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SEPARATION OF LIQUIDS IN A CONVENTIONAL HYDROCYCLONE

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INTRODUCTION

Generally a cyclone can be either a cylindrical tube, a hollow truncated cone, or a combination of both. The latter is the most common design today. The feed entrance tube is always installed tangentially but usually in the upper portion of the cylindrical section. Two concentric outlets are provided at opposite ends. The upper outlet is commonly known as the vortex finder tube or overflow discharge and the lower outlet the discharge nozzle or underflow apex.

The most attractive feature of the cyclone is its simplicity in both construction and operation (e.g., no moving parts) and low capital investment (as compared with a centrifuge, for example). However, the practical advantage of a cyclone is that almost any mixture of immiscible fluids or solid-containing suspension with a density gradient can be separated into two enriched portions, provided the flow throughout is substantial enough to generate adequate vortex action within the cyclone. When a clear liquid is present in the feed, two vortex phenomena can be observed. The outer vortex represents the bulk flow swirling downward in a rotating spray at the apex where the inner vortex, essentially a column of air usually known as the air core, is drawn spirally and co-directionally upward to carry the lighter phase through the vortex finder tube and to exit as the overflow (Figure 1). Since most liquid fluids are several hundred times

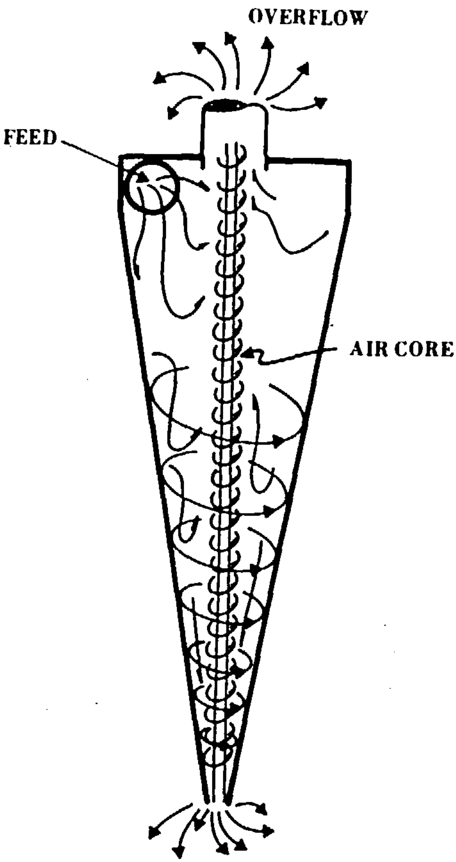

FIGURE 1

Vertical, radial and tangential flow pattern in a hydrocyclone

denser than air and owing to the conservation of momentum at the apex, the tangential velocity of the air-column can be expected to be several hundred time* greater than that of the bulk flow at

*Estimated from high-speed motion pictures.

the discharge nozzle. It is mainly due to this air core that the lighter phase of the feed mixture is separated through the vortex finder tube. One may also note that the dual-vortex mechanism experienced in a hydrocyclone is different from the single-vortex flow which has been extensively investigated by hydrodynamicists.

The flow pattern of a single fluid in a hydrocyclone has been determined by several investigators with findings in good agreement. Both Crainer[1] and Kelsall[2] maintained that the product of tangential velocity and radius to the nth power is constant.

$$V_\theta \cdot r^n = \text{constant} \qquad (1)$$

as long as the total input energy to the systems remains unchanged; i.e., the law of conservation of angular momentum is applicable. However, as shown in Figure 2, n can vary from -1 to +1 depending on the internal friction loss. For a fluid of infinite viscosity n is -1. Driessen[3] derived the basic mathematical relationship between tangential velocity and radius for a vortex flow involving a single fluid, which compared favorably with the measured values. Rietema[4] has plotted the reduced tangential velocity as a function of the reduced radius using the sum of kinematic viscosity and turbulent viscosity as a parameter, and it provided correlations for the optimum design of solid-liquid separation, which has since been a standard reference in this technology. Mixon[5] further substantiated the correlation by reinterpretations which are expected to pave the way for the future study of three-phase separations.

In contrast to numerous publications on solid-liquid separation by the technology of hydrocyclone, the study on liquid-

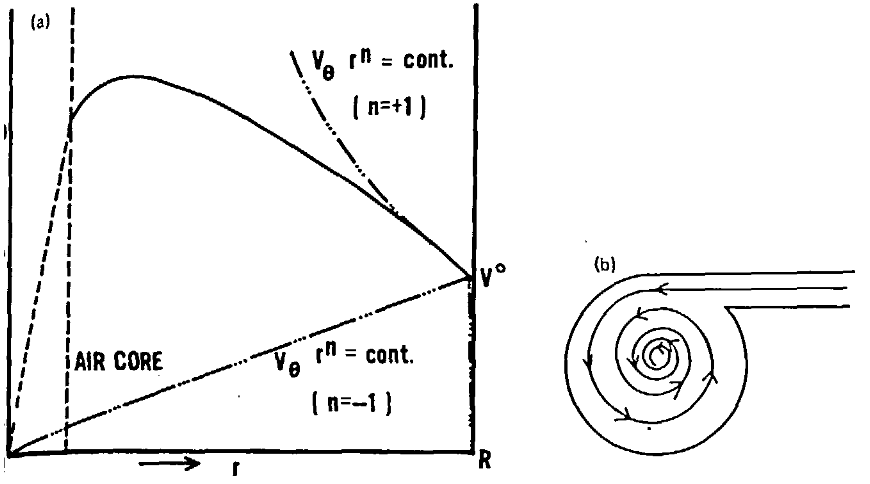

FIGURE 2 (a)

Typical tangential velocity profile near the entrance tube

FIGURE 2 (b)

Streamline flow pattern

liquid separation has been meager. The major differences between these two mechanisms are: 1) solid particles remain intact while liquid particles tend to split into finer sizes due to high sheer stresses near the air core and 2) solid particles to be separated from the liquid nearly always have a density much greater than that of the liquid, whereas the dispersed liquid particles may have a density either slightly greater or less than that of the continuous phase.

Unlike the centrifuge in which a particle, either of liquid or solid, experiences a unique force, the particle moving through a fluid medium in a hydrocyclone experiences unbalanced pressures on opposite sides of the particle normal to the direction of flow. In addition, the source of power for the separation of phases in a hydrocyclone is inherent in the stream; hence, any separation in a hydrocyclone is always complemented by a certain degree of turbulent mixing of the phases, notably in the upper conic section near the feed entrance tube. This inevitable turbulence causes a damaging effect in a solid-liquid case where solids could by dynamically "retained" near the air core and then mechanically carried off to the overflow. In the case of a liquid-liquid system, the effect is even more detrimental if the liquid particles tend to emulsify with the continuous medium. When an emulsion is formed, the function of a hydrocyclone is merely reduced to the separation of the denser emulsion from the lighter emulsion of an essentially homogeneous mixture. However, the presence of a solid phase in a liquid-liquid system tends to discourage the emulsion forming presumably due to the reduction of surface contact area - especially when the solid is preferentially wetted by one of the liquids. It is mainly from the standpoint of practical interest that this presentation is devoted mostly to the study of turbulent mixing in a hydrocyclone by a proposed mathematical model. The purpose of this model is to express the turbulence in terms of dimensional "length" when the required experimental variables become available.

One of the major factors in the commercial acceptance of a unit of equipment is its economic feasibility. The main reason that the hydrocyclone has not yet been generally adopted for liquid-liquid separation by commercial operations is its low efficiency at the present state-of-art. Therefore, one of the objectives in this presentation is to demonstrate the separation efficiency of a two-phase, liquid system in the presence of a solid. It is hoped that this study will eventually yield some perspective knowledge leading to the amelioration of economic feasibility of liquid separation by the technology of hydrocyclone.

