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SEPARATING SMALL PARTICLES FROM LIQUIDS WITH THE HYDROCYCLONE

PART I – CONCLUSIONS AND RECOMMENDATIONS ARISING FROM LITERATURE SEARCH

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Abstract

A literature search has shown that a two stage hydrocyclone is required to give maximum concentration simultaneously with maximum clarification. For design purposes it is necessary to consider each operation separately.

Concentration and clarification efficiencies have been proposed which will enable a choice of the major dimensions of a hydrocyclone to be made for each operation once experimental data are available for various systems.

The programme of experimental work required to provide this information as well as information on operation methods is given.

CONTENTS

1. INTRODUCTION

The separation of finely divided solids from liquids is an essential operation in many processes in the chemical industry and in general, two types of equipment are used for this purpose. They are:

(a) Filters and centrifuges which separate solid as a cake and produce a clear filtrate or overflow.

(b) Thickeners which separate solid as a thick sludge and produce a clear or slightly turbid overflow.

In the nuclear energy field, the problem of remote handling arises and conventional filters, centrifuges and thickeners are in general unsuitable without extensive modification. Attention has, therefore, been given to other methods of solid–liquid separation and although they are basically classifiers, hydrocyclones have been proposed because of their simplicity of design and operation.

Hydrocyclones have been used for the separation of fission and corrosion products from the homogeneous aqueous reactor (1). They have been suggested as a means of removing the fuel particles from a liquid metal fuelled reactor (2) and they are also envisaged as a means of clarifying feed solutions to solvent extraction plants processing irradiated fuels. Because of the interest of the A.A.E.C. in dispersion type fuels, whose solutions would require maximum clarification and maximum sludge concentration before processing a literature search was undertaken to establish the optimum design details and operating conditions for hydrocyclones to give maximum concentration of solid and maximum clarification of liquid.

This report gives the results and recommendations arising from this search.

2. THE HYDROCYCLONE AS A THICKENER

The hydrocyclone is basically a classifier (3) in which, a greater proportion than present in the feed of the smaller particles appears in the overflow and a greater proportion of the larger particles appears at the underflow. Sharp separation is never achieved in practice and for the minimum concentration of solid in the overflow, the underflow must be relatively dilute (4). If conditions are adjusted to obtain a concentrated underflow, the overflow becomes more concentrated. However, the action of a thickener may be approached by connecting two hydrocyclones in series (4), (5). The first unit is operated to produce maximum concentration in the underflow and its overflow is fed to the second unit, which is operated to give the clearest possible overflow. The underflow from the second unit is returned to the feed of the first unit.

3. MAJOR ASPECTS OF HYDROCYCLONE PERFORMANCE

(a) Pressure Drop – Flow Rate Relationship

This has been examined by numerous workers covering a wide range of variables and fairly good agreement has been reached. Expressions such as that proposed by Haas (1) are available and

$$\Delta p = \frac{K\, Q^{2.27}}{(D_c)^{0.8}\,(D_i)^{1.3}\,(D_o)^{2.0}}$$

can be used to evaluate pressure drop for small hydrocyclones. Further work on pressure drop correlations is not considered necessary at this stage.

(b) Solids Separation

In order to assess this aspect of hydrocyclone performance, some method of measurement is required and several definitions of efficiency have been suggested for this purpose.

One efficiency used is the solids elimination efficiency, defined as that fraction of the feed solids which appears at the underflow i.e., if there are 100 particles of a given particle size in the feed and N of these are discharged through the underflow, the efficiency is equal to $\frac{N}{100} \times 100$ percent.

In a given system for a given particle size, a point efficiency can be defined by

$$E_1 = N = \frac{x_u \; W_u}{x_f \; W_f} \times 100$$

where E_1 = solids elimination efficiency

x_u = weight (or volume) fraction <u>of the given size</u> in the underflow stream

W_u = mass (or volume) flow rate through the underflow

x_f = weight (or volume) fraction <u>of the given size</u> in the feed stream

W_f = mass (or volume) flow rate of feed

It has been shown (6) that this efficiency varies with particle size and a true overall picture can only be obtained from a separation curve, in which E_1 is plotted against particle size (4), (6), (7).

