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The Use of Hydrocyclones for Small Particle Separation

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ABSTRACT

Hydrocyclone operating characteristics have been studied by measuring the capacity for separating haematite, magnetite and silica particles suspended in water. The effects of viscosity (achieved by changing temperature) and throughput have been investigated and are satisfactorily correlated. The measurements demonstrate that under appropriate conditions of high pressure drop and low viscosity, particles below the usually accepted limit of 2 μm can be separated.

Measured particle separation is expressed as a hydrocyclone efficiency, and its variation with particle size is shown. Anomalous results with magnetite and haematite suspensions are suggested to occur because these materials exist as agglomerates with effective density less than half that of the bulk material.

INTRODUCTION

In many industries, liquid process streams contain particulate matter which it is desirable to remove from the stream, or to separate into fractions based on the size or density of the material.

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A simple technique for performing such separations is use of the hydrocyclone (hydroclone). All aspects of the design, performance and use of the hydrocyclone have been reviewed in Bradley's 'The Hydrocyclone' (1) and more recently, by Svarovsky (2), Purchas (3) and Trawinski (4). In addition to the more obvious uses, hydrocyclones have been used for density separation of mineral ores, catalyst recovery, pre-filtration and pump lubricant cleaning. The advantages of the hydrocyclone include low capital and operating costs, low maintenance requirements and reduced space for accommodation.

In general, it has been found that small hydrocyclones are more efficient for separating small particles than are large hydrocyclones; but no improvement is found for the use of units or diameter less than 10 mm.

The smallest particles which may be separated have been quoted as around 2 or 3 µm. The values stated are, however, somewhat confused due to ambiguities in the definition of separation size as the hydrocyclone does not make a sharp cut at any well defined size. 'Size of separation' or 'cut size' is defined variously as the diameter of particle which is separated with an efficiency of 50 or 95%; for a hydrocyclone operating under normal conditions, there is a difference of around a factor of two between these definitions.

Previous workers have studied the performance of small diameter hydrocyclones (5,6,7,8,9,10). These workers' results have in general tended to confirm each other, and the hydrocyclone theory, showing separating performance increasing with increasing pressure drop (and thus flow rate), decreasing viscosity and increasing density difference between solid and liquid phases.

Many studies of hydrocyclone performance have produced correlations based on the 'overall efficiency' of separation of the polydispersed feeds used. The performance of the hydrocyclone is, however, highly dependent on particle size and any efficiency quoted without reference to particle size is of doubtful value.

For this reason, the use of 'overall' efficiency has been avoided in the present work, all results having been calculated as efficiency of separation for each size particle in the range measured. From these a value of d_{50}, the particle size which is separated with an efficiency of 50%, may be calculated, and the efficiency of separation for other sizes of particle shown as a plot of efficiency against diameter/d_{50} (a 'reduced efficiency' curve).

Similarly, many previous studies have used 'gross' efficiencies (i.e. the fraction of the feed or of a given fraction of the feed leaving the hydrocyclone in the underflow) for expressing results of overall efficiency or d_{50}. Unfortunately, on this basis, a hydrocyclone with all flow of liquid and solids passing to the underflow would be said to have a (gross) efficiency of 100%, and no d_{50} could be found. Assigning an efficiency of 100% to such a 'separation' seems unreasonable as the condition of the slurry is the same at the outlet as at the inlet. To compensate for the fraction of solids leaving the hydrocyclone in the underflow (associated with the liquid flow in the underflow) some workers, e.g. Van Ebbenhörst, Tengbergen and Rietema (11) proposed that the efficiency (E_r) be calculated by substracting the fraction of liquid from the feed passing to the underflow from the fraction of solids passing to the underflow:

$$E_r = \frac{W_u}{W_f} - \frac{M_u}{M_f} = E_g - R_f \qquad (1)$$

where

W_u, W_f mass flow rates of solids in the underflow and feed respectively.

M_u, M_f mass flow rates of liquid in the underflow and feed respectively.

E_g = gross efficiency, i.e. W_u/W_f.

R_f = ratio M_u/M_f.