HISTORICAL BACKGROUND

Of all the cyclones in existence today, the gas-solid cyclone, commonly known as the cyclone separator, probably has the longest history of usage.

Although the first hydrocyclone patent was granted in the U.S. in 1891 to Bretney and a five-foot diameter hydrocyclone was employed by the phosphate industry as early as 1914, commercial installations were not too prevalent until the late 1930's--mostly confined to the pulp and paper industry for cleaning dilute pulp stock.

It was not until the early 1940's when the Dutch State Mines inaugurated coal-washing and ore-processing in large tonnage that the acceptance of hydrocyclone generated any appreciable momentum. From then on, numerous papers appeared in the literature and many ingenious designs and modifications for a broad spectrum of applications became available on the market. The art of hydrocyclone technology then began to flourish.

With the exception of independent theoretical studies on vortex hydrodynamics, engineering research on the hydrocyclone, particularly in correlation of performance and applicability to various processes, was meager until it received concerted support from both the U.S. Atomic Energy Commission and U.K. Atomic Energy Authority during World War II. In the ensuing years, more sophisticated efforts, incorporating hydrodynamic principles and analyses, appeared in published papers. It is due to the limited scope of this presentation that readers are referred to the book The Hydrocyclone[6] which contains the most complete bibliography available. Over 600 papers on hydrocyclone and related subjects and 55 patent reviews are presented.

While the hydrocyclone has been standard equipment in various fields of technology for solid-liquid separation, the 1960's saw a revived interest in special laboratory uses and diversified applications—notably in the chemical industry for liquid-liquid extraction, solid-liquid leaching, crystallization, and in space technology where separation in a zero-gravitational field is required. Recently, in the petrochemical industry, considerable effort has been expended to increase the operating efficiency of the cyclone separator in order to permit its use in general liquid-liquid separation on a commercial scale. A cursory review of current information seems to indicate that the general trend is toward adopting a system consisting of multiple, small- or even miniature-cyclones with common feed entrance and discharge exits. It is generally regarded that a small cyclone yields a higher efficiency. Hence, for handling large capacities, multiple, small units can be used to circumvent the problems of scale-up. In addition, the effect of various dimensions and apex angles on separation efficiency can be minimized in a smaller cyclone.

Since the scope of this presentation is primarily in the realm of liquid-liquid separations, a brief review of the previous work in this aspect is pertinent.

While the literature is abundant in solid-liquid separation work, little is available on liquid-liquid separations. The earliest recorded investigation was conducted by Tepe and Woods[7] of the U.S. Atomic Energy Commission in 1943 in which the separation efficiency was derived. Van Rossum[8] in 1953 conducted investigations on the separation of water-in-oil emulsions in a 3-inch cyclone using oils of different viscosities and densities as the continuous phase. Effects of viscosity on separation efficiency were also determined. Simkin and Olney[9] in 1956 determined by a series of experiments the most favorable conditions for separating liquids in a 4-inch cyclone. Values of separation efficiencies as a function of effluent split at various feed compositions, feed rates, and geometric factors of the cyclone were obtained. The relationship between the mass transfer efficiency and the degree of phase separation was also discussed. In the same year, Bradley[10] proposed a scheme to use the cyclone as an extractor-separator which was followed by Hitchon's[11] experiment to measure both the separation efficiencies and mass transfer efficiencies in a 10 mm. cyclone as an extracting-separating device for a tri-component system. In similar manner, Molyneaux[12] investigated the possibility of liquid-liquid extraction and solid-liquid leaching in a dual-cyclone for other tri-component systems and reported the findings in the form of mass-transfer coefficients. In addition, Breeze[13] reported some separation results and qualitative conclusions from a high-speed "dual jet-cyclone" as a substitute for a mixer-settle unit.

Academically, Klein[14] in 1950 investigated the applicability of a cyclone to the separation of a liquid mixture in a 3-inch cyclone. Although optimum effluent splits were obtained for various feed compositions and pressure drops across the cyclone. emulsification remained serious. Ellefson[15] continued the work by employing an 8-inch cyclone in order to simulate the commercial-scale operation. He reported the range of optimum volume at various parameters as well as the correlation of energy requirement to the inlet and overflow diameters. Recently, Sweet Water Development[16] has conducted massive experimental runs using various designs and modifications of cyclone for a liquid-solid-liquid system in which the solid, a propane hydrate, has an intermediate density between brine and propane. However, no tabulation of separation efficiency and correlation of data are presented.

In 1976, Johnson, Gibson and Libby[17] measured the capability of two small cyclones to separate Freon drops from water and from an ice-brine slurry at various flow rates and drop sizes. The drop sizes were observed and recorded by using the technique of photomicrography and data were treated by the method developed by

Rietema. For the larger cyclone, agreement between theory and experimental was good. For the smaller one, the data fell below the theory because of liquid particle disintegration within the cyclone.

A SIMPLIFIED MODEL

A theoretical model based on the principle of hydrodynamics has been proposed by Sheng.[18] Basically, it is postulated that a cyclone is consisted of numerous flat cylindrical "disk" of various diameters (in reducing order). However, in this presentation, a simplified version is adopted to demonstrate its applicability for separating a liquid-liquid mixture.

In reality, when a mixture of immiscible liquids is charged into a hydrocyclone at a given rate, Q_f, substantial enough to generate some centrifugal action, there will be a certain turbulent mixing region extending a length "d" from the upper base (Figure 3). Therefore, at least this much of the hydrocyclone is extremely ineffective for separation. However, as the liquid mixture moves from the turbulent region into the separation region, a particle of the dispersed (discontinuous) phase at a radial distance, say C_o, will take a certain time to reach the air core of radius "a". By defining radial velocity V_r as

$$V_r \, dt = dr \tag{2}$$

and

$$(Q/L) = r \, V_r \tag{3}$$

then

$$dt = \frac{r dr}{(Q/L)} \tag{4}$$

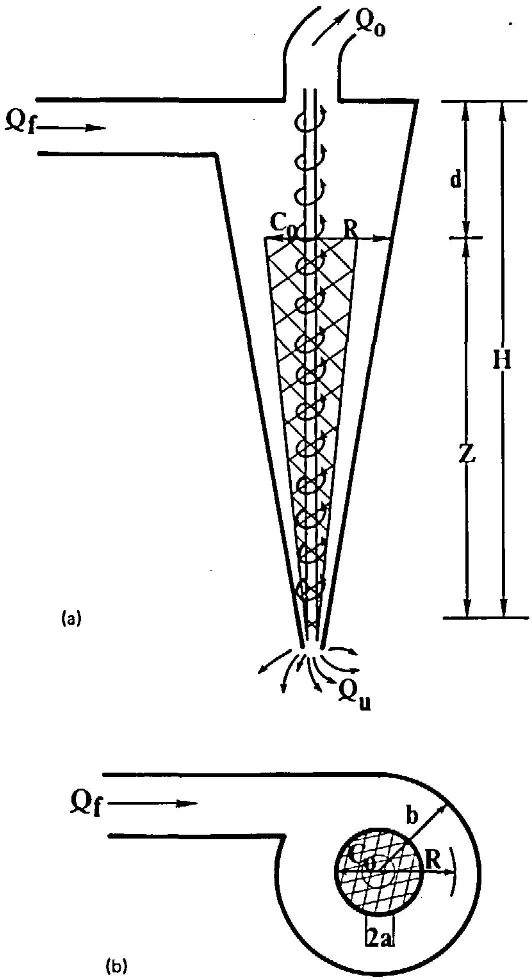

FIGURE 3

Vertical and cross-sectional view of a hypothetical model within a cyc

$$\int_0^t dt = \int_a^{C_o} \frac{rdr}{(Q/L)}$$

$$t = \frac{C_o^2 - a^2}{2(Q/L)} \qquad (5)$$

the time requirement can be determined. Since the particle travels downward until it reaches the air core to be carried off in the overflow, the downward distance covered by this particle is also equal to "Z". With the presence of the turbulent region, the maximum distance of "Z" is therefore

$$Z = H - d \qquad (6)$$

where H is the height of the cyclone.

