq. in.) results in a d_{50} which is above the size of an appreciable fraction of the particles. To predict the concentrating effectiveness with thoria-urania slurry it is therefore necessary to describe quantitatively the behavior of particles below the d_{50} size.

This problem was considered in the work of Yoshioka and Hotta (*20*) on full-sized hydroclones. These investigators studied the velocity distribution in several hydroclones and the classification of clay slurries in a 6-in. hydroclone with a 20-deg. included angle. The solids-removal efficiency at a given particle size was defined as the percentage of feed particles of a given size which is removed by the underflow. The ratio Q_s/Q_1 was found to have a significant effect on the separation efficiency. For a specific clone at a fixed feed rate, Yoshioka and Hotta found that

$$100 - E = K(1 - Q_s/Q_1) \qquad (1)$$

To allow for the underflow effect, they defined d'_{50} as the particle size at which $(100 - E)/(1 - Q_s/Q_1)$ is equal to 50%. The values of d'_{50} they obtained are correlated by

$$d'_{50} = 2\left(\frac{\mu_l}{\rho_p - \rho_l}\right)^{0.5} \frac{D^{0.1} F^{0.6} O^{0.8}}{Q^{0.5}} \qquad (2)$$

Solids-removal efficiencies at other particle sizes were graphically correlated by a fractional recovery curve showing $(100 - E)/(1 - Q_s/Q_1)$ as a function of d/d'_{50}.

EXPERIMENTAL PROGRAM

The present experimental study of miniature hydroclone performance was divided into two phases. The first phase was a room-temperature investigation, aimed at providing enough basic information to allow the formulation of generalized correlations describing the concentrating action of miniature hydroclones. The second phase was the testing of prototype clones with thoria-urania slurries at reactor plant conditions (550°F. and 2,000 lb./sq. in.)

The hydroclones tested in this program ranged from 5 to 50 mm. in diameter. The detailed dimensions of the units used are tabulated in Figure 1. It may be seen that both individual clones and assemblies of several clones in parallel were tested. (Owing to the small throughput of the individual clones, plant-sized units would consist of such assemblies.)

EXPERIMENTS AT ROOM TEMPERATURE

The concentrating action of 50- and 10-mm. clones (clone assemblies *A* and *C* of Figure 1) was investigated by the use of a bypass line of a 50 gal./min. test loop. The flow rates were measured by rotameters, and valved tees were provided for sampling. Samples were taken of overflow, underflow, and feed to determine concentrations, settling rates, and particle size distributions. To ensure that the loop concentration was uniform, data were taken only after the slurry had circulated for 1 hr.

10-mm. Clone Assembly

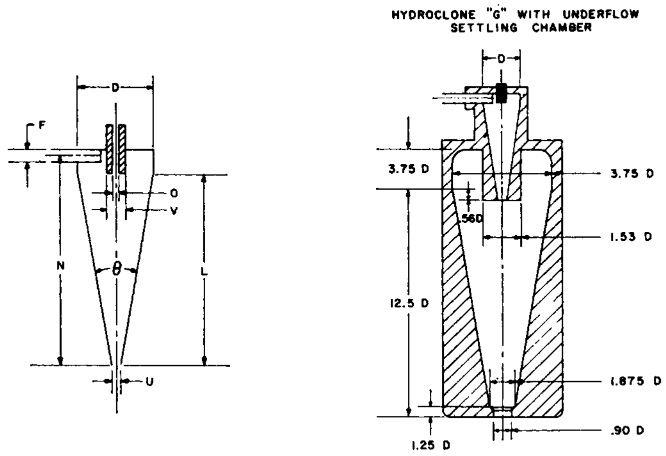
The 10-mm. clone assembly was tested with a thoria-urania slurry of a type and composition similar to that proposed for the reactor plant (weight ratio of urania to thoria = 0.03) used. Microscopic examination of the thoria urania showed that many of these particles were collected in large flocs having diameters of 20 to 150 μ. Particle-size determinations by the Andreasen sedimentation pipette method (*1*, *2*) in the presence of a sodium-silicate dispersant showed these flocs to be composed of particles ranging from approximately 0.3 to 7 μ in size. The particle size so determined, rather than the floc size, was taken to be representative of the conditions within the hydroclones. This assumption is based on the results of Bennett and Thomas (*3*), which indicated that the high shearing force developed in the hydroclones reduces the large, loose thoria flocs into individual particles.