This efficiency unfortunately has limits of 0 and 1- R_f, i.e. a separation is only said to be 100% efficient if all solids pass to the underflow and the liquid flow rate in the underflow is zero. Kelsall (12) considered that the fluid passing to the underflow was not available for separation and proposed an efficiency (E_k) defined as:

$$E_k = \frac{\frac{W_u}{W_f} - \frac{M_u}{M_f}}{1 - \frac{M_u}{M_f}} = \frac{E_g - R_f}{1 - R_f} \qquad (2)$$

Although Dabir et al. (13) have further modified this efficiency concept to allow for the change in solids concentration between feed and underflow, it is Kelsall's efficiency concept which is most commonly used.

Unfortunately, in many cases there is a lack of clarity as to the basis used for correlations of hydrocyclone performance, Bradley (1) stating that the d_{50} is the 'particle size which gives a centrifugal efficiency of 50 per cent', but quoting the correlations of several previous workers, all of whom seem to have used d_{50} values calculated for gross efficiency.

The differences may be small at low underflow ratios (as $\frac{M_u}{M_f}$ tends to zero, so E_r and E_k tend to E_g), but these become very large as $\frac{M_u}{M_f}$ increases, indeed if $\frac{M_u}{M_f}$ exceeds 0.5, 'Rietema' efficiencies cannot be greater than 50%, nor gross efficiencies less than 50%, i.e. no values for d_{50g} or d_{50r} can be found.

As Chaplain (14) points out, the value of d_{50} used for all correlating purposes should clearly be d_{50k} (Equation 2).

EXPERIMENTAL WORK

The separation which was originally required was a reduction of the spread of the size distribution of magnetite and haematite particulates used for the study of deposition phenomena in heat exchanger fouling. It was desired to remove as many particles as possible of diameter greater than, say, 3 μm, i.e. to use the hydrocyclone to 'split' the feed at the smallest diameter possible. In order to achieve this, the literature suggested use of high flow rate (necessitating a high pressure drop across the hydrocyclone), low viscosity (achieved by heating the feed suspension) and using a low solids concentration. Additionally, as there was no premium for obtaining a high solids concentration in the underflow, a high underflow to feed ratio could be used.

After initial experiments using a 15 mm hydrocyclone with variable diameter inlet and outlet jets, and a 10 mm hydrocyclone, the 15 mm unit was discarded, as it was felt desirable to reduce the number of variables being investigated by using a single hydrocyclone of fixed dimensions.

The performance of the hydrocyclone with magnetite and haematite feed solids left much to be desired, as the overall separation was found not to be as good as expected, and plots of efficiency against particle diameter were found to be very irregular (see Figure 1).

Clearly, either the hydrocyclone was not operating efficiently under these extreme conditions of high pressure (96 psi) and low viscosity (0.5 cp), the iron oxide particles were behaving in some irregular manner or the method of size analysis or data processing was in error.

In order to establish the cause of the irregular results, tests were carried out over a range of conditions using silica suspension feeds of two size ranges (known to behave in a stable manner in water) at very low solids volume fractions in the feed, and a silica feed at higher volume fraction. Further testing of the magnetite and haematite suspensions using additional preparation techniques for size analysis was subsequently carried out.

