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Drop-Size Distribution and Dispersed Phase Hold-up in a Large Rotating Disc Contactor

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ABSTRACT

The effect of drop size and size distribution and the dispersed-phase hold-up on the performance of an extraction column are the most important hydrodynamic characteristics, because under steady operating conditions, drop size and hold-up are proportional to the interfacial area. Correspondingly, the efficiency of mass transfer is a function of drop size as well as hold-up.

A number of experimental investigations using the rotating disc contactor (RDC) have reported the measurement of dispersed-phase hold-up, drop size, and size distribution. However, most of the published data are for very small RDCs of <7.5-cm diameter. All the correlations introduced to describe the column hydrodynamics give unreliable results when applied to large-scale RDC operation and with different systems to those studied. Therefore, RDC hydrodynamics in the absence of mass transfer have been studied on a 450-mm-diam column, 4.3-m high, and the results obtained have been compared with those reported previously from small extraction columns. Wide divergences have been found. The results of this study have been correlated to predict the drop size in each compartment. Agreement has been within 10% of the experimental data. When the results of this and previous studies are analyzed together by including the column dimensions, the agreement between predicted and experimental results is generally within 15%.

Introduction

The Rotating Disc Contactor (RDC) is a mechanically agitated extraction column widely used in oil refining, the processing of nuclear fuels and the manufacture of chemicals and foodstuffs (1). As in other agitated columns, e.g. the Oldshue-Rushton and Schiebel columns, mechanical energy is applied to achieve a high mass transfer efficiency. The correct design of such columns for a specific duty is important both to minimize energy consumption and to enable the optimum solvent:feed ratio to be used, hence reducing the significant energy costs generally associated with solvent and solute recovery.

The RDC consists of a number of compartments formed by a series of stator rings with a rotating disc centered in each compartment and supported on a rotating shaft. Operating efficiency and volumetric capacity of this extractor vary with rotor speed. However the effects of drop size, drop size distribution and dispersed phase hold-up on the performance of an extraction column are the most important hydrodynamic characteristics. In most operating conditions, interfacial area is inversely proportional to the drop size so that correspondingly the efficiency of mass transfer is a function of drop size as well as the prevailing dispersed phase hold-up.

In many continuous counter-current columns, the phase which is to be dispersed is invariably introduced into the continuous phase via a distributor plate in an attempt to obtain a uniform initial drop size distribution. However in an agitated system, drop size distribution results from coalescence and redispersion of the drops arising from the application of external energy, and considerable work has been done to describe extractor performance in terms of fundamental droplet behaviour; i.e. drop size, drop size distribution and dispersed phase hold-up. However most of this work has been limited to specific systems and small scale columns. The purpose of the work described here was to develop a more realistic model of the hydrodynamics of an RDC in the absence of mass transfer using data collected from a 450 mm diameter, 4.30 m high column together with published data and hence to improve the design procedure.

i) Drop Size and Drop Size Distribution

Hinze (2) proposed an equation for maximum stable drop size based on the Kolmogorov (3) theory of isotropic turbulence where the microscale of turbulence is smaller than the drop size.

$$d_{max} = C_1 \left(\frac{g_c \sigma}{\rho_c}\right)^{3/5} . E^{-2/5} \qquad (1)$$

where C_1 = 0.72 based on an analysis of the rotating cylinder data of Clay (4). Strand et al. (5) suggested that the coefficient C_1 can be adjusted to match specific conditions accompanying mass transfer, and the tendency of drops to coalesce and break-up. An illustration of the application of the Hinze equation for drop break-up in an RDC has been provided by experimental work (5) in a 6 inches diameter RDC where, for a dispersed organic phase, the range of C_1 varied between 0.4 to 0.6. Again from the work of Kolmogorov (3) and later Levich (67), Jeffreys and Mumford (7) suggested that the stable drop radius can be represented by

$$r_{s.d} = \sqrt{2} \left(\frac{\sigma}{K_f \rho}\right)^{3/5} \left(\frac{L^{2/5}}{V^{6/5}}\right) \qquad (2)$$

where K_f is the Kolmogorov constant ≈ 0.5.
It was proposed that equation (2) can be applied to an RDC provided the discs were non-wetted by the dispersed phase. However the drop size thus calculated is the maximum in the turbulent system so that an empirical relationship has to be applied to find a representative size.