A similar efficiency to E_1 is that defined as that fraction of the feed solids of a given size appearing at the underflow, corrected for the fraction of the feed solids which would appear at the underflow irrespective of cyclone action. This efficiency was suggested by Kelsall (6) and described by Bradley (8) as the centrifugal efficiency, or efficiency of separation by centrifugal action. It is given by

$$E_c = \frac{E_1 - 100\, R_f}{100 - 100\, R_f} \times 100$$

where

E_c = centrifugal efficiency

E_1 = solids elimination efficiency as defined previously

$R_f = \frac{\text{underflow flow rate}}{\text{feed flow rate}}$

In order to obtain a single finite numerical value for overall efficiency, without the use of a separation curve, the term d_{50} was introduced. This is defined as the particle size in microns which appears 50 percent at both the overflow and the underflow. Dahlstrom (9) presented an empirical relationship for d_{50} for large cyclones

$$d_{50} = \frac{81\,(D_o\, D_i)^{0.68}}{Q^{0.53}} \times \left[\frac{1.73}{\rho_s - \rho_o}\right]^{0.5}$$

and Matschke and Dahlstrom (10) modified this for miniature cyclones to

$$d_{50} = \frac{87.2\,(D_o\, D_i)^{0.65}}{Q^{0.60}} \times \left[\frac{1}{\rho_s - \rho_o}\right]^{0.50}$$

Large cyclones are considered to be those with diameters of 3 inches or more and small cyclones those with diameters from 10 to 40 millimetres.

Yoshioka and Hotta (11) stated that separation curves have the same form. They proposed a single curve, in which the reduced fractional recovery R (equivalent to the centrifugal efficiency E_c) is plotted against d/d_{50}. Bradley (8) pointed out that knowing d_{50}, this curve gives the centrifugal efficiency for particles of any size from which the actual efficiencies (E_1) can be calculated and a separation curve prepared. Bradley (8) presented an equation for the determination of d_{50} based on certain assumptions and compared his theoretical results with actual plant data for the separation size. However, the original plant data references did not report the method used to determine particle size and as wide differences can be obtained between different methods of measurement of particle size for sub-sieve particles (12) this equation for d_{50} requires further experimental confirmation. Subsequently, as the result of experimental work using the Perspex spheres previously used by Kelsall (6), Bradley and Pulling (13) modified Bradley's original expression for d_{50} to

$$\frac{d'_{50}\;D'_c}{(D'_i)^2} = \frac{3(0.38)^n}{\infty}\left[\frac{\mu_1(1-R_f)}{Q'(\rho_s-\rho_1)}\;D'_c\;\tan\frac{\theta}{2}\right]^{0.5}$$

Bradley (14) found also that the R vs d/d_{50} curve for small hydrocyclones was somewhat different to the Yoshioka and Hotta curve.

Most of the work done to date has been on single hydrocyclones, in which a compromise has been obtained between concentration and clarification with accent on the maximum recovery of solids. In order to achieve both maximum concentration simultaneously with maximum clarification a two stage unit is required, in which one hydrocyclone operates as a concentrator and one as a clarifier. To design such a unit for optimum results, it is necessary to consider each operation separately and to define both a concentration efficiency and a clarification efficiency.

Concentration Efficiency, E_2.

The degree of concentration may be represented by the increase in concentration from the feed to the underflow.

If feed concentration = x_f

Underflow concentration = x_u

Increase in concentration = $x_u - x_f$

Maximum increase in concentration occurs when $x_u - x_f$ is a maximum i.e. when $x_u = 1$ and concentration efficiency E_2 is given by $\frac{x_u - x_f}{1 - x_f} \times 100$.

Clarification Efficiency, E_3

The degree of clarification may be expressed by the decrease in concentration from the feed to the overflow.