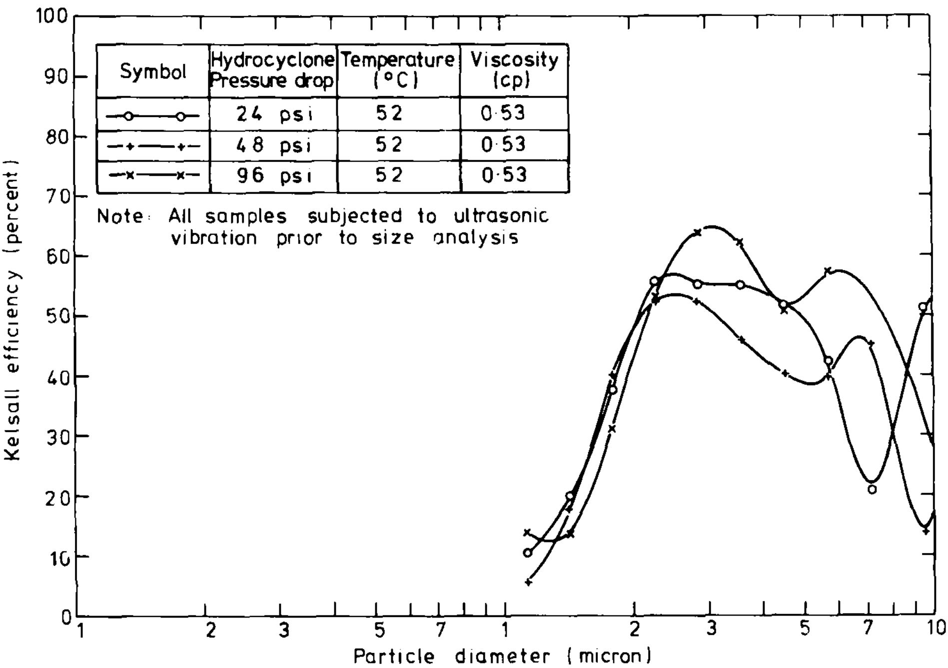


FIG. 1 THE RESULTS OF HYDROCYCLONE EFFICIENCY MEASUREMENTS WITH HAEMATITE SUSPENSIONS.

APPARATUS AND EXPERIMENTAL TECHNIQUE

The apparatus used was a simple recirculating loop with slurry from a 60 litre tank fed by a centrifugal pump to a single 10 mm Dorr-Oliver type TM 10 hydrocyclone (see Figures 2 and 3). Three bypasses were available to regulate the inlet pressure at the hydrocyclone and provide stirring for the feed tank. A heater was available to raise the feed temperature and thus lower its viscosity. Pressure drop was measured using a single pressure gauge at the inlet of the hydrocyclone, preliminary measurements having shown that the pressures at underflow and overflow outlets are negligible.

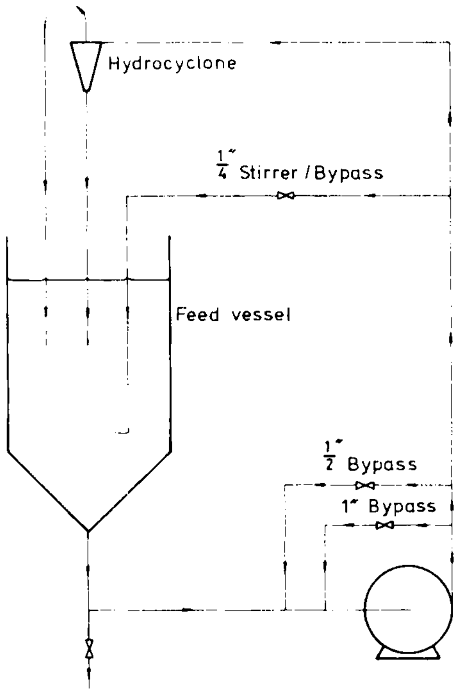


FIG.2 HYDROCYCLONE TEST APPARATUS

Samples of outlet streams for size analysis using a Coulter Counter and for concentration measurement were taken by whole-stream sampling. Overflow and underflow rates were measured using a measuring cylinder and stopwatch. No feed samples were taken, the feed properties being obtained by mass balance. Slurry viscosities were calculated using the Kunitz equation (15) and measured (at low shear rates) in an Ostwald viscometer (u-tube viscometer) recalibrated for transition regime flow. All slurries with low solids concentration (around 0.05 % v/v) were found to have the same viscosities as pure water at the same temperature.