Misek (8,9) studied the break-up of drops in an RDC and distinguished three regions of operation depending on the Reynolds Number (Re). The correlations proposed for each region are in Table 1. Mumford and Al-Hemiri (10) have also proposed a correlation for estimating the drop size in any

Table 1
Correlations for Drop Size in the Absence of Solute Transfer

Author and Ref	Correlation	Column Diameter cm	Remarks
Strand et al. (5)	$d_{max} = C_1 \left(\frac{\sigma g_c}{\rho_c}\right)^{3/5} E^{-2/5}$ where $E = 4P/(\pi n \rho H D_c^2)$	15.24	C_1-constant dependent solvent dispersed, value range 0.4 - 0.6. n=number of compartment.
Jeffreys and Mumford (7)	$r_{s.d} = \sqrt{2} \left(\frac{\sigma}{K_f \rho}\right)^{3/5} \left(\frac{L^{2/5}}{V^{6/5}}\right)$ where K_f = Kolmogorov constant = 0.5 V = velocity component in the vicinity of rotor disc.	10.16	For discs non-wetted by dispersed phase.
Misek (9)	i) $\frac{d_o N^2 D_r^2 \rho_c}{\sigma \exp(0.0887 \Delta D)} = 16.3 \left(\frac{H}{D_c}\right)^{0.46}$ where $\Delta D = \frac{D_c - D_r}{2}$ ii) $\frac{d_o N^2 D_r^2 \rho c}{\sigma \exp(0.0887 \Delta D)} = 1.345 \times 10^{-6} (Re)$ iii) $d_o = 0.38 \left[\frac{\sigma}{\Delta \rho g_c}\right]^{0.5}$	25.0	$Re > 6.0 \times 10^4$ $Re = \frac{D_r^2 N \rho_c}{\mu_c}$ ΔD= distance between column wall and agitator d_o = mean drop size when $Re < 6.0 \times 10^4$ when Re is very low
Mumford and Al-Hemiri (10)	$d_{32} = 4.7 \times 10^{17} D_R X^{0.225} \left[\frac{N D_r \mu_c}{\sigma}\right]^2 \left[\frac{N' D_r \rho_c}{\mu_c}\right]^{-3.33} \left[\frac{\mu_d}{\mu_c}\right]^{-0.23} \left[\exp\left(0.4 \frac{n}{N_c}\right)\right]$	10.16	N'=Rotor speed rpm N_c=Total no. of compartments.

Table 2

Property of Dispersions	Normal Distribution	Log-Normal Distribution
Proportion of smaller droplets (by volume)	Lower	Higher
Mean mass transfer coefficient	Higher because more drops are circulating	Lower - more stagnant drops
Interfacial area	Lower	Higher
Settling rate	Higher	Lower
Tendency to flood column	Lower	Higher

compartment as a result of their studies using a 100 mm diameter R.D.C. and very recently Blazej et al. (17) have proposed correlations for drop size under mass transfer conditions for water-acetone-toluene system in a 65 mm diameter column. In all these studies there has been considerable disagreement over the shape of the drop size distribution curve in the agitated system. Some investigations reported a normal distribution (17,18,19,20) while others found the distribution to be log-normal (21,22,23,24,25). This is of practical significance in the analysis of the performance of an extraction column. Thus for a fixed volumetric throughput, a comparison of the two types of dispersion is given in Table 2 (26).

Table 2 shows that a normal distribution, where the mode is equal to the mean, results in more drops being nearer to the mean size would be preferable to a log-normal distribution for predicting the characteristics of an RDC. However Chartres and Korchinsky (24) have confirmed Olney's (23) conclusion that the drop size distribution in an RDC obeys the upper limit distribution proposed by Mugele and Evans (27)

$$\frac{dv}{dr} = \frac{\delta}{\sqrt{\pi}} \exp(-\delta^2 r^2) \qquad (3)$$

where $r = \ln \left[\frac{a'd}{d_m - d}\right]$ (4)

The upper limit distribution is a modified log-normal distribution which may be compared with the standard form of the log-normal distribution

$$\frac{dv}{dr} = \frac{\delta}{\sqrt{\pi}} \exp(-\delta^2 r^2) \quad (5)$$

$$\text{where } r = \ln \frac{d}{d_{vg}} \quad (6)$$

Chartres and Korchinsky (24) have shown that Olney's (25) data are accurately represented by the upper limit distribution rather than the log-normal distribution. In addition Korchinsky and Azimzadeh-Khateylo (25) found that the upper limit distribution accurately represented the drop size data in an Oldshue-Rushton column. They emphasised the importance of applying drop size distribution in the mass transfer calculation instead of using the Sauter mean diameter. Olney (23) has also shown that d_{32} may not be the proper mean drop size to represent the transfer rate for the total drop population and concluded that the upper limit distribution well represents the drop size distribution in an RDC. The significance of the distribution parameters a' and δ was emphasised. Finally in a very recent study Chartres and Korchinsky (28) stated that the size of sample of drops used to represent a dispersion is also extremely important. They also pointed out the marked effect of inlet drop size on column drop size and measured extraction efficiency.