If feed concentration = x_f

Overflow concentration = x_o

Decrease in concentration = $x_f - x_o$

Maximum decrease in concentration occurs when $x_f - x_o$ is a maximum i.e. when $x_o = 0$ and clarification efficiency, E_3, is defined as

$$\frac{x_f - x_o}{x_f} \times 100.$$

This is similar to Lindner's Separation Index (15)

$\epsilon_A = \frac{x_f - x_o}{x_f}$ and it can be readily shown that

$\frac{x_f - x_o}{x_f} \times 100$ is equal to Bradley's Centrifugal Efficiency, E_c.

For the proposed nuclear energy applications, it is anticipated that the particle sizes will always be well into the sub–sieve range. For sub–sieve particles different methods of size analysis give different results and this is particularly true for particles with diameters less than 30 microns. The preparation of separation curves using d_{50} relationships for sub–sieve particles, therefore is not useful, unless the size analysis method used for the feed gives the effective diameters applicable to hydrocyclone operation. No such method is known at present, particularly for irregularly shaped particles normally encountered in separation work.

A finite numerical value may be obtained by calculating gross concentration and clarification efficiencies from the total solids concentration in the various streams. Such gross efficiencies could be affected by the particle size distribution of the feed solids, the correct values for which are unknown. However, it is considered that the effect of the feed particle size, if this is important, can be assessed from efficiencies experimentally determined for systems with a range of particle size distributions measured by a specified method, which gives reproducible results.

4. HYDROCYCLONE DESIGN AND OPERATION

The hydrocyclone design most frequently used is shown diagrammatically in Figure 1. The hydrocyclone consists of an inverted cone surmounted by a closed cylindrical section with the same diameter as the base of the cone. The feed stream under pressure enters the cylindrical section tangentially near the top and splits into the underflow and overflow streams. The underflow stream appears at the apex of the cone and the overflow stream is removed via the vortex finder, which extends from the centre of the top of the cylindrical section vertically downwards into the cyclone body.

(a) Design Variables

The major design variables affecting solids separation in such a unit are considered to be:–

1. Cyclone diameter, D_c.
2. Included angle, θ.
3. Cyclone length, L (cone length L_1 + cylinder length L_2).
4. Vortex finder length, VFL.
5. Vortex finder outside diameter, VFOD.
6. Feed diameter, D_i.
7. Overflow diameter, D_o.
8. Underflow diameter, D_u.

For large hydrocyclones and materials in the sieve range, Moder and Dahlstrom (16) claim that solids elimination efficiency is independent of cyclone diameter. On the other hand Trawinski (4) shows that smaller particles can be separated as the cyclone diameter is decreased. Trawinski also states that absolute clarification requires several cyclones in series with smaller cyclone diameters in succeeding stages and that the minimum size capable of separation is 3 to 5 microns. For removal of solids in the sub-sieve size range, cyclone diameters of the order of 10 millimetres are indicated (5).

For large cyclones, it has been found that reduction of included angle improves solids separation but not beyond a value of 15° (9). Slight improvement has been found by increasing the length of the cylindrical section (9) and an increase in the vortex finder length increases the separation of larger particles at the expense of smaller ones (6).

Using a 3- inch cyclone, Kelsall (6) found that for maximum recovery of solids there is an optimum feed diameter and that the optimum feed diameter increases as the overflow diameter increases. Kelsall (6) also found that slightly better separation was obtained by using a rectangular feed port with the long side parallel to the cyclone axis.

Bradley (8) considered the normal cyclone configuration to be

$$D_i = D_c/7$$

$$D_o = D_c/5$$

$$D_u = D_c/15$$

and stated that the choice of D_i and D_o corresponded to that which would achieve the maximum recovery of feed solids. The choice of D_i and D_o was made as a result of a critical review of the literature, where wide ranges of these dimensions are reported, rather than from specific experimental work.

Bradley (7) considered that the work of Kelsall (6) and others showed that the underflow diameter had some effect on solids separation but an arbitrary underflow diameter $D_c/15$ was chosen by Bradley on the basis of suitable volume split with a minimum of throttle adjustment.