Assuming the oil-water mixture in the hydrocyclone is consistently well-proportioned as in the feed, we can propose that the ratio of a hypothetical conic volume of radius C_o (Figure 3) to that of a radius R is proportional to the ratio of the actual fraction of the volumetric rate of oil exiting in the overflow to that of its ideal fraction, thus

$$\frac{\frac{1}{3} Z\pi\,(C_o^2 - a^2)}{\frac{1}{3} Z\pi (R^2 - a^2)} = \frac{(Q_o x_o / Q_f x_f)_{exp.}}{(Q_o x_o / Q_f x_f)_{ideal}}$$

or

$$\frac{(C_o^2 - a^2)}{(R^2 - a^2)} = \frac{(Q_o x_o / Q_f x_f)_{exp.}}{(Q_o x_o / Q_f x_f)_{ideal}} \qquad (7)$$

$$R = \frac{b \cdot Z}{H} \qquad (8)$$

while Q_o, Q_f = volumetric flow rate of the overflow and feed, respectively, and

X_o, X_f = volumetric fraction of the lighter phase in the overflow and feed respectively.

Both d and H are physical dimensions of the cyclone, and $(x_o, x_f)_{ex}$ are measured volumetric fractions of the oil in the overflow and in the feed, respectively. The $(x_o, x_f)_{ideal}$ are defined in the next section of this chapter. One must bear in mind that this hypothetical model has no physical correlation.

The Physical Model

A conventional hydrocyclone normally consists of three stationary parts: 1) Vortex finder tube (VFT), 2) Main body with tangential feed entrance tube, and 3) Discharge apex nozzle. For a certain size of a main body, which is essentially a short cylindrical section in conjunction with a truncated cone, a given interchangeable vortex finder tube and certain discharge apex nozzles are combined to satisfy a specific requirement for separation. In the case of solid-liquid separation, for instance, the larger the diameter of the vortex finder tube, the coarser the separation; i.e., more solid particles exit with the liquid in the overflow. On the other hand, a large discharge apex orifice yields greater underflow. Thus the primary function of the apex nozzle is to control the effluent split (Q_o/Q_u). In certain industrial applications, apex nozzles with variable diameters are often employed in order to suit a range of specific needs.

DEFINITION OF SEPARATION EFFICIENCY

Before the overall separation efficiency for a three-phase system is defined, it is worthy to note some nomenclature and material balance equations for a two-phase system.

$$Q_f = Q_o + Q_u \quad (9)$$

where Q_f, Q_o, Q_u = volumetric flow rate of the feed, overflow and underflow, respectively.

$$x_o + y_o = 1.0 \quad (10)$$

where x_o, y_o = volumetric fraction of the lighter phase and the denser phase in the overflow, respectively.

The following material balance equations are also useful:

$$x_u + y_u = 1.0 \quad (11)$$

$$Q_o x_o + Q_u x_u = Q_f x_f \quad (12)$$

$$Q_o y_o + Q_u y_u = Q_f y_f \quad (13)$$

Tepe and Woods'[21] definition of overall separation efficiency for a liquid-liquid system is not only confined to the hydrocyclone but it is also applicable to other separating devices as well. Briefly, the overall efficiency is the sum of each liquid phase (immiscible) efficiency. Thus

$$E = E_1 + E_2 \quad (14)$$

where E_1 is the phase efficiency of the lighter liquid phase and E_2 that of the denser phase. Since the lighter phase is expected to exit in the overflow and the denser in the underflow, by definition

$$E_1 = \frac{1}{Q_f} \left(Q_o x_o - Q_o \ (1-x_o) \frac{Q_f x_f}{Q_f (1-x_f)} \right) \qquad (15)$$

$Q_o x_o$ is the measured volumetric flow rate of the lighter phase in the overflow, and $Q_o(1-x_o)\left(\frac{x_f}{1-x_f}\right)$ is the proportional amount of of the lighter phase in the overflow had there been no enrichment of the lighter phase based on the presence of the heavier phase.

$$E_2 = \frac{1}{Q_f} \left(Q_u y_u - Q_u \ (1-y_u) \frac{Q_f y_f}{Q_f (1-y_f)}\right) \qquad (16)$$

Combining Eq. 15 with Eq. 16 yields

$$E = E_1 + E_2 = \frac{Q_o \ (x_o - x_f)}{Q_f \ (1 - x_f)} + \frac{Q_u \ (y_u - y_f)}{Q_f \ (1 - y_f)} \qquad (17)$$

With the aid of material balance equations, Eq. 17 could be reduced further to

$$E = \frac{Q_o \ (x_o - x_f)}{Q_f \ x_f \ (1-x_f)} \qquad (18)$$

Overall Separation Efficiency for a Three-Phase System: In the case of a three-phase separation in a conventional hydrocyclone where only two outlets are accessible, the third phase will have to exit either through the vortex finder tube or the discharge apex, or both simultaneously. Hence, in defining the overall separation efficiency, the desirability of the third phase to exit in either outlet dictates the format of the equation. If it is desired that the third phase exit in the overflow, the phase efficiency for the lighter phase would be

$$E_1 = \frac{1}{Q_f} [Q_o x_o - Q_o (1-x_o-Z_o) \frac{Q_f x_f}{Q_f(1-x_f-Z_f)}] = \frac{Q_o}{Q_f}$$

$$[\frac{(x_f Z_o - x_o Z_f) + (x_o - x_f)}{(1-x_f-Z_f)}] \quad (19)$$

re z_o = fraction of third component in the overflow.

z_f = fraction of third component in the feed.

phase efficiency for the denser phase is identical to Eq. 16.

ewise, the phase efficiency for the third phase would be

$$E_3 = \frac{1}{Q_f} (Q_o Z_o - Q_o (1-x_o-z_o) \frac{Q_f Z_f}{Q_f(1-x_f-Z_f)})$$

$$= \frac{Q_o}{Q_f} (\frac{(x_o Z_f - x_f Z_o) + (Z_o - Z_f)}{(1-x_f-Z_f)}) \quad (20)$$

overall separation efficiency for a three-phase system is refore

$$E_1 + E_2 + E_3 = \frac{Q_o[(x_o-x_f) + (Z_o-Z_f)]}{Q_f (1-x_f-Z_f)} + \frac{Q_u (y_u-y_f)}{Q_f (1-y_f)} \quad (21)$$

case it is desired that the third phase exit in the underflow,

$$E = \frac{Q_o (x_o-x_f)}{Q_f (1-x_f)} + \frac{Q_u[(y_u-y_f) + (Z_u-Z_f)]}{Q_f (1-y_f-Z_f)} \quad (22)$$

Tengbergen and Rietema[19] listed eleven basic requirements an acceptable overall separation efficiency value. The major nts were

1. The highest value should be reached only when both phases are obtained completely pure after separation.
2. If one effluent stream contains a pure phase, the

efficiency should be equal to the ratio of the quantity of this pure stream over the quantity of this phase in the feed.