Test conditions for the 10-mm. clone assembly included pressure drops ranging from 10 to 50 lb./sq. in. and concentrations ranging from 30 to 300 g./liter. At each condition the flow distribution was varied over a large range by throttling the valve in the underflow line.

Separation efficiencies as a function of particle size were obtained in essentially the same manner as described by previous investigators (*4*, *19*, *20*). The Andreasen pipette technique was used to give the particle-size distribution in terms of weight fraction of particles having free-settling rates higher than any given free-settling rate. Multiplication of the respective particle-size distribution curves by the fraction of total feed solids in each stream yielded curves of the cumulative weight fraction of feed solids. The solids-removal efficiency at a given free-settling rate equals one hundred times the ratio of the slopes of the underflow and feed curves at that settling rate.

Figure 2 shows a typical set of data calculated by the above procedure. The pronounced effect of the underflow ratio should be noted. The general shapes of the curves are in agreement with the observations of Yoshioka and Hotta (*20*). At very small particle sizes the solids-removal efficiency approaches the underflow ratio, and the curves for the various underflow ratios approach each other as *E* approaches 100%. There exists a settling rate above which all particles enter the underflow. As expected, the settling rate at which this occurs decreases with increasing pressure drop.

The observed underflow-ratio effect was compared with the relationship by Yoshioka and Hotta [Equation (1)]. It was found that their relationship holds for



CLONE	NO OF CLONES IN PARALLEL	D MM	L/D	EQUIV. F/D	O/D	U/D	V/D	N/D	INCLUDED ANGLE, θ DEGREES	PRESSURE RATING PSI
A	1	50	5.5	.286	.35	.22	—	5.5	8.125	80
B	1	25.4	6.0	.141	.125	.334	.25	6.4	6.00	50
C	4	10	8.2	.248	.22	.22	.4	8.09	5.45	300
D	7	10	8.0	.248	.22	.22	.4	8.11	5.20	2500
E	1	10	8.2	.248	.22	.22	.4	8.32	5.45	2500
F	7	5	8.9	.240	.22	.22	.44	9.0	5.03	2500
G	1	10	5.68	.295	.25	.25	.375	5.82	7.20	2500

Fig. 1. Dimensions of miniature hydroclones used in this investigation.

low values of r but gives poor agreement as r is increased. It was found that over the range of r used (0.03 to 0.3), $E/100-E$ is directly proportional to $r/1-r$. In the calculation of r it was assumed that the thoria particles were half water. By defining a concentration factor α such that

$$\alpha = \left(\frac{E}{100-E}\right) \cdot \left(\frac{1-r}{r}\right) \qquad (3)$$

one can describe the hydroclone performance independently of the underflow ratio being used. It will be noted that α represents the ratio of the concentration of a given size particle in the underflow to the concentration of the same size particle in the overflow, or

$$\alpha = C^*_3/C^*_2 \qquad (4)$$

This concentration factor is quite similar to the concentration factor defined by Haas *et al.* (*11*) for hydroclone operation with an underflow pot.

The data indicate that α is a function of feed concentration as well as head loss across the clone. Figure 3 shows the effect of feed concentration on α with the pressure drop across the clone fixed at 40 lb./sq. in. Although there is appreciable scatter, there is an observable increase in α as the feed concentration is decreased. Fitch and Johnson (9) cited a similar dilution effect.

50-mm. Clone

The 50-mm. hydroclone was tested with a glass-bead–water slurry of suitable particle size (10 to 40 μ). The tests were conducted at feed concentrations of approximately 200 to 50 g./liter and fluid head losses ranging from 50 to 500 cm. Concentrations, settling rates, and particle-size distribution were measured in the manner previously described. These data could be correlated in the same fashion as those obtained with thoria. It was found that the ratio Q_3/Q_1 differed negligibly from r for the thoria slurries used but that there was an appreciable difference between those quantities for the glass slurries. A noticeably poorer correlation of the glass data results if r is replaced by Q_3/Q_1.