ii) Dispersed Phase Hold-up

Only the average values of the dispersed phase hold-up have been determined in this work and in many other studies (1,11,12,13,14,15). A few studies have determined point values of the hold-up by withdrawing two phase samples through probes located at various points along the column length (10.5). Some of the more important investigations reported in the literature relating to the average hold-up in an RDC are summarised in Table 3. Most of the researchers have used the simultaneous shut-off method (12,13,14,15) in which all the inlet and outlet valves were shut-off simultaneously after steady state had been attained in the column after which the shift in the interface level was determined. Laddha et al. (1) used the displacement method in which all the incoming and outgoing flows were shut-off simultaneously and after the phases had separated the continuous phase was restarted until the level of the interface returned to its original position. The amount of the dispersed phase displaced from the column represented the measured hold-up. Kung and Beckmann (11) used a radio-isotope technique. Most of the analyses of hold-up of the dispersed phase in an RDC have been made on the basis of Pratt's (16) characteristic velocity approach (1,11,12). Thus the correlation of hold-up with the characteristic velocity achieved for spray columns and packed columns appears to have been applied without question to the RDC in which the velocities of droplet travel are a function of the external energy input.

Kasatkin et al. (14) and recently Murakami et al. (15) have proposed correlations for hold-up based on dimensional analysis, but the Kasatkin (14) correlation presents difficulties in the method of treating the dimensionless groups which are based on the flooding flow rates estimated for an RDC. Murakami's (15) correlation is more realistic for estimating the hold-up in an RDC, but the exponents of the dimensionless groups were estimated by plotting the various groups and then estimating the slope of the line to obtain the exponent of the dimensionless term.

Equipment and Liquid-Liquid System

A pilot scale RDC with 14 compartments was designed and constructed as illustrated in Figure 1. The flow diagram is reproduced as Figure 2.

The principal dimensions were:-

Column internal diameter, mm	450
Column working height, mm	4300
Disc diameter, mm	225
Compartment height, mm	225
Stator opening, mm	337.5

Table 3

Correlations of Dispersed Phase Hold-up and Characteristic Velocity in an RDC

Author and Reference	Correlation	RDC diameter D_c cm	Remarks
	Hold-up correlation		
Logsdail et al. (12)	$\frac{V_d}{X} + \frac{V_c}{1-X} = V_N\ (1 - X)$	7.62	V_N is constant for all flowrates of V_d and V_c for any given rotor speed below flooding.
Kung and Beckman (11)	$\frac{V_d}{X} + k_1\ (\frac{V_c}{1 - X}) = V_N\ (1 - X)$ where $k_1 = 2.1$ for $\frac{D_s - D_r}{D_c} \leqslant \frac{1}{24}$ $k_1 = 1.0$ for $\frac{D_s - D_r}{D_c} > \frac{1}{24}$	15.24	
Strand et al. (5)	$\frac{V_d}{X} + \frac{V_c}{1-X} = C_R V_N\ (1 - X)$	15.24, 106.68	C_R = minimum constriction factor dependent on the column geometry.
Misek (8,9)	$\frac{V_d}{X} + \frac{V_c}{1-X} = V_N\ (1-X)\ \exp\left[(\frac{Z}{\alpha} - 4.1)X\right]$ $Z = 1.52x10^{-2} \left[\frac{D_c \rho_c}{\mu_c} (\frac{\sigma}{\rho_c d_c})^{0.5}\right]^{0.5}$ $\alpha = f\ (d_o \cdot V_N \rho_c / \mu_c$	25.0, 50.0	z = coalescence correlation factor α = backmixing correlation factor d_o = mean drop size.
Kasatkin et al. (14)	$X = 1.58 \left[\frac{ND_r}{V_c}\right] \left[\frac{V_d}{V_c}\right]^{0.96} \left[\frac{D_s^2 - D_r^2}{D_c^2}\right]^{-0.7}$ $\left[\frac{H}{H_c}\right]^{-0.426} \left[\frac{\Delta\rho}{\rho_c}\right]^{-1.31} \left[\frac{\rho_c V_c D_c}{\mu_c}\right]^{-0.13}$ $\left[\frac{\rho_c D_c V_c^2}{\sigma}\right]^{0.245} \left[\frac{V_c^2}{g_c D_c}\right]^{0.96}$	5.4	D_c = effective column diameter. $De = D_s - D_r$ H_c = total column height.