3. If the feed is split up into 2 streams having the same composition as the feed, the efficiency number should be zero.

4. The efficiency should remain the same if the 2 phases or the 2 effluent streams are interchanged.

For a two-phase system, they defined the efficiency to be

$$E = \left| \frac{Q_o x_o}{Q_f x_f} - \frac{Q_o y_o}{Q_f y_f} \right| = \left| \frac{Q_o x_u}{Q_f x_f} - \frac{Q_u y_u}{Q_f y_f} \right| \tag{23}$$

Extending this definition to a multiphase system yields

$$E = \left| \frac{\sum_1^{A_n} (A)_o}{\sum_1^{A_n} (A)_f} - \frac{\sum_1^{B_n} (B)_o}{\sum_1^{B_n} (B)_f} \right| = \left| \frac{\sum_1^{A_n} (A)_u}{\sum_1^{A_n} (A)_f} - \frac{\sum_1^{B_n} (B)_u}{\sum_1^{B_n} (B)_f} \right| \tag{24}$$

where A_1, A_2, A_3, . . . A_n are lighter phases desired to leave the overflow.

B_1, B_2, B_3, . . . B_n are denser phases desired to leave the underflow, and

$$(A_1 + A_2 + A_3 + . . . + A_n)_o + (B_1 + B_2 + B_3 + . . . + B_n)_o = Q_o \tag{25}$$

$$(A_1 + A_2 + A_3 + . . . + A_n)_u + (B_1 + B_2 + B_3 + . . . + B)_u = Q_u \tag{26}$$

$$(A_1 + A_2 + A_3 + \ldots + A_n)_f + (B_1 + B_2 + B_3 + \ldots + B_n)_f = Q_f \tag{27}$$

Examples illustrating the identity of Eq. 17 with Eq. 22 and Eq. 20 with Eq. 23 can easily be exercised by the reader. It has been demonstrated in the literature[19] that numerous different algebraic manipulations are available to compute the identical overall efficiency value.

Definition of Ideal Separation Efficiency: When a feed stream containing two immiscible fluid phases of a given proportion is charged to a hydrocyclone, the most ideal separation would be for the overflow to contain only the pure lighter phase and the underflow the pure denser phase. Consequently, the ratio of the overflow to underflow (effluent split) will be identical to the ratio of the lighter phase to denser phase (x_f/y_f) in the feed. With reference to Eq. 17 both

$$(x_o)_s = 1.0, \quad (y_u)_s = 1.0$$

and the ideal efficiency, E_s, is unity.

$$E_s = \frac{Q_o + Q_u}{Q_f} = 1.0 \tag{28}$$

In case the desired effluent split is not identical to x_f/y_f, the best separation would be for one exit flow to contain a pure phase; i.e., either x_o, or y_u, equals 1.0. In such a case the shape of the curve of the ideal efficiency, E_s, versus effluent split will be of a "roof-type" with the highest E_s value (1.0) at $Q_o/Q_u = x_f/y_f$. Since the ideal efficiency values can be obtained independent of experimental data, a FORTAN computer program has been developed to generate these values. For a three-phase system, the determination of E_s values follows the same logic as discussed in this section. If it is desired to have the third phase exit with the lighter phase, then

$$(x_o + z_o)_s = 1.0, \ (y_u)_s = 1.0 \qquad (29)$$

otherwise

$$(x_o)_s = 1.0, \ (y_u + Z_u)_s = 1.0 \qquad (30)$$

and both Eq. 20 and Eq. 21 can be reduced to unity respectively at $Q_o/Q_u = x_f/y_f$. (See Figures 4, 5, and 6.)

The utilization of the ideal efficiency curve is not only limited to hydrocyclones in general but to any phase separation device as well. In employing the ideal curve as a guide (in a somewhat similar manner as the equilibrium curve in the extraction operation), it enables the designer to select the most optimum range of effluent split when the actual efficiency values are available for comparison.

Relative Efficiency

The relative efficiency is defined as the actual overall separation efficiency divided by the ideal efficiency at the same effluent split (Q_o/Q_u) and feed phase ratio $(x_f + z_f)/y_f$. It is a measure of the proximity to an ideal state and its maximum value is unity. The relative efficiency is particularly useful in process design calculations as will be demonstrated later. Figures 7 and 8 summarize a total of 240 experimental runs for an oil-water system (specific gravities 0.76 and 1.0, respectively). The actual

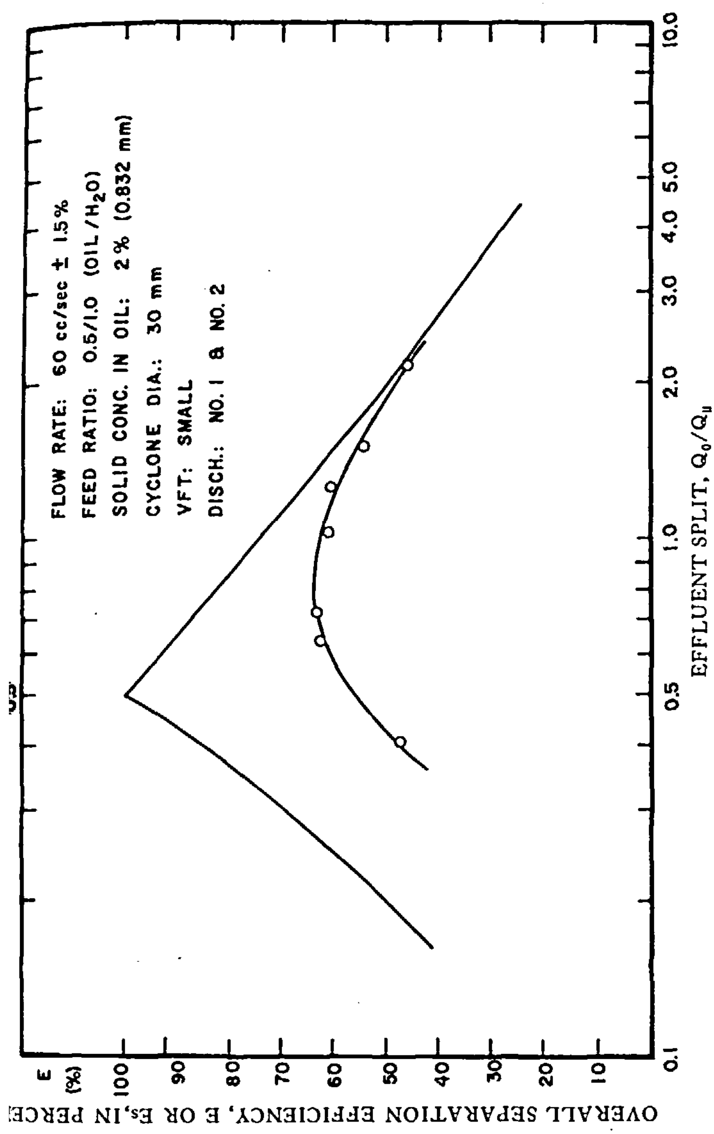

FIGURE 4

The variation in overall efficiency with volumetric effluent split for a feed of one-half volume of oil to one volume of water.