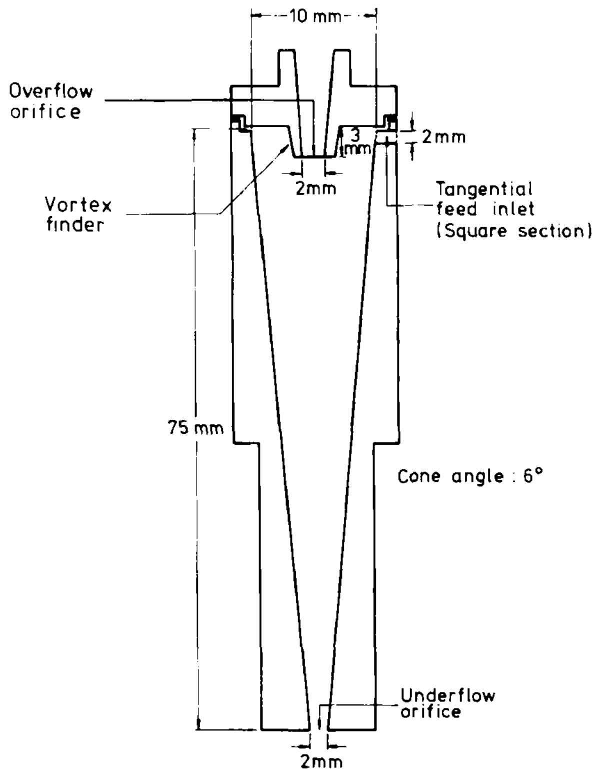


FIG 3.DIMENSIONS OF DORR - OLIVER TYPE TM 10 HYDROCYCLONE

Solids concentrations of the overflow and underflow samples were determined by passing a standard volume through a pre-weighed 0.22 μm pore diameter 'Millipore' filter, drying and re-weighing the filter and dry solids.

The solids were suspended in demineralised water, and the apparatus cleaned using 'Decon 75' detergent and demineralised water for rinsing between runs.

TABLE 1

Particles used for the Studies

Material	Supplied as	Bulk solid density g/cm^3
Silica	95% below 5 μm	2.6
Silica	95% below 15 μm	2.6
Haematite (Fe_2O_3)	commercial grade	5.24
Magnetite (Fe_3O_4)	commercial grade	5.18

Table 1 gives details of the particles used in the work, and Table 2 gives the range of experimental conditions. Measurements of hydrocyclone capacity using water flow only (i.e. without particles) were also made at various temperatures.

RESULTS

Hydrocyclone Capacity - Tests with Water Flow only

The total flow rate through a hydrocyclone is often referred to as its 'capacity'.

In addition to the data gathered on capacity during the solids separation tests, the influence of pressure drop and the viscosity of pure water feed, controlled by temperature, were investigated.

TABLE 2

Experimental Conditions

Material	Conc % v/v	Temperature °C	Pressure Drop psi		
Two silica particle feeds (see Table 1)	0.05	20,50,80	24	48	96
Larger silica particle feed	5.0	50	24	48	96
Magnetite and haematite	0.05	50	24	48	96

The results of this brief study are shown in Figure 4, which shows the capacity increasing with increasing pressure drop and increasing feed viscosity.

The ratio of underflow to feed flow rate, R_f, was found to remain more or less constant at a value of around 0.55 for most runs. A few variations were found, but it is felt that these may have been due to partial blockage of the hydrocyclone or flow disturbances.

The data have been correlated in the usual form giving a 'best fit' of:

$$Q_f = 0.469 \Delta P^{0.539} \mu^{0.101} \quad (3)$$

where

Q_f is the total flow rate, l/min

ΔP is the pressure drop across the hydrocyclone, p.s.i.

μ viscosity of suspension, centipoises

which fitted the data with a regression coefficient, r^2, of 0.987.

The data found in the literature for the relationship between Q_f and operating conditions varies. A pressure drop exponent of around 0.5 is nearly always found. The data of different workers, using different hydrocyclones under different conditions, disagrees even as to whether increasing viscosity increases or decreases flow rate.

The 'fits' for the present data show the exponent on ΔP varies with viscosity, the exponent decreasing from 0.591 when μ = 0.356 cp to 0.509 when μ = 1 cp. This effect is in the opposite direction to that found by Trinh et al. (8) and by Chaplain (14); unfortunately, these workers used significant fractions of solids in their feeds and measured liquid viscosity rather than effective slurry viscosity.

The exponent on μ in the present work varies from 0.163 to 0.053 as ΔP increases from 24 to 96 p.s.i.

In view of the form of the data shown in Figure 4, and of the dependence of the pressure exponent on viscosity and the viscosity exponent on pressure, there must be doubt that Equation 3 is the best form to fit to the data. The present data shown on Figure 4 are much more sensibly correlated by:-