Table 3 (continued)

Correlations of Dispersed Phase Hold-up and Characteristic Velocity in an RDC

Author and Reference	Correlation	RDC diameter D_c cm	Remarks
Murakomi et al. (15)	$X = 3.3 \left[\frac{N D_r}{V_c}\right]^{0.55} \left[\frac{V_d}{V_c}\right]^{0.8} \left[\frac{D_s^2-D_r^2}{D_c^2}\right]^{-0.3} \left[\frac{H}{D_c}\right]^{-0.66} \left[\frac{D_r}{D_c}\right]^{0.4} \left[\frac{\Delta\rho}{\rho_c}\right]^{-0.13} \left[\frac{\rho_c D_c V_c^2}{\sigma}\right]^{0.18} \left[\frac{V_c}{g_c D_c}\right]^{-0.6}$	7.9, 10.5, 30.0	
	Characteristic Velocity Correlation		
Logsdail et al. (12)	$\frac{V_N \mu_c}{\sigma} = 0.012 \left[\frac{\Delta\rho}{\rho_c}\right]^{0.9} \left[\frac{g_c}{D_r N^2}\right]^{1.0} \left[\frac{D_s}{D_r}\right]^{2.3} \left[\frac{H}{D_r}\right]^{0.9} \left[\frac{D_r}{D_c}\right]^{2.7}$	2.3 7.62	
Kung and Beckmann (11)	$\frac{V_N \mu_c}{\sigma} = k \left[\frac{\Delta\rho}{\rho_c}\right]^{0.9} \left[\frac{g_c}{D_r N^2}\right]^{1.0} \left[\frac{D_s}{D_r}\right]^{2.3} \left[\frac{H}{D_r}\right]^{0.9} \left[\frac{D_r}{D_c}\right]^{2.6}$	2.3 15.24	$k = 0.0225$ for $\frac{D_s-D_r}{D_c} \leq \frac{1}{24}$ $k = 0.012$ for $\frac{D_s-D_r}{D_c} > \frac{1}{24}$
Laddha et al. (1)	$V_N = 0.01 \left[\frac{\sigma\Delta\rho g_c}{\rho_c}\right]^{1/4} \left[\frac{g_c}{D_r N^2}\right]^{1.0} \left[\frac{\sigma^3\rho_c}{\mu_c^4 g}\right]^{1/4} \left[\frac{\Delta\rho}{\rho_c}\right]^{0.6} \left[\frac{H}{D_r}\right]^{0.9} \left[\frac{D_s}{D_r}\right]^{2.1} \left[\frac{D_r}{D_c}\right]^{2.4}$	7.62 10.0	

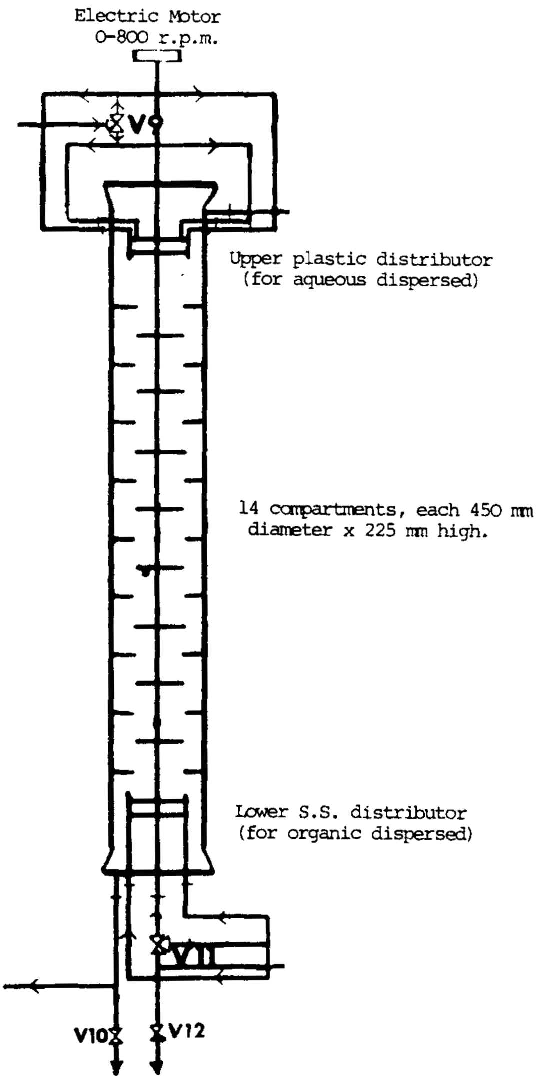

FIGURE 1. General Arrangement of Rotating Disc Contactor.