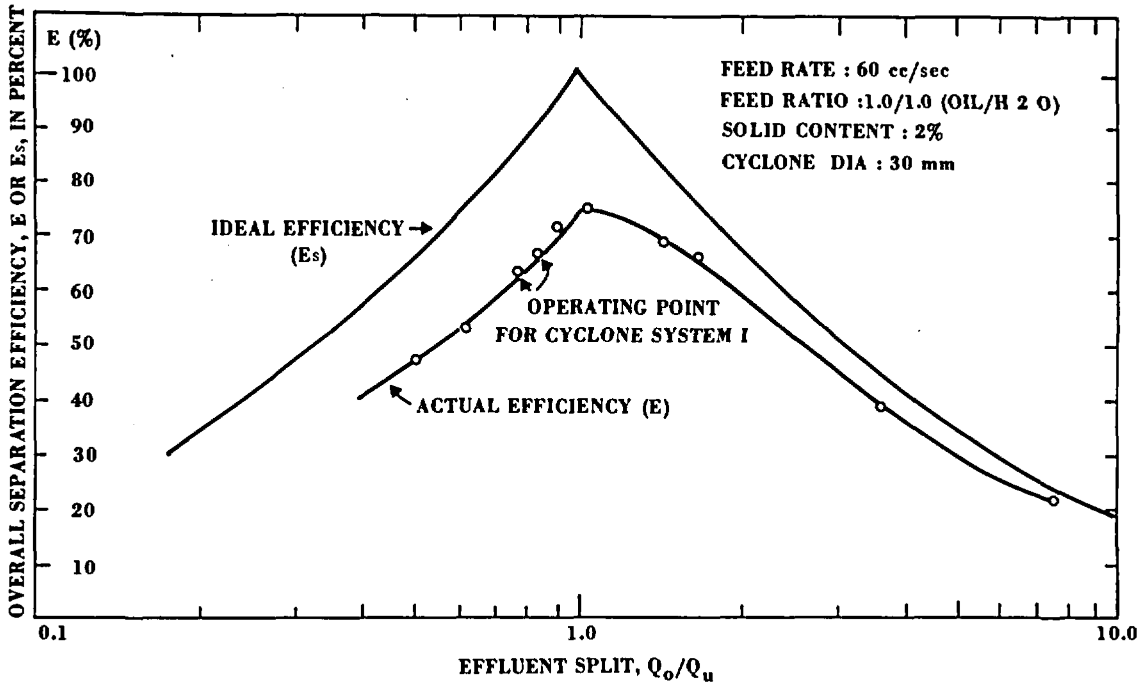

FIGURE 5

The variation in overall efficiency with volumetric effluent split for a feed of one volume of oil to one volume of water.

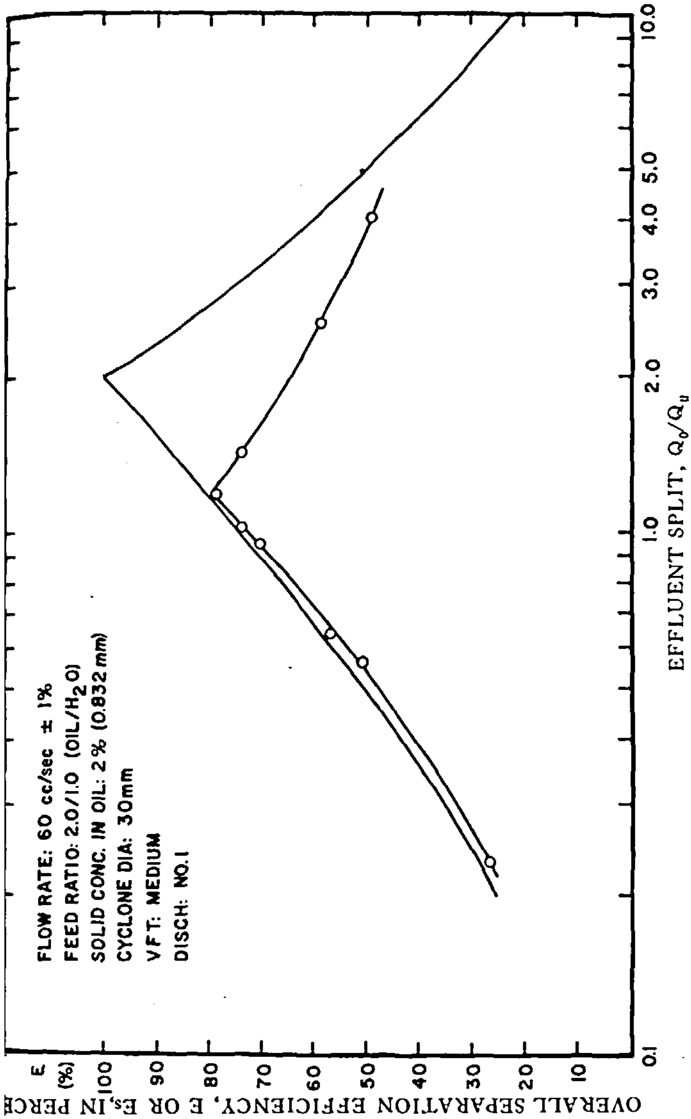

FIGURE 6

The variation in overall efficiency with volumetric effluent split for a feed of two volumes of oil to one volume of water.