$$Q_f = 0.35\Delta P^{0.55} + 0.73\mu, \quad (4)$$

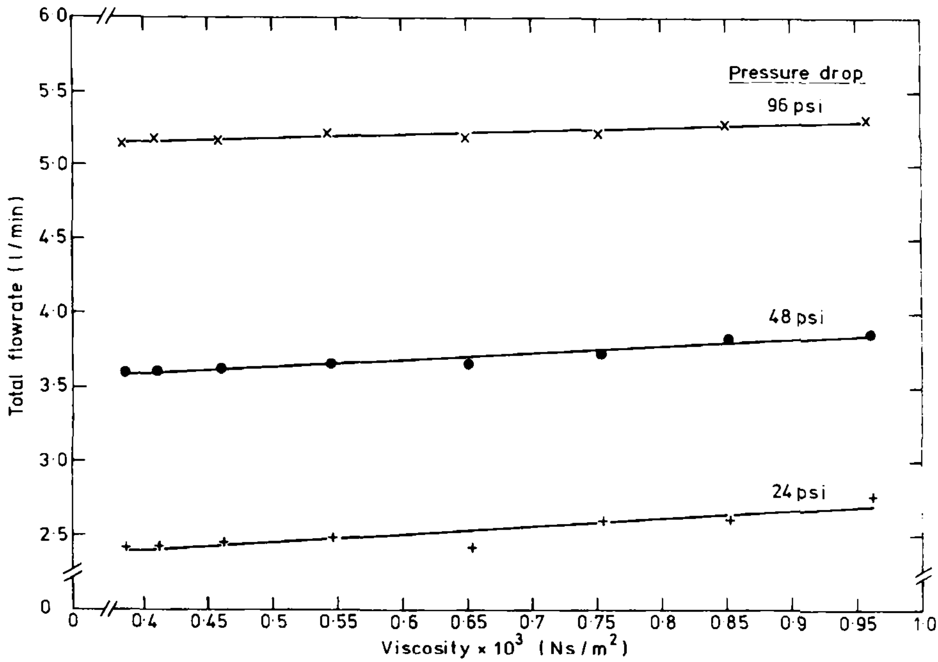


FIG.4 THE RESULTS OF EXPERIMENTS WITH PURE WATER FLOW

units as in Equation 3, although there is no theoretical basis for fitting an equation of this kind.

The experimental data on Figure 4 shows increasing flow rate with decreasing temperature, which suggests an effect of increasing viscosity. This is apparently anomolous, but this effect was also found by Van Kooy (16) who altered feed viscosity by altering dissolved sucrose content, Bradley (1) (who may have been quoting Van Kooy's data) and Chaplain (14) who found that increasing feed solids content and thus effective viscosity increased flow rate. Furthermore, the work reported here also showed that increasing viscosity at a fixed temperature by solids addition, the same trend occurred.

The opposite effect was found by Wagner and Murphy (17), controlling viscosity with glycerine, Trinh et al (8), controlling viscosity using glycerine and then adding solids, and Lynch and Rao (18), varying solids content.

Two possible explanations (1,8,18) have been offered for these differing results for very simple experiments where the data can be considered accurate. These are the varying ratio of 'centrifugal' to inlet and outlet pressure drops and the variation in effective overflow and underflow outlet size as the air core passing through them changes in diameter.

Silica Particles at Low Concentrations

In order to obtain results for the operation of the hydrocyclone with a stable feed under favourable conditions, the performance of the hydrocyclone was investigated for two silica particle feeds, specified as 95% below 5 and 15 μm respectively. The solids concentration used was around 0.05% v/v solids in order to avoid any effects of settling hindrance due to collisions between particles.

The performance was found to improve (i.e. the value of d_{50k} found to decrease) as the pressure drop across the hydrocyclone (and thus flow through it) increased, and as the feed viscosities decreased. The performance was found to continue to improve as the pressure drop was increased to its maximum experimental value of 96 p.s.i. and as the feed viscosity was decreased to its minimum value of 0.35 cp (corresponding to water at 80^{o}C).

It was therefore concluded that up to these limits at least, the flow regimes inside the hydrocyclone remain stable and that the results found under similar conditions for haematite and magnetite particle feeds were due to some property of these feeds.

The variation of d_{50k} with flow rate and viscosity is shown in Figure 5.

There is a difference, on average, of around 0.2 μm in d_{50k} values between the data for the two silica particle feeds. No satisfactory explanation has been found for this difference, despite considering density difference, solubility difference and differences in hindrance to settling. It is concluded that the differences in d_{50k} value must be due to error in control of the experiments, sampling and analysis.