The vortex finder outside diameter also appears to have some effect on solids separation (6) but no information is available on this aspect for small cyclones.

(b) Operating Variables

The major operating variables affecting solids separation are considered to be:-

1. Flow rate, Q.
2. Solid density, ρ_s.
3. Liquid density, ρ_l.
4. Liquid viscosity, μ_l.
5. Particle size distribution of feed solids.
6. Concentration of feed solids, x_f.
7. Type of underflow discharge.
8. Back pressure.

Bradley (8) found theoretically that $d_{50} \propto \frac{1}{Q^{0.5}}$ and this is supported by the experimental work of Kelsall (17) and Dahlstrom (9) who obtained exponents for Q of 0.56 and 0.53 respectively.

By substituting centrifugal acceleration for gravitational acceleration and assuming that Stokes' law holds for particle motion within the cyclone several authors (4), (8), (11) have shown that

$$d_{50} \propto \frac{\mu_l}{\rho_s - \rho_l}.$$

Some results for individual particle sizes are given by Kelsall (6) but only isolated references (5), (18) give sufficient details to determine gross efficiencies for materials having a given size distribution. Similarly little information on the effect of feed concentration is available. Moder and Dahlstrom (16) state that feed concentration has no effect for concentrations of up to 8 percent by weight for spherical particles or 4 percent by weight for markedly non–spherical particles. Fitch and Johnson (3) claim that separation is not affected by volume concentrations of up to 11 percent. Yancey and Geer (19) claim that the underflow concentration is affected by a number of factors, including the feed concentration and Lindner (15) indicates that there is an optimum feed concentration for a given cyclone.

Three types of underflow discharge, vortex, "sausage" and rope (overloaded) have been described (19). With vortex discharge, an air core is present extending from the underflow port along the hydrocyclone axis towards the overflow port and maximum gross solids elimination efficiencies are obtained (19). With "sausage" discharge described as a compromise between vortex and overloaded conditions (9) and with overloaded discharge, the air core associated with a vortex discharge is not present. Compared with a vortex discharge, increased concentration of underflow is obtained with "sausage" and overloaded discharges but gross solids elimination efficiencies are reduced (7). Yancey and Geer (19) give the conditions required to produce the various discharges for large cyclones but no information is available for small units.

Data for the quantitative effect of back pressure on underflow and overflow are inconclusive (5), (16). The effect of back pressure should not be overlooked as back pressure would be encountered in multi–stage units, where the overflow of one hydrocyclone flows directly to the feed port of a succeeding hydrocyclone.

5. CONCLUSIONS AND RECOMMENDATIONS

For maximum concentration together with maximum clarification by the use of hydrocyclones, a two–stage unit is required, the first hydrocyclone concentrating and the second clarifying.

To design such a unit for optimum results each stage must be considered separately and simple expressions for concentration and clarification efficiencies have been proposed.

Detailed information is lacking on the effects of numerous variables on the performance of hydrocyclones and further experimental work is required particularly on small diameter hydrocyclones.

The experimental work should cover:–

(1) Establishment of optimum feed diameter, overflow diameter, underflow diameter and vortex finder outside diameter for both maximum concentration and maximum clarification for a range of flow rates for one particular system initially.

(2) Investigation of the effects of feed solid concentration and particle size distribution, solid density and liquid viscosity on concentration and clarification efficiencies.

(3) Investigation of the connection, if any, between the nature and conditions of formation of the air core and efficiency.

(4) Determination of the effect of application of back pressure to overflow and/or underflow.

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7. SYMBOLS

d = particle diameter, microns.

d_{50} = size of particle appearing 50 percent by weight at both underflow and overflow, microns; d'_{50} , cm.

D_c = hydrocyclone diameter, in.; D'_c , cm.

D_i = feed diameter, in.; D'_i , cm.

D_o = overflow diameter, in.

D_u = underflow diameter, in.

E_c = centrifugal efficiency, percent.

$E_1 = N$ = solids elimination efficiency, percent.