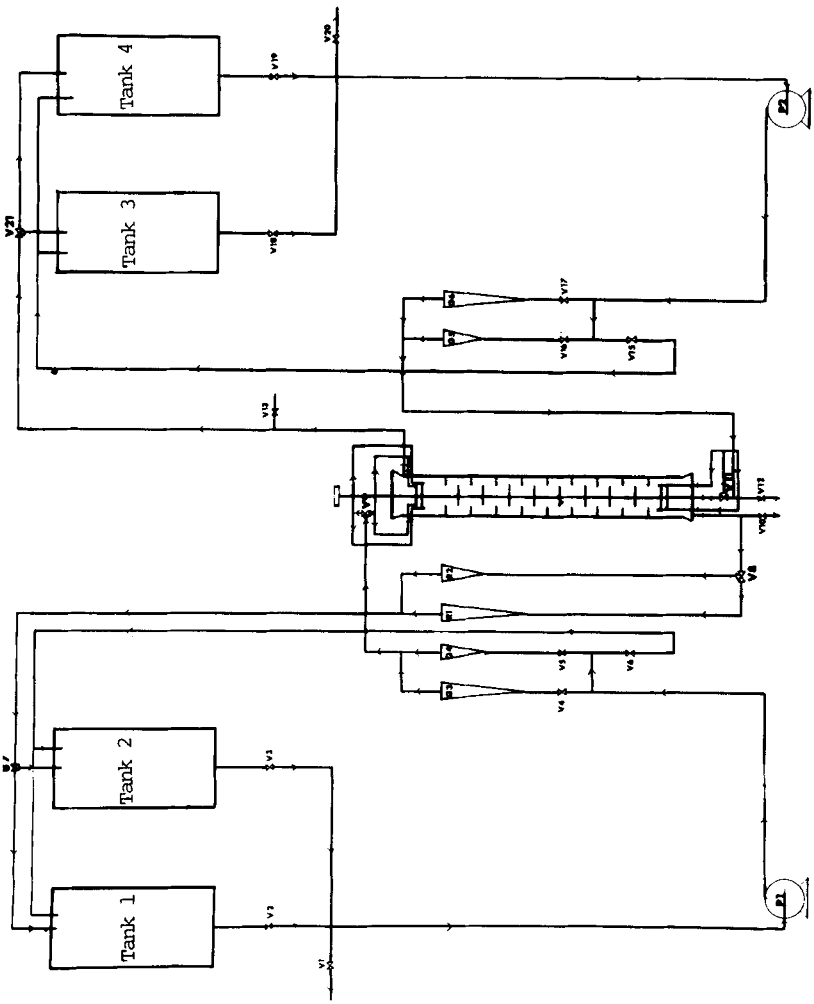

FIGURE 2. Flow Diagram.

The column was assembled from Q.V.F. glass sections and the internals and end flanges were made of stainless steel. The rotor was driven by a 185 watt motor whose speed was controlled by a gear box over the range 0-800 r.p.m. The speed of rotation was measured by an electronic tachometer in association with a photo-electric probe focussed onto a mark on the shaft at the top of the column. Four 2.0 metre^3 stainless steel tanks were installed as feed and solvent reservoirs and the liquid-liquid system studied was Clairsol-350 and water. The physical properites of Clairsol 350, a paraffinic hydrocarbon solvent with a distillation range of 205 to 230^{o}C are:

density - 0.783 gm/cc

kinematic viscosity - 2.112 cs

interfacial tension - 39.2 dyne/cm

The water was filtered Birmingham tap water.
In the experiments reported here water constituted the continuous phase, so that the rotors were non-wetted with respect to the dispersed phase (10).

Experimental Method

i) Drop Size and Drop Size Distribution

The phases were mutually saturated prior to each run by extended recirculatio through the equipment. Preliminary observations confirmed that, as reported by other workers (8,10,29), drop size and drop size distribution were greatly affected by continuous phase flow rate. Therefore observation and photography of the droplet phenomena and drop size in the absence of mass transfer were carried out with a constant continuous phase flow rate. A Nikkarmat 35 mm still camera together with appropriate lighting by a 1000 watt quartz-iodine lamp and Ilford 400 ASA films were employed to photograph the dispersed phase; the aperture opening, shutter speed and focal length were adjusted according to the lensometer reading. In most cases a shutter speed of 1/1000 sec was sufficient. For each experiment two or three photographs were taken for each compartment, after steady state operation had been attained. The criterion for steady state was taken to be a steady interface in the top phase separation section, indicative of a constant rate of arrival of drops within a given distribution; this was usually attained within 10 minutes after any change in the operating conditions.