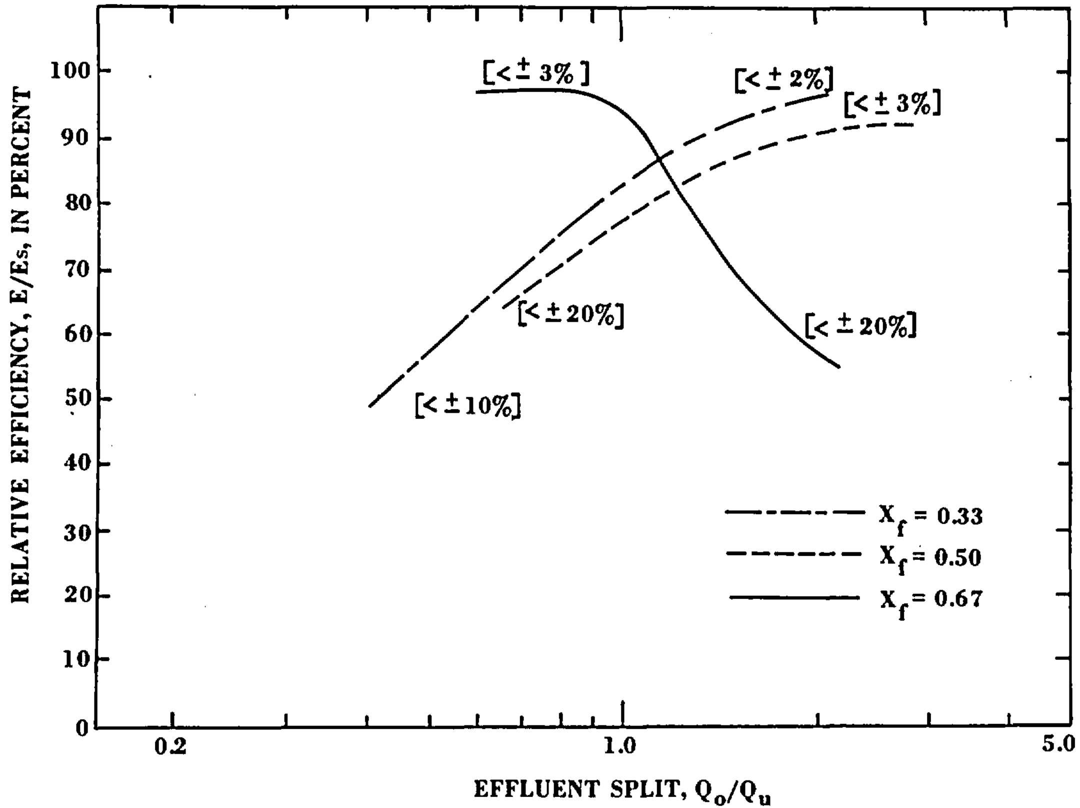

FIGURE 7

The variation in relative efficiency with volumetric effluent split for

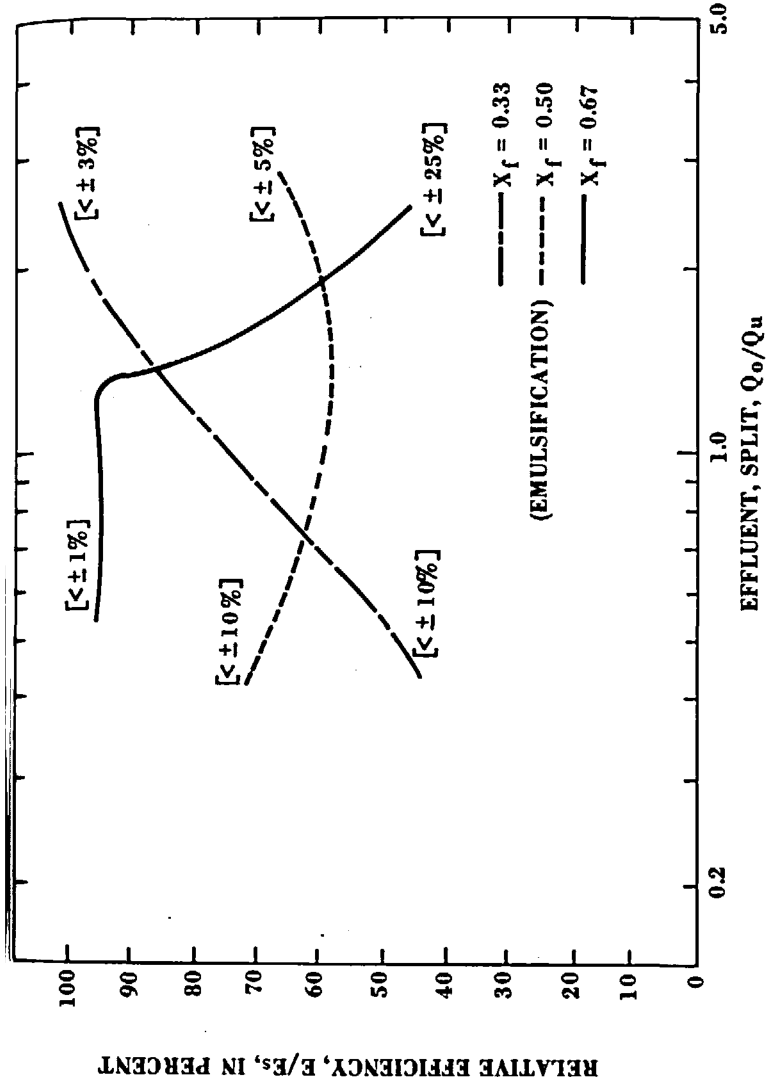

FIGURE 8

The variation in relative efficiency with volumetric effluent split for three feed composition (x_f) at a feed (Q_f) of 75 cc/sec.

data scattered over a band; the approximate limits of which are given numerically at the extremities of each curve.

It can be noted from these figures that

1. The general trend of each curve is governed by the phase ratio (oil/water) in the feed, irrespective of flow rates, except when emulsification occurs.

2. The size and percentage of solids have only a small effect on the efficiency values, except for inhibiting emulsification which is detrimental to liquid-liquid phase separation.

3. At the highest flow rate (75 cc/sec) and a phase ratio (oil/water) of 1.0, intense emulsification occured. It was attributed to the shear force which caused size reduction among the liquid particles. When emulsification occurs, the function of the cyclone is reduced to separating a dense emulsion from a lighter emulsion of an essentially homogeneous mixture. No meaningful comparison can be made between a non-emulsified run and its emulsified counterpart.

4. The actual efficiency, E, of a cyclone can be found from the ideal efficiency, E_s, by means of Equation (2) and the relative efficiency curves shown in Figures 7 and 8. If a curve of actual efficiency is plotted as a function of Q_o/Q_u, the maximum will usually occur between Q_o/Q_u of about 0.8 to 1.2, at least over the range of feed compositions covered in this study. For an oil-lean feed, operation is slightly more efficient for Q_o/Q_u slightly less than 1.0 and for an oil-rich feed, efficiency improves slightly for Q_o/Q_u slightly greater than 1.0.

5. In view of intense emulsification taking place at higher flow rates, it is advisable to keep the flow rate to a minimum to be consistent with efficient separation.

APPLICATION TO CYCLONE PROCESS DESIGN

As a result of this study, a method for estimating additional relative efficiency values (E/E_s) as a function of effluent split (Q_o/Q_u) for three x_f values (0.33, 0.50 and 0.67), the E/E value at, say $x_f = 0.8$ can be readily obtained by cross-plotting the known relative efficiency value versus x_f at various effluent splits and extrapolating to $x_f = 0.8$. Since the ideal separation efficiency values can be computed independently of flow rate and experimental data, the estimated overall efficiency is simply the extrapolated relative efficiency value (E/E_s) at $x_f = 0.8$ multiplied by its corresponding ideal efficiency value also at $x_f = 0.8$. This method should give good estimates of the overall efficiency for values of x_f between 0.2 and 0.8 provided at least three experimentally-determined E's are known. An estimated efficiency curve for $x_f = 0.8$ is shown in Figure 9.

A practical example of the application of relative efficiency to cyclone process design is illustrated by comparing two cyclone systems. System 1 in Figure 10 operates at a flow rate of 60 cc/sec and contains 50% oil in the feed. It is desired to separate the feed stream into two effluents with the overflow containing about 86% oil. Separation is to be accomplished by using a 30 mm cyclone, and the operating effluent splits (Q_o/Q_u) are chosen from the

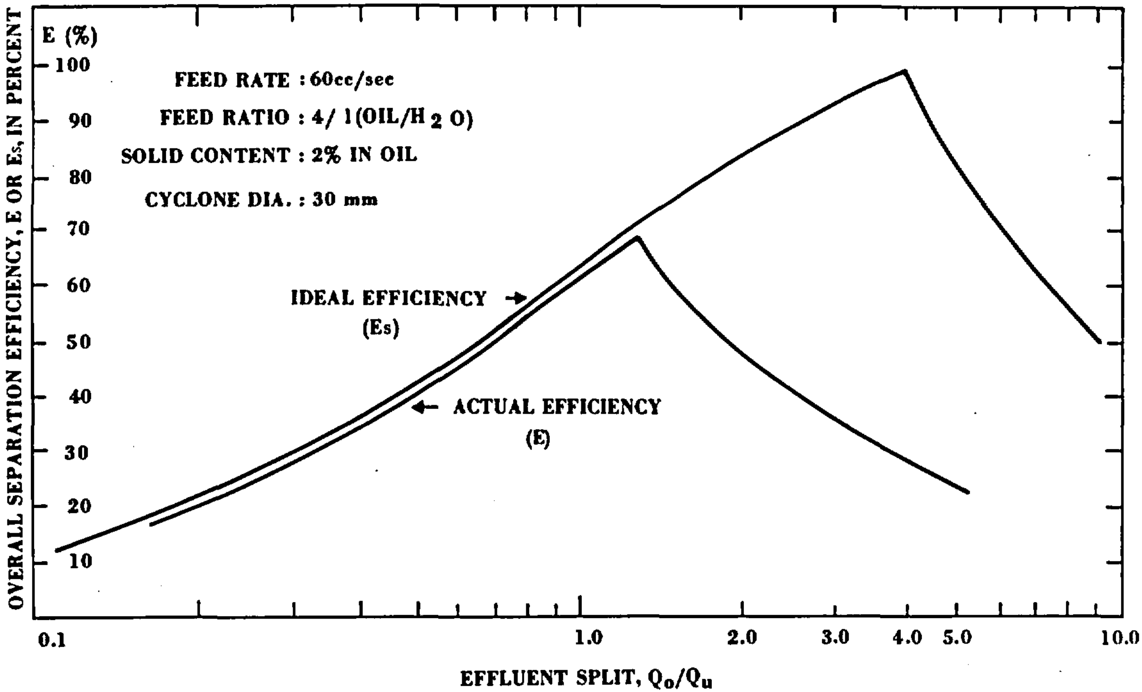

FIGURE 9

The variation in overall efficiency with volumetric effluent split for a feed of 4 volumes of oil to 1 volume of water.