E_2 = concentration efficiency, percent.

E_3 = clarification efficiency, percent.

K = constant in pressure drop – flow rate relationship by Haas (1).

$L = L_1 + L_2$ = hydrocyclone length, in.

L_1 = length of hydrocyclone conical section, in.

L_2 = length of hydrocyclone cylindrical section, in.

n = exponent in expression for d_{50} by Bradley (13).

$N = E_1$ = solids elimination efficiency, percent.

Δp = pressure drop, ft. liquid.

Q = flow rate, U.S. gpm; Q', cc/sec.

$R = E_c$ = reduced fractional recovery (11).

R_f = $\frac{\text{underflow flow rate}}{\text{feed flow rate}}$

VFL = vortex finder length, in.

VFOD = vortex finder outside diameter, in.

W_f = feed flow rate, g/sec.

W_u = underflow flow rate, g/sec.

x_f = weight fraction of solids in feed stream.

x_o = weight fraction of solids in overflow stream.

x_u = weight fraction of solids in underflow stream.

ϵ_A = Separation Index (15)

θ = hydrocyclone included angle, degrees.

α = inlet velocity loss ratio (13).

ρ_s = solid density, g/cc.

ρ_l = liquid density, g/cc.

ρ_o = overflow slurry density, g/cc.

μ_l = liquid viscosity, g/(cm)(sec).

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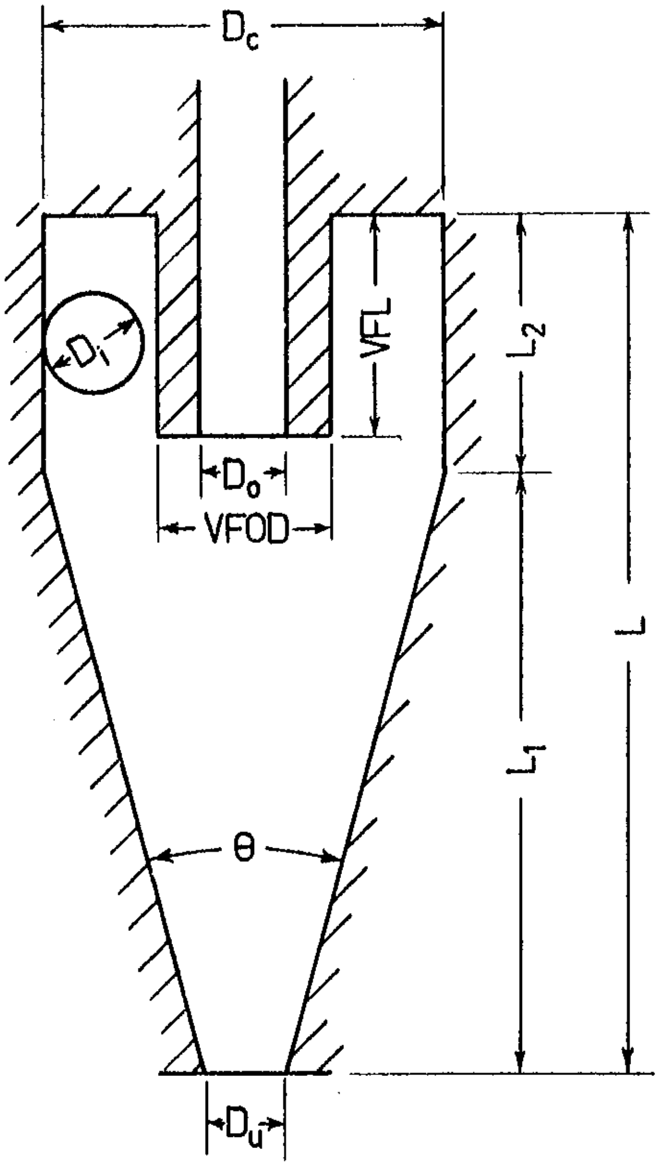

FIG. 1
DIAGRAMMATIC SKETCH
OF HYDROCYCLONE