Drop size measurements were made from photographic prints with approximately a 2x magnification using a Carl-Zeiss Particle Size Analyser TG.Z.3 when 200 drops were counted in each photograph.

ii) Dispersed Phase Hold-Up

The average value of the dispersed phase hold-up was determined by operating the column at the desired conditions until steady state had been reached; then the inlet and outlet valves were simultaneously closed (8,12,14,15) and the agitator stopped and complete phase separation was allowed to take place. The average hold-up was then determined from the change in the position of the interface. Experiments were performed at dispersed phase flowrates in the range 0.2 litres/sec to 2.0 litres/sec with a constant continuous flowrate of 0.5 litres/sec and agitator speeds 0-300 r.p.m. and the results obtained are summarised below.

Results and Discussion

i) Drop Size and Size Distribution

Typical experimental results of the variation of drop size along the column at different rotor speeds are presented in Figure 3 (these are in terms of d_{32} defined in equation (2). They demonstrate that the drop size changed rapidly in the first four compartments and a stable drop size was not attained after fourteen compartments when the agitator speed was 300 r.p.m. All the drop size results obtained from this study have been correlated by equation 7 obtained by regression of a dimensional analysis,

$$\frac{d_{3.2}}{D_r} = 5.52\times10^{-8} \left[\frac{V_d H \rho_c}{\mu_c X}\right]^{1.14} \left[\frac{N^2 \rho_c D_r^3}{\sigma}\right]^{-0.14} \left[\frac{V_d^2}{c D_c X_2}\right]^{-0.38} \left[\frac{n}{N_c}\right]^{0.06} \qquad (7)$$