Many previous workers have correlated gross efficiencies against operating conditions (usually correlating d_{50g}). The present data have been correlated as d_{50} for Kelsall's corrected efficiency (Equation 2) against viscosity and flow as suggested by Chaplain (14), the following 'best fits' being obtained.

$$\text{for } d_{50k} = c\, Q_f^{\,a}\, \mu^{b} \qquad (5)$$

where the appropriate values are:-

particle feed silica type	a	b	c	r^2
'95% < 5 μm'	-0.526	0.536	4.00	0.964
'95% < 15 μm'	-0.351	0.364	3.28	0.845
overall	-0.47	0.476	3.75	0.863

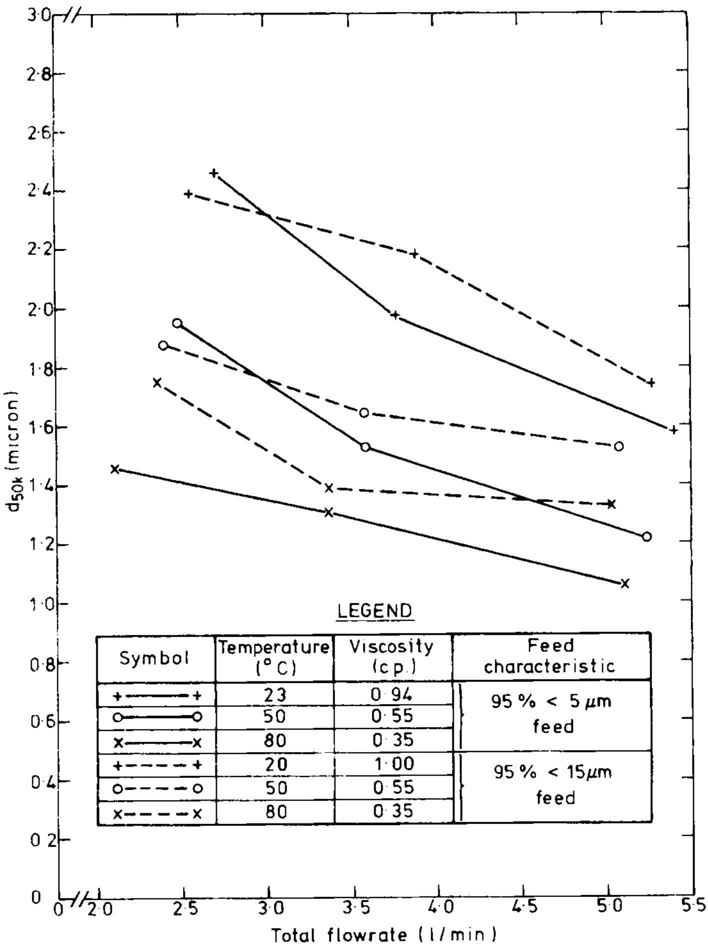


FIG. 5 THE RESULTS OF EXPERIMENTS WITH SILICA FEEDS VARIATION OF d_{50k} WITH FLOWRATE AND TEMPERATURE

The variation in value obtained between the feed types is believed to be due to the limited amount of data fitted, and the results may therefore be somewhat uncertain.

The values of a and b are, however, in broad agreement with the theoretical values and those of previous workers (see Bradley (1)), which suggest values of −0.5 for a and 0.5 for b.

Silica Particles at 5% v/v Solids Content

The d_{50} values for the 5% v/v silica suspension at $50^{o}C$ (see Figure 5), with effective viscosity measured at low shear as 0.682 cp fall between those at the same pressure drop for 1 and 0.5 cp liquid viscosity measured in the experiments for 0.05% v/v particulate silica suspension.