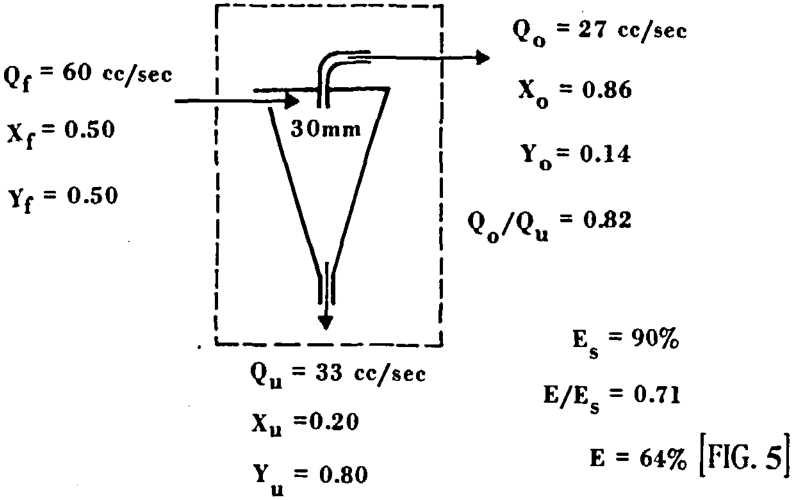

FIGURE 10

Cyclone system 1 (total number of cyclones in operation = 1).

actual overall efficiency curve given in Figure 5, because the information on the feed conditions and the overflow composition are available. The data also show that

$$Q_o = 27 \text{ cc/sec}, \quad Q_u = 33 \text{ cc/sec}$$

$$x_u = 0.20, \quad E/E_s = 71\%$$

Here, the total flow requires pumping of 60 cc/sec and only one cyclone unit is needed.

Suppose it is now desired to upgrade the oil content in the overflow to $x_o = 0.98$ while maintaining the same feed rate, feed composition, and overall effluent splits as in System 1. Two cyclone batteries in series, designated as System 2 in Figure 11 are devised for comparative study. By assuming an effluent ratio for each battery and by using the efficiency curves (Figure 7), one can determine the inter-stream flow rate and flow composition with the aid of simple material balance equations (9 through 13). The relative efficiency, E/E_s, for any feed ratio other than those shown in Figure 7 is obtained by cross-plotting the relative efficiencies at the desired effluent split, Q_o/Q_u, versus the feed composition, x_f, and interpolating or extrapolating to the desired feed composition. Figure 9 shows the result of such an extrapolation for $x_f = 0.8$. The remainder of the design parameters are shown in Figure 11. Thus, for

Battery I;	Q_f'	= 213 cc/sec
Battery II:	$Q_f'' = Q_o$	= 180 cc/sec
Total flow requires pumping		= 393 cc/sec

If each unit cyclone is to process the same feed rate (60 cc/sec) as in System 1 (Figure 10), then for

Battery I: Number of cyclones required $= \dfrac{213 \text{ cc/sec}}{60 \text{ cc/sec}} = 3.55$ or 4

Battery II: Number of cyclones required $= \dfrac{180 \text{ cc/sec}}{60 \text{ cc/sec}} = 3.0$

Total number of cyclones required = 6.55 or 7

This compares with 60 cc/sec flowing through one unit in Figure 10. Additional power for inter-cyclone pumping (393 cc/sec - 60 cc/sec = 333 cc/sec) will be required to provide further en-

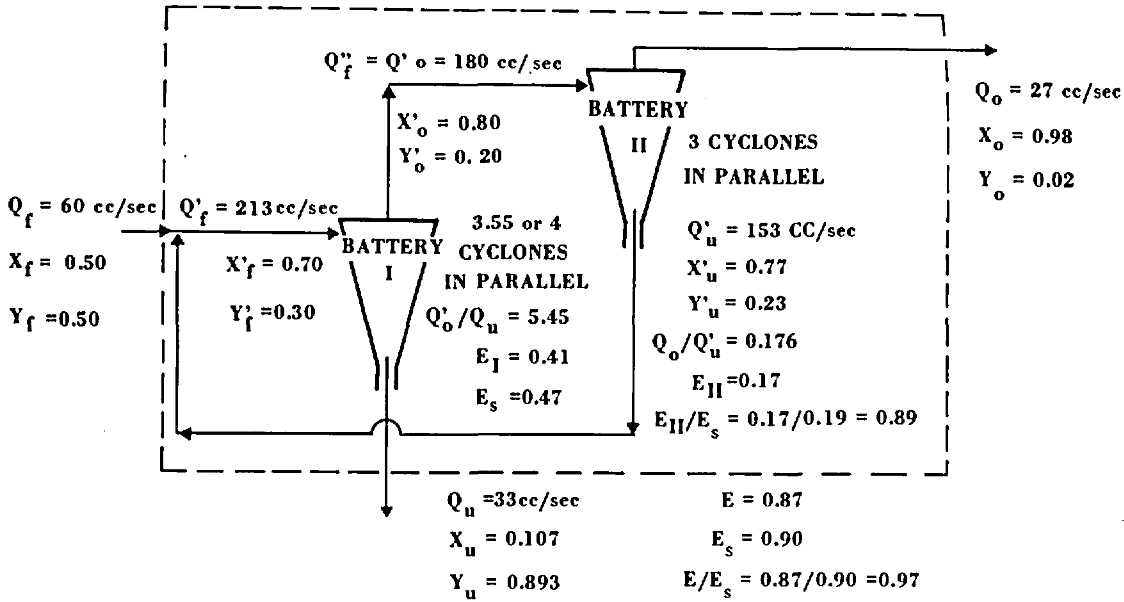

FIGURE 11

Cyclone system 2 (dual battery in series; total number of cyclones in operation = 6.55 or 7).

richment of both the overflow and underflow streams. In essence, the upgrading process is accomplished by taking advantage of extreme effluent splits (Q_o'/Q_u = 5.45 in Battery I and Q_o'/Q_u' = 0.176 in Battery II) where relative efficiency values are close to unity. One may also note that the overall relative efficiency value for System 2 is 0.97 in comparison with 0.71 for System 1.

The method presented heretofore is not restricted to hydrocyclone operation; it is also applicable to any phase separation device as well, provided that relative efficiency data for that particular process are available.

THE EFFECT OF MATERIALS OF CONSTRUCTION ON PERFORMANCE

It is known that the wettability of a solid surface by a liquid depends on the contact angle formed between the liquid and the solid surface. The contact angle, from 180° to 0° representing non-wettability to complete wettability respectively, can be found either in the literature or estimated. Figure 12 gives the contact angles formed between solid surfaces and water or n-decane similar to the oil used in this study. Figure 12 is only for the purpose of giving a visual impression of the differences in contact angle on various solid surfaces. Thus, only the values of the contact angle as shown on the two vertical lines, labeled water and n-decane, have any physical significance. For this reason, the sloping lines between the two vertical lines for the various solids are purely imaginary and are depicted as dashed lines.