GENERALIZED CORRELATION OF ROOM-TEMPERATURE DATA

To arrive at a means for relating the glass- and thoria-slurry data and to develop a correlation for the concentration ratio in terms of system properties and operating conditions, it is desirable to consider the behavior of a particle within the hydroclone. The radial movement of a given particle is determined by the relative values of the water radial velocity and the radial settling velocity of the particle generated by the centrifugal forces developed in the clone. It therefore seems plausible, for a given underflow ratio, that the ratio of the mass of a given particle-size class collected in the underflow to the mass of the same particle-size class collected in the overflow is related to the ratio of the particle radial settling velocity to the water radial velocity; that is

$$\frac{E}{100-E} = f\left(\frac{v_r}{U}\right) \qquad (5)$$

At any radius in the hydroclone the radial settling velocity of the particle is given by

$$v_r = \frac{V^2}{R} \cdot \frac{v_p}{g} \qquad (6)$$

provided that the particles are in the size range to which Stokes's law normally applies. Noting that the corresponding values of R are proportional to the hydroclone diameter and making use of Kelsall's (*16*) observation that U/V at any radius is independent of throughput, one may restate Equation (5) as

$$\frac{E}{100-E} = f'\left[\frac{v_p}{g}\left(\frac{V}{D}\right)\right] \qquad (7)$$

For hydroclones where the ratios of O/D and F/D are held constant the tangential velocity would be very nearly proportional to the square root of the product of the acceleration of gravity and the fluid head loss across the hydroclone. The experimental data of Kelsall (*16*) show this to be a very close approximation of the facts. Consequently the functional relationship is modified to

$$\frac{E}{100-E} = f''\left[\frac{v_p}{D}\left(\frac{\Delta H}{g}\right)^{1/2}\right] \qquad (8)$$

Since the experimental results show,

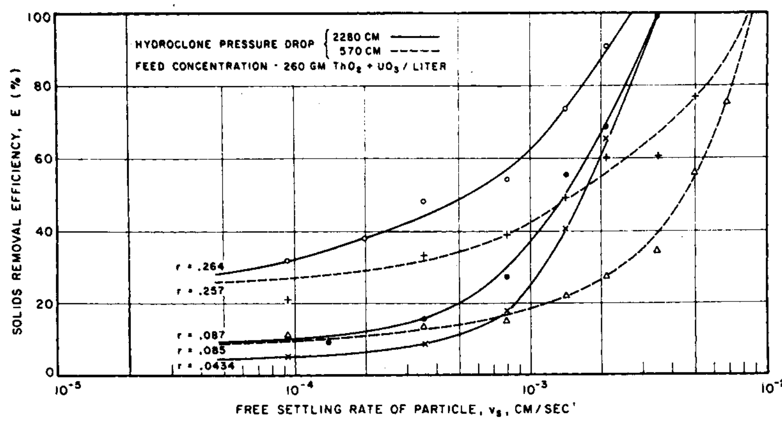


Fig. 2. Typical curves of separation efficiency as a function of particle settling rate and underflow ratio.

for a given slurry and hydroclone operating over a range of underflow to overflow ratios, that $E/(100-E)$ is directly proportional to $r/(1-r)$, this dependence is inserted explicitly. The correlation expression then becomes

$$\alpha = f''' \left[\frac{v_p}{D} \left(\frac{\Delta H}{g} \right)^{1/2} \right] = f'''(\Psi) \quad (9)$$

If one extends this correlation to include the effect of feed and overflow port sizes, one has

$$\alpha = f'''(\Psi) \times f'''' \left(\frac{O}{D}, \frac{F}{D} \right) \quad (10)$$

It should be noted that Ψ is dimensionless.

In computing v_p an allowance must be made for the effect of slurry concentration. For the glass-bead system this was done on the basis that v_p should show the same concentration dependence as the slurry hindered settling rate. The value of v_p at any concentration was then computed as the product of v_s and the ratio of the hindered settling rate at the given concentration to the extrapolated value at zero concentration.

The above procedure was not readily applicable to the thoria suspensions owing to the marked floc formation of these slurries. In this case the approximation was made that Stokes's law can be applied if the properties of the liquid are taken as those of the slurry mixture considered as homogeneous fluid medium. This does not strictly apply unless the particle under consideration is appreciably larger than those surrounding it. However Happel's (*13*) comparison of various sedementation velocity correlations shows that this approach is in fairly good agreement with the available experimental data. Basing v_p on the properties of the slurry feed, one then has

$$v_p = v_s \cdot \left(\frac{\mu_l}{\mu_{ml}} \right) \left(\frac{\rho_p - \rho_{ml}}{\rho_p - \rho_l} \right) \quad (11)$$

The above relationship is not adequate for non-Newtonian fluids such as the thoria slurries investigated in this study. Since these slurries approximate Bingham plastic behavior and since the yield value may be disregarded at the high values of shear in the hydroclone, the slurry viscosity may be replaced by the modulus of rigidity:

$$v_p = v_s \left(\frac{\mu_l}{\eta_1} \right) \left(\frac{\rho_p - \rho_{ml}}{\rho_p - \rho_l} \right) \quad (12)$$

Values of η were measured for the thoria slurries, and the particle density was calculated on the basis that the thoria particles were half water.