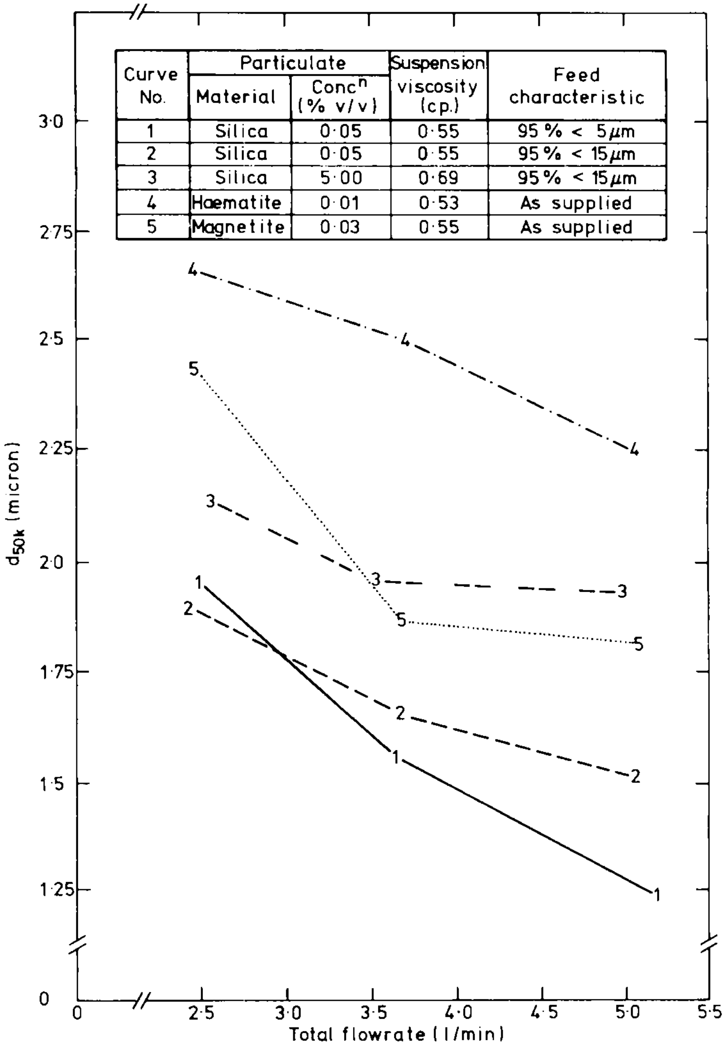
The results are sufficient to indicate that the effects of hindrance and non-Newtonian rheology are relatively small for these conditions, and a reasonable estimate of the performance could be obtained by assuming 'dilute suspension' behaviour for the feed and using its 'effective viscosity'.

Haematite and Magnetite Particles at Low Concentration

The cause of the earlier irregular results for iron oxide particulate feeds was considered to be due to breaking down of agglomerates during preparation for size analysis. This observation suggests that agglomerates are not (fully) broken down when passing through the hydrocyclone and is in contradiction to Bradley's (1) information. It seems sensible that the degree of deagglomeration caused by shearing in the hydrocyclone will be largely dependent on the strength of the bonding in the agglomerates.

The size analyses for this work were obtained using a Coulter Counter Model TAII and attempting not to break up agglomerates.

The values of d_{50k} found for magnetite and haematite (Figure 6) were, on average, around twice as large as those obtained for silica particles under similar conditions. If the density of the magnetite and haematite particles is assumed to be the same as for



Curve No.	Particulate		Suspension viscosity (cp.)	Feed characteristic
	Material	Conc^n (% v/v)		
1	Silica	0·05	0·55	95 % < 5 μm
2	Silica	0·05	0·55	95 % < 15 μm
3	Silica	5·00	0·69	95 % < 15 μm
4	Haematite	0·01	0·53	As supplied
5	Magnetite	0·03	0·55	As supplied

FIG.6 VARIATION OF d_{50k} WITH FLOWRATE FOR ALL FEEDS AT 50°C

the bulk mineral (around 5.2 g/cm^3), the d_{50k} values would be expected to be considerably lower than those for silica (density 2.64 g/cm^3).

It is believed that the values of d_{50k} obtained are those for the agglomerated particles' true density. This may be estimated from these data as less than half that for the bulk material. S.E.M. photographs show that the magnetite and haematite particles agglomerate readily and their individual shape is not very different from spherical.

The Shape of the Efficiency - Size Curves (Figure 7)

The relationship of efficiency and particle size is generally shown as a 'reduced efficiency plot' showing efficiency measured against particle diameter divided by d_{50k} particle diameter. The data points on Figure 7 have not been smoothed or 'corrected' in any way. The points in general follow the expected 'S' shape, but few curves reach the expected upper limit of 100%. (The numbers on the individual curves are simply references to individual experiments).