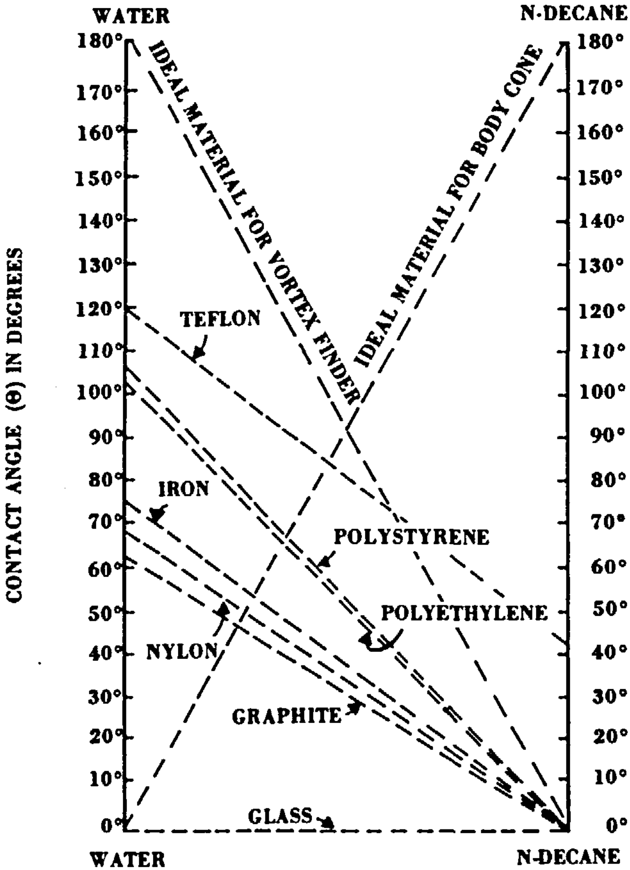

FIGURE 12

ntact angles between liquids and various solid surfaces (this pictorial lustration is not a plot; therefore values for the contact angle, other an those that are identified on the vertical lines labeled either water n-decane have no physical meaning).

Since the hydrocarbon phase is desired to exit in the overflow through the vortex finder tube, it would be ideal for the surface of the vortex finder tube to be completely wetted by the hydrocarbon (0^{o} contact angle) and not by water (180^{o} contact angle). The reverse is true for water and the cyclone body cone. Thus, the most effective material for the vortex finder tube would be one having the largest difference between the contact angles for water and n-decane. From Figure 12, it can be observed that for the solid materials shown, either polystyrene or polyethylene should be the best choice for the vortex finder tube (as indicated by the absolute magnitude of the "negative slope of the imaginary lines"). Teflon, iron, nylon, graphite, and glass would be subsequent choices in descending order of effectiveness. Conversely, the most effective material for the body cone would be one with the maximum "positive slope of the imaginary lines"). Since none of the materials shown in Figure 12 have this characteristic, the best remaining option is glass having essentially a "zero slope". These values for the contact angle are applicable for only essentially smooth surfaces; it is possible to achieve significant changes in the contact angle by artificially roughening the solid surfaces.

In order to determine the quantitative effect of materials of construction on the separation efficiency, three different materials were used for the vortex finder tube while retaining glass for the body cone in all experiments. A series of runs was conducted at 1:1 oil-water ratio with glass, nylon and polyethy-

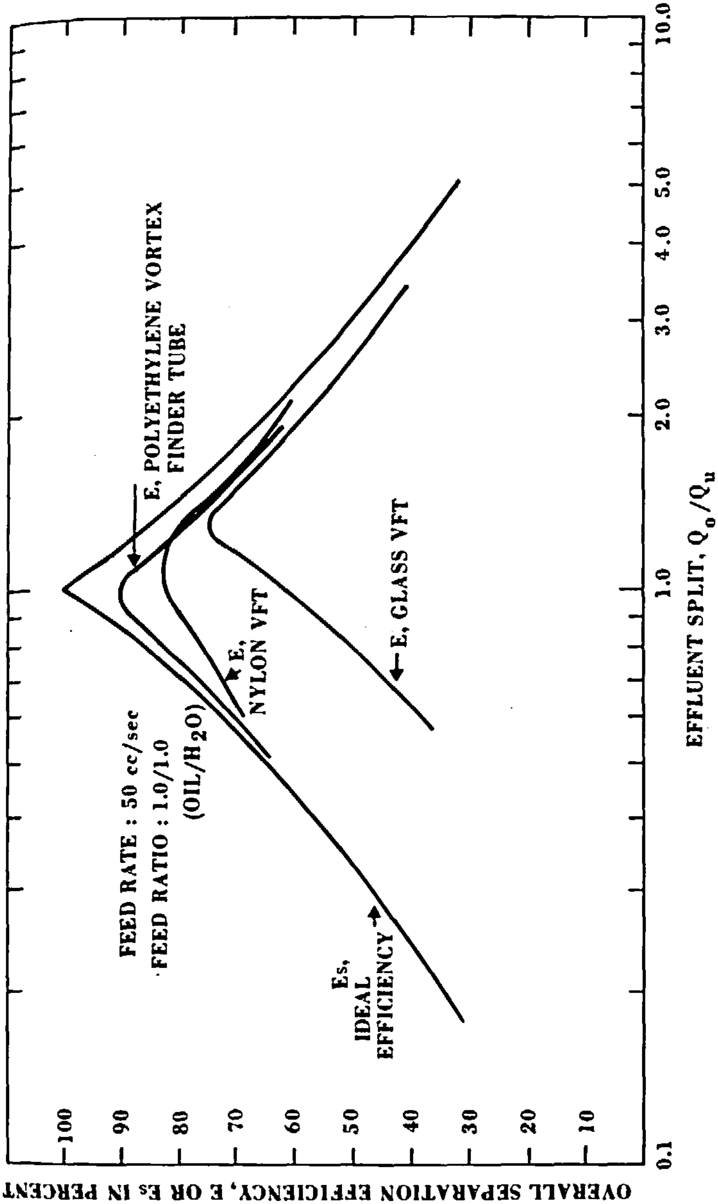

FIGURE 13

Variation in efficiency for various vortex finder tube materials.

lene vortex finder tubes. The separation efficiencies for each tube are plotted in Figure 13. The fact that the polyethylene vortex tube yields the highest efficiency at $Q_o/Q_u=1$ confirms the effect of contact angle as predicted from Figure 12. Note that the difference in the maximum separation efficiency is not trivial; it increases from 76% for glass to 91% for polyethylene.[20] Although hydrocarbon perfectly wets all three surfaces, the relative non-wettability between water and one of the three surfaces ultimately determines the "excludibility" of water from passing through the vortex finder tube.

It should be noted that this observed effect of materials of construction on separation efficiencies is not restricted to cyclones but is likewise applicable to other devices for resolving liquid-liquid mixtures.

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NOMENCLATURE

a the lighter component of a system to be treated by a cyclone.

b radius of the air core (cm).

C_o radius of the upper base of a cyclone (cm).

d radius of a hypothetical cone with a height Z from the apex of the cyclone (cm).

E length of the turbulent region extended downward from the upper base - this region is completely ineffective for separation (cm).

overall separation efficiency (dimensionless).

E_s ideal overall separation efficiency (dimensionless).

EVF effective volume fraction - complementary volume fraction for ineffective separation determined by "d".

g gravitational acceleration (cm/sec^2).

g_c gravitational conversion factor (dimensionless).

H height of a cyclone including the distance extrapolated from the apex (cm).

h_1 height of the cylindrical (vertical) section of a cyclone (cm).

h_2 height of the conical section of a cyclone (cm).

L average length of an element normal to flow in a cyclone (cm).

M mass of the liquid displaced by a solid or a liquid particle of a dispersed phase (gm).

m mass of the dispersed particle (gm).

m' slope of a line.

m_o the apparent mass of a particle moving in a fluid (gm).

m^o abbreviated for m-M.

n an exponential order.

P pressure (gm/cm-sec^2).

Q_f volumetric flow rate of the feed (cc/sec).

Q_o volumentric flow rate of the overflow (cc/sec).

Q_u volumetric flow rate of the underflow (cc/sec).

r radius in cylindrical coordinates (cm).

R radius of the conic section of the cyclone (cm).

t time (sec).

$\overline{\overline{v}}$ relative velocity of a particle with respect to the continuous fluid phase in motion (cm/sec).

V_o tangential velocity at the outer perimeter of the air core (cm/sec).

V_r radial velocity (cm/sec).

V_θ tangential velocity (cm/sec).

V_z vertical velocity (cm/sec).

x volumetric fraction of the lighter liquid component.

y volumetric fraction of the heavier liquid component.

Z height of the cyclone effective in separation (cm).

z volumetric fraction of the solids in the flow.