In Figure 4 all the room-temperature data for both glass-bead and thoria slurries are plotted as $\alpha - 1$ vs. Ψ. The graph shows that the data for various concentrations and head losses are brought into agreement. At values of Ψ below 2×10^{-3} the data for the 10-mm. clone assembly can be represented by the equation

$$\alpha - 1 = 2.4 \times 10^5 (\Psi)^{1.5} \quad (13)$$

The data for the 50-mm. clone, which has O/D and F/D ratios higher than those of the 10-mm. units, are represented by

$$\alpha - 1 = 5.5 \times 10^4 (\Psi)^{1.5} \quad (14)$$

It would appear that the concentrating factor may therefore be expressed by equations of the form

$$\alpha - 1 = (K\Psi)^{1.5} \quad (15)$$

where K is dependent on the O/D and F/D ratios. To evaluate further the effect of O/D and F/D the data of Matschke and Dahlstrom (*18, 19*) on the classification of clay slurries by miniature hydroclones were recomputed. Happel's correlation (*13*) of hindered settling rate with void volume was used for calculation of v_p. From these data and the results of the present study it was found, as shown in Figure 5, that K is inversely proportional to the cube of $(\sqrt{OF}/D)$. Care should be used in extending this proportionality to values of $(\sqrt{OF}/D)$ below 0.16. One would not expect hydroclone performance to improve continuously as $(\sqrt{OF}/D)$ is decreased, but an optimum should be reached. This has been observed by other investigators (*12, 19*). The fact that the lowest value of $(\sqrt{OF}/D)$ tested exhibits a K below the general correlation may indicate that the optimum is somewhat above this ratio. This would be in agreement with Fitch and Johnson's observation (*9*) that the

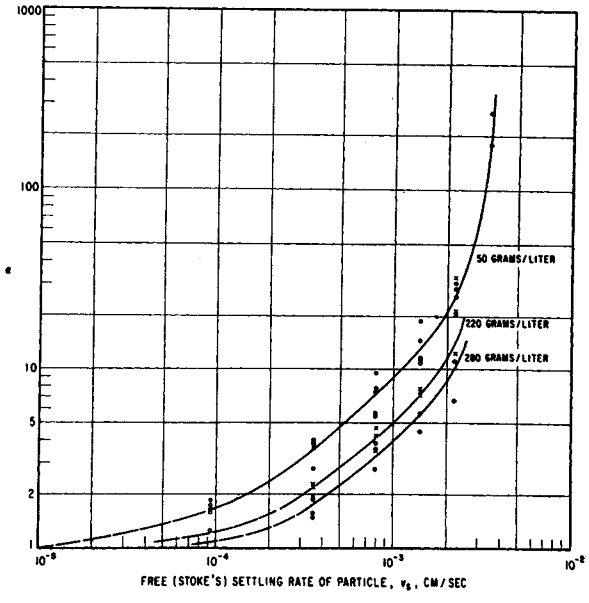


Fig. 3. Concentration factor as a function of particle settling rate and slurry concentration.

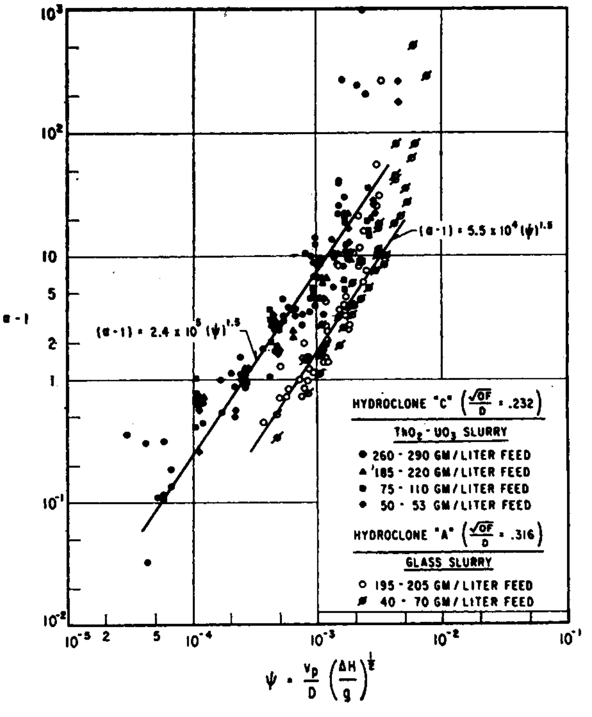


Fig. 4. Correlation of concentration factors obtained with thoria and glass-bead slurries.