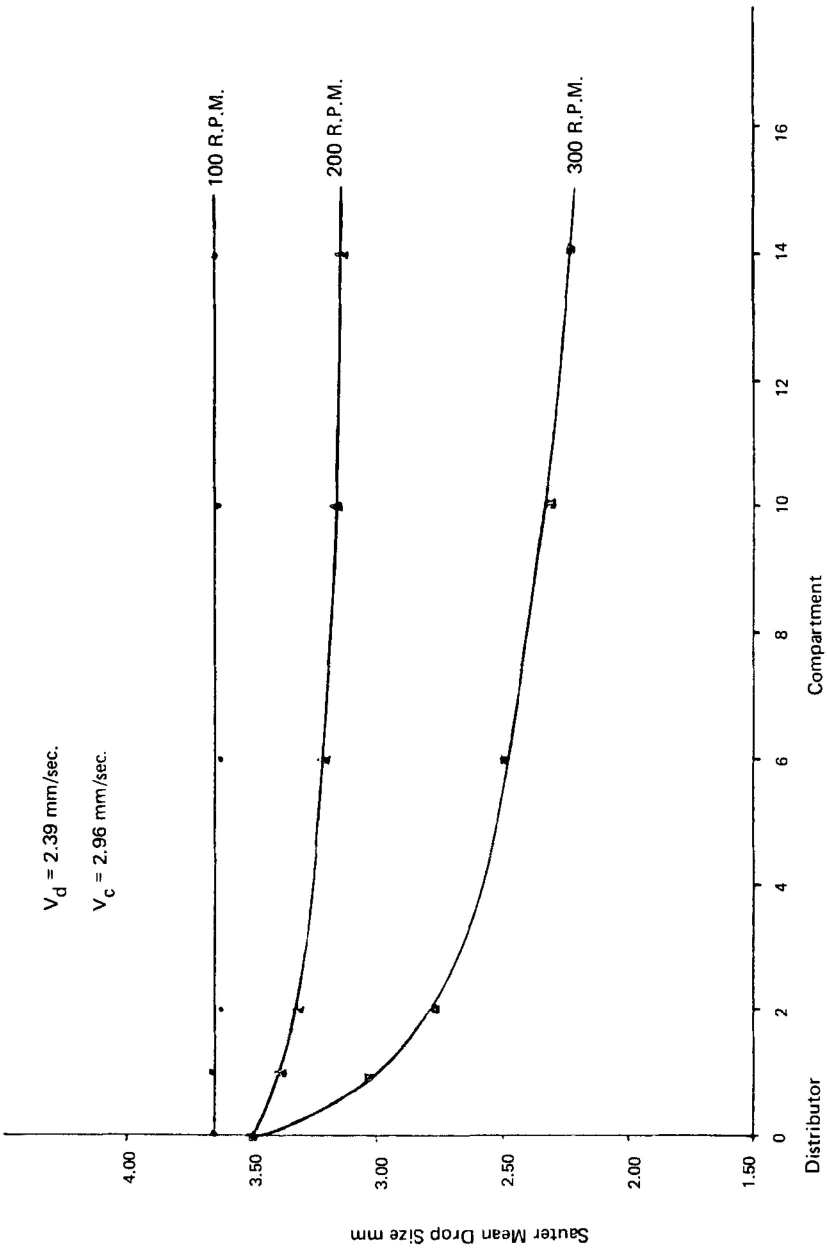

FIGURE 3. Drop Size Profile Along Column.

The results obtained are shown in Figure 4 where it was found that the average percentage error was 8% with the experimental results and 68% of the results were within ± 10% of equation 7 and 87% within ± 15%.

The results obtained from this study were also compared with those reported previously from studies on small extraction columns (23,28) of up to 10.0 cm diameter, and large differences have been observed. However by extending the dimensional analysis in equation 7 to include the column dimensions the following correlation was obtained,

$$\frac{d_{3.2}}{D_r} = 1.48\left[\frac{V_d H \rho_c}{\mu_c X}\right]^{-0.23}\left[\frac{N^2 D_r^3 \rho_c}{\sigma}\right]^{-0.004}\left[\frac{V_d}{g_c D_c X^2}\right]^{0.44}\left[\frac{\Delta\rho}{\rho_c}\right]^{-0.57}\left[\frac{H}{D_c - D_s}\right]^{-0.24}\left[\frac{n}{N_c}\right]^{-0.07} \quad (8)$$

Equation 8 was applied to all the results available and it was found that the average percentage error between the experimental drop size and those predicted by equation 8 was 17%. Further 64% of the results were within ± 15% and 78% within ± 25% as shown in Figure 5.

The drop size cummulative volume curve for compartment No.14 for two rotor speeds, viz 200 r.p.m. and 300 r.p.m., is given in Figure 6. These were chosen arbitrarily from all of the data for all the compartments and at many different rotor speeds to check the drop-size distributions. From this graph $d_{10}:d_{50}$ and d_{90} were determined and the upper limit distribution parameters d_m, a' and δ were calculated by applying the equations (27) proposed by Mugele and Evans and these are plotted in Figures 7 and 8.

$$\frac{d_m}{d_{50}} = \frac{d_{50}(d_{50} - d_{10}) - 2d_{90}d_{10}}{d_{50}^2 - d_{50}d_{10}} \quad (9)$$