All curves seem to become horizontal at around 80% 'Kelsall' efficiency, for d = 1.5 d_{50k} which could well be due to 'short circuit' liquid flow of around 20% (Kelsall (19), found values in the region of 15% for short circuit flow).

The curves above about d = 3 d_{50k} become irregular, probably due to small errors in size analysis which become magnified in calculations relating to low particle numbers in particular size ranges.

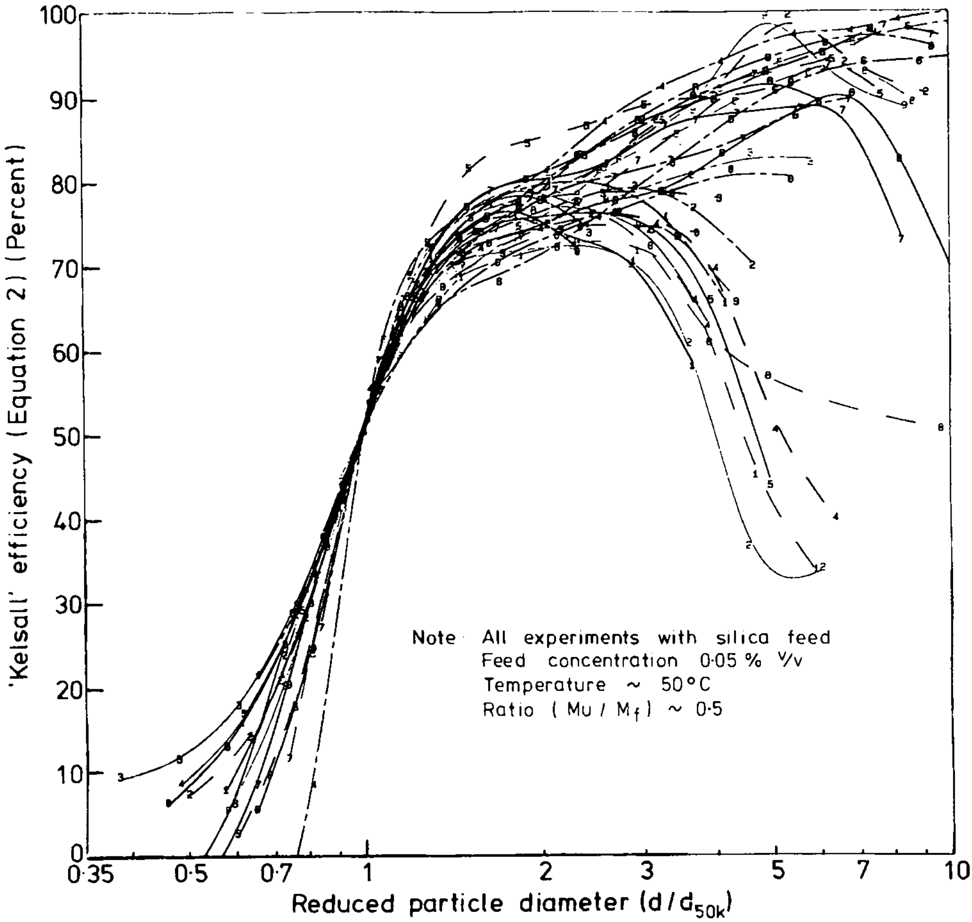


FIG.7.REDUCED EFFICIENCY CURVES

CONCLUSIONS

From the measurements, the following conclusions are drawn:-

1. Hydrocyclone separation efficiency increases, as expected, with increasing pressure drop; and it is also shown to

increase with decreasing suspension viscosity. In considering energy availability, reducing the viscosity might be preferable to increasing the pressure drop. Furthermore, lower operating pressure may be preferable from the point of view of design and operation.

2. Operation at viscosities lower than usually reported and modest pressure drop has yielded d_{50k} values as low as 1 μm, whereas 2 to 3 μm is usually quoted as the lower limit of separation.

3. For suspensions of particle concentration where the viscosity differs from that of water (e.g. 5% v/v), performance can still be correlated provided the measured effective viscosity is used in calculations.

4. From the experiments with magnetite and haematite suspensions in comparison with silica measurements, it is deduced that magnetite and haematite exist as agglomerates in suspension having an effective density somewhat less than half that of the bulk material.

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