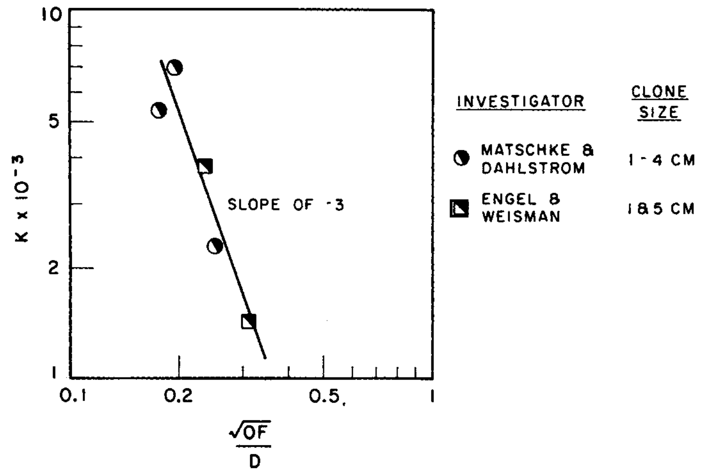


Fig. 5. Variation of coefficient of Equation (15) with hydroclone dimensions.

optimum occurs at $(\sqrt{OF}/D)$ values between 1/5 and 1/6. Additional data at lower $(\sqrt{OF}/D)$ ratios are needed to establish definitely this optimum for miniature clones.

The results of the generalized correlation are shown in Figure 6. It is seen that the data for the various miniature clones tested are brought into reasonable agreement. For values of $\Psi(\sqrt{OF}/D)^{-3}$ below 0.15 the data can be correlated by

$$\alpha - 1 = 350[\Psi(\sqrt{OF}/D)^{-3}]^{1.5} \tag{16}$$

At values of $\Psi(\sqrt{OF}/D)^{-3}$ above 0.22 α may, for all practical purposes, be considered infinite. From the dotted lines on Figure 8 it can be observed that for the vast majority of points the ratio of the experimentally determined value of E to the value predicted by Equation (16) lies between 0.65 and 1.35.

Use of Equation (16) allows one to predict the concentrating action of a given miniature hydroclone providing the properties and size distribution of the slurry feed are known. The simplest procedure is probably one similar to that used by Yoshioka and Hotta (20) with their fractional recovery curve. The feed size distribution is plotted in terms of weight percentage per size class. Values of α and E are then computed for each size class. The over-all solids-removal efficiency is the weighted average of the individual values of E. The values of E can also be used to compute the size distribution in the overflow and underflow.

To determine the utility of α and Ψ in correlating the performance of full-size hydroclones the data of Dahlstrom (4) and Yoshioka and Hotta (20) were recomputed in those cases where there was enough information to do so. Again the correlation of Happel was used to estimate the hindered settling rate of the slurries used. The results of these recalculations are shown in Figure 7. The data of Dahlstrom for a 9-in. clone with a 20-deg. included angle was fairly well correlated by Equation (16). However a somewhat better fit is obtained with

$$\alpha - 1 = 1{,}000[\Psi(\sqrt{OF}/D)^{-3}]^{2} \tag{17}$$

The data of Yoshioka and Hotta's 6-in. clone with a 20-deg. included angle fall to the right of Dahlstrom's data. Yoshioka and Hotta's data for the various values of $(\sqrt{OF}/D)$ tested were brought into agreement and can be correlated by

$$\alpha - 1 = 250[\Psi(\sqrt{OF}/D^{-3}]^{2} \tag{18}$$

The reason for the discrepancy between these data and those of Dahlstrom is not known.

HYDROCLONE PERFORMANCE TESTS AT REACTOR-PLANT CONDITIONS

To test miniature hydroclones under conditions similar to those at which they might be used in a slurry reactor plant several units suitable for operation at temperatures up to 600°F. and pressures up to 2,500 lb./sq. in. were obtained (hydroclone assemblies *D*, *E*, and *F* of Figure 1). The units were all constructed of 300 series stainless steel, since tests had shown this material to be resistant to corrosion erosion by high temperature thoria slurries.

The high-pressure hydroclones together with the necessary test instrumentation were mounted on portable dollies. High-temperature rotameters were used for flow measurements, dif-

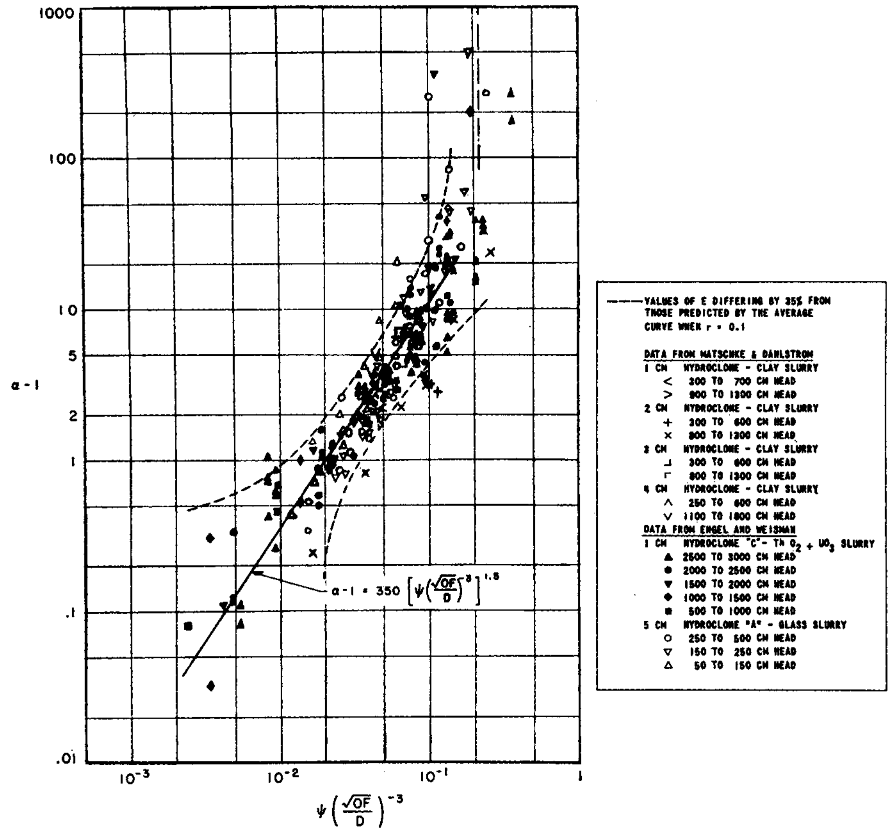


Fig. 6. Generalized correlation of miniature hydroclone concentration factors.

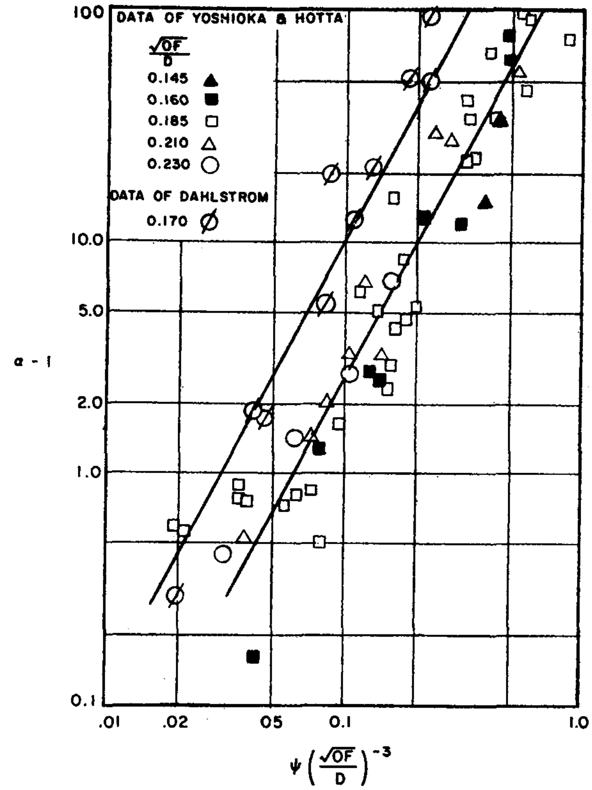


Fig. 7. Correlation of full size hydroclone concentration factors.

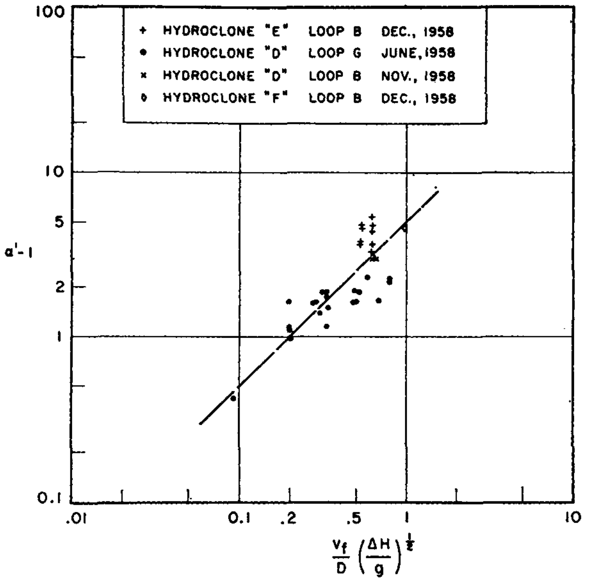


Fig. 8. Correlation of hydroclone performance with thoria slurries at elevated temperatures.

ferential pressure cells for measurement of head loss, and thermocouples for temperature measurements. Valved tees with cooling coils provided the means for withdrawing samples. A high-temperature thoria-slurry source was provided by connecting the dolly across one of the high-temperature corrosion test loops which have been described elsewhere (14). Since the test-loop volume was relatively low, most of the experiments were conducted by returning both the underflow and overflow to the loop. The temperature level was kept constant during each run but was varied from 250° to 550°F. during the course of these experiments.

For most of the operation a large (2-in. diameter) scalping clone preceded the miniature clones to insure the removal of any large particles. This is believed highly desirable, since examination of the scalping unit showed it had collected a number of large-size pieces of dirt which might have been capable of plugging the small clones.

Tests were conducted with a mixed thoria-urania slurry (loop *G* runs) and a thoria slurry (loop *B* runs). The preparation of these slurries differed considerably, and the pure thoria slurry had a high temperature settling rate considerably greater than the mixed thoria-urania slurry. As would be expected the concentrating performance was appreciably better with the more rapidly settling material.

The Andreasen pipette technique (*1*, *2*) for determining particle size distribution did not yield fruitful results when applied to samples taken from the high temperature hydroclone tests. This difficulty arose from the fact that the average particle size of the material in the high-temperature loop (99% below 1 μ) was appreciably less than encountered in the room-temperature tests. It was found however that the data could be represented approximately by the use of an overall concentration factor:

$$\alpha' = \left(\frac{E'}{100 - E'}\right)\left(\frac{1-r}{r}\right) \quad (19)$$

It seems reasonable to assume that the hindered settling rate of the slurry flocs is related to the average settling rate of the particles which comprise the flocs. If this is the case, it would be expected for clones having a constant $(\sqrt{OF}/D)$ ratio that the values of α' could be approximately correlated by an equation of the form

$$\alpha' - 1 = f\left(\frac{v_f}{D}\right)\left(\frac{\Delta H}{g}\right)^{1/2} \quad (20)$$

To determine the applicability of the above equation the high temperature settling rates of the slurries tested were determined as a function of concentration and temperature. Two methods were used for this determination. In the first of these a sample of slurry is placed in an agitated autoclave. Upon cessation of the agitation the slurry interface is followed by means of a float having a density intermediate between the slurry and the supernate. The position of the float is indicated by a magnetic follower located outside the autoclave. In the second of these methods the settling rate is determined in a vertical bypass line connected to the test loop itself. When flow through the line is stopped, settling occurs. The rate of movement of the slurry interface is determined by the time required to pass between two heated wire probes. The passage of the interface over one of the wires is observed by a change in temperature of the wires. Details of these procedures are described by Garber and Taylor (*10*) and Kivenson and Foster (*17*).

Figure 8 shows the high temperature performance data treated in the manner indicated by Equation (20). Although there is appreciable scatter in the data, they can be approximately fitted by

$$\alpha' - 1 = 5\left[\frac{v_f}{D}\left(\frac{\Delta H}{g}\right)^{1/2}\right] \quad (21)$$

Comparison of the data of Figure 8 with those of the 10mm. clone in Figure 4 shows that equivalent values of α were obtained at particle settling rates approximately 1/900 of the floc settling rates. This is additional evidence that the high shear rates existing in the clone break down the flocs into their component particles. The action of a standard hydroclone in this case would appear to be somewhat self-defeating, since the high shear rates required to separate small particles produce even smaller particles for the clone to separate. Haas and Unger (*12*) have designed a hydroclone with a feature which partly counteracts the shearing of the slurry flocs. This unit, shown as hydroclone *G* in Figure 1, is equipped with an integral underflow settling tank. Here a low shear-stress region is provided where the flocs can reform and settle out. This unit was given preliminary tests under the same conditions used for the standard design. In all cases an underflow stream was continuously removed. These tests showed the unit with the integral underflow pot to provide values of α' approximately 1½ times that of the standard hydroclone.

Operational experience with the high-temperature hydroclones was highly satisfactory. No clogging difficulty was encountered during normal operation. However with the rapidly settling pure-thoria slurry it was found that if stagnant slurry remained in the lines overnight, it was necessary to backflush the clones with water before taking the data. When this was not done, the hydroclones exhibited an appreciably lower efficiency than usual.

HEAD-LOSS STUDIES

Head loss across the clone, as a function of flow rate, was measured throughout the room-temperature and elevated-temperature tests. All of the clones shown in Figure 1 were used for these flow tests. It was found that Matschke and Dahlstrom's (*19*) empirical equation

$$Q = 14.8(O \times F)^{0.8}(\Delta H)^{0.5} \quad (22)$$

fits the data for each clone with an average deviation of less than 5%.

CONCLUSIONS

This investigation has provided a generalized correlation which can be used to predict the concentrating effectiveness of a given miniature hydroclone providing the properties and particle size distribution of the slurry feed are known. Recalculation of the available literature data indicated that the same type of relationship is also applicable to full-size hydroclones.

The range of performance of miniature hydroclones handling thoria slurries at temperatures up to 550°F. was established. The applicability of the generalized correlation to the high-temperature data could not be established, since the available technique for particle size determination was not adequate for the small sizes encountered. While it would have been desirable to use a centrifuge technique for particle size determinations, the termination of the contractual arrangements under which this program was pursued precluded this additional work.

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NOTATION

- C = total slurry concentration, g./liter of suspending fluid
- C^* = concentration of given size particle, g./liter of suspending fluid
- D = hydroclone diameter, cm.
- d = particle diameter, cm.
- d_{50} = particular particle diameter 50% of which goes into underflow of hydroclone, cm.
- E = solids-removal efficiency for given particle size = weight of given particle size in underflow/weight of same particle size in feed × 100, %
- E' = over-all solids-removal efficiency = $(C_3/C_1)r$ = mass of solids in underflow/mass of solids in feed × 100, %
- f′, f″, etc. = functional relationship
- F = equivalent diameter of feed port, cm.
- g = local acceleration due to gravity (981 cm./sec.^{2})
- ΔH = head-feed to overflow- at feed concentration, cm.
- O = overflow port diameter, cm.
- Q = flow rate, (cc./sec.)
- r = underflow ratio = underflow liquid rate/feed liquid rate, dimensionless
- R = radial distance from center of hydroclone (cm.)
- U = water radial velocity (cm./sec.)
- v_f = hindered settling rate of slurry flocs, cm./sec.
- v_p = gravitational settling rate of individual particle in slurry feed (cm./sec.)
- v_r = radial settling rate of particle in hydroclone (cm./sec.)
- v_s = Stokes settling rate of particle in an infinitely dilute suspension in water at room temperature (cm./sec.)
- V = tangential liquid velocity in hydroclone (cm./sec.)

Greek Letters

- α = concentration factor for given particle size, $[(1-r)/r] \cdot [E/(100-E)]$, dimensionless
- α = over-all performance factor, $[(1-r)/r] \cdot [E'/(100-E')]$
- η = coefficient of rigidity of slurry (g./sec. cm.)
- μ = viscosity (g./sec. cm.)
- Ψ = performance parameter $(v_p/D)(\Delta H/g)^{1/2}$
- ρ = density, g./cc.

Subscripts

- 1 = feed stream
- 2 = overflow stream
- 3 = underflow stream
- l = suspending liquid
- m = slurry mixture (mixture being considered as homogeneous medium)
- p = solid particle

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