$$a' = \frac{d_m - d_{50}}{d_{50}} \quad (10)$$

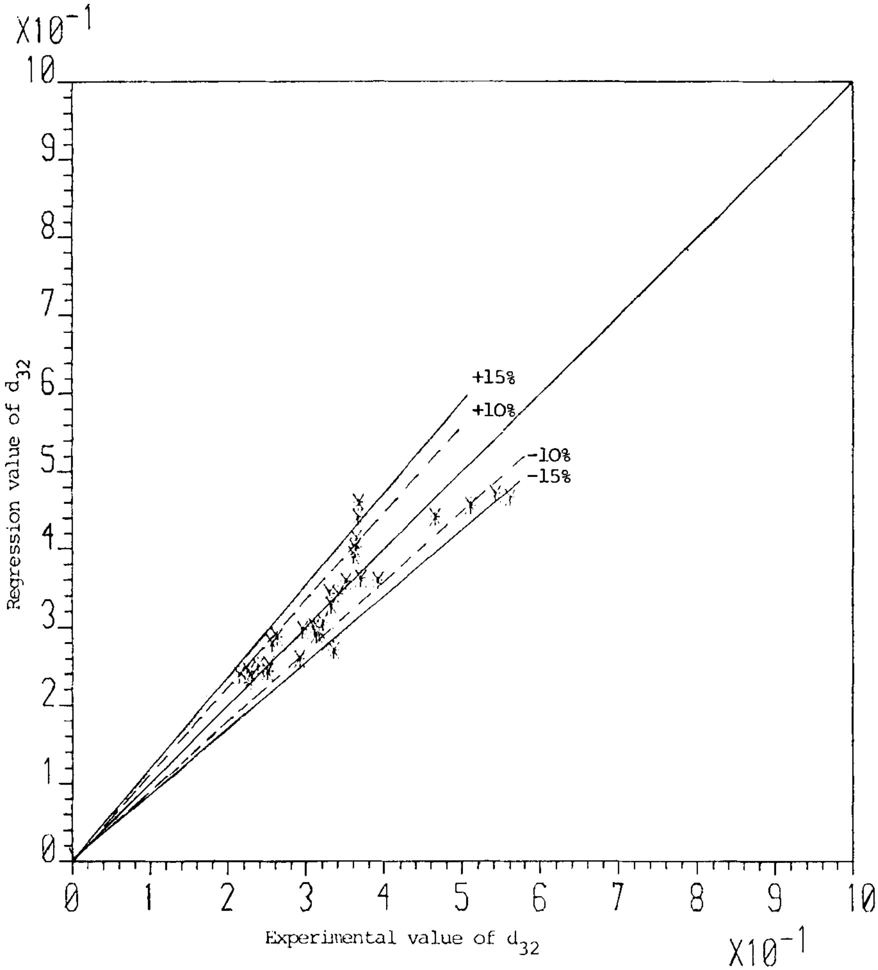

FIGURE 4. Correlation of Experimental d_{32} Data with Equation 7.

$$\delta = \frac{0.907}{\ln\left(\frac{d_{90}}{d_m - d_{90}} \cdot \frac{d_m - d_{50}}{d_{50}}\right)} \tag{11}$$

These distributions are in excellent agreement with the experimental volume drop size and the upper limit density distributions with the parameters, for

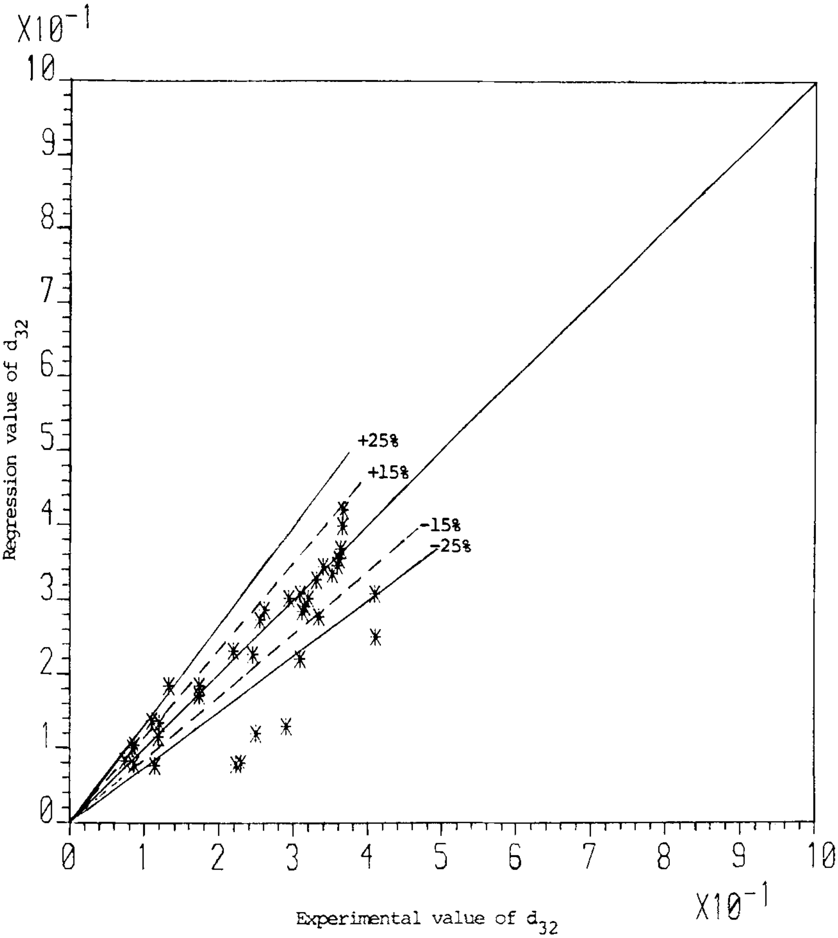

FIGURE 5. Correlation of Experimental d_{32} Data with Equation 8.

the chosen samples of the data. This agreement is confirmed by comparing d_{32} for the data calculated from equation 12

$$d_{32} = \frac{\Sigma n_i d_i^3}{\Sigma n_i d_i^2} \qquad (12)$$

and d_{32} from the upper limit distribution which is calculated (27) from equation 13 by Mugelle and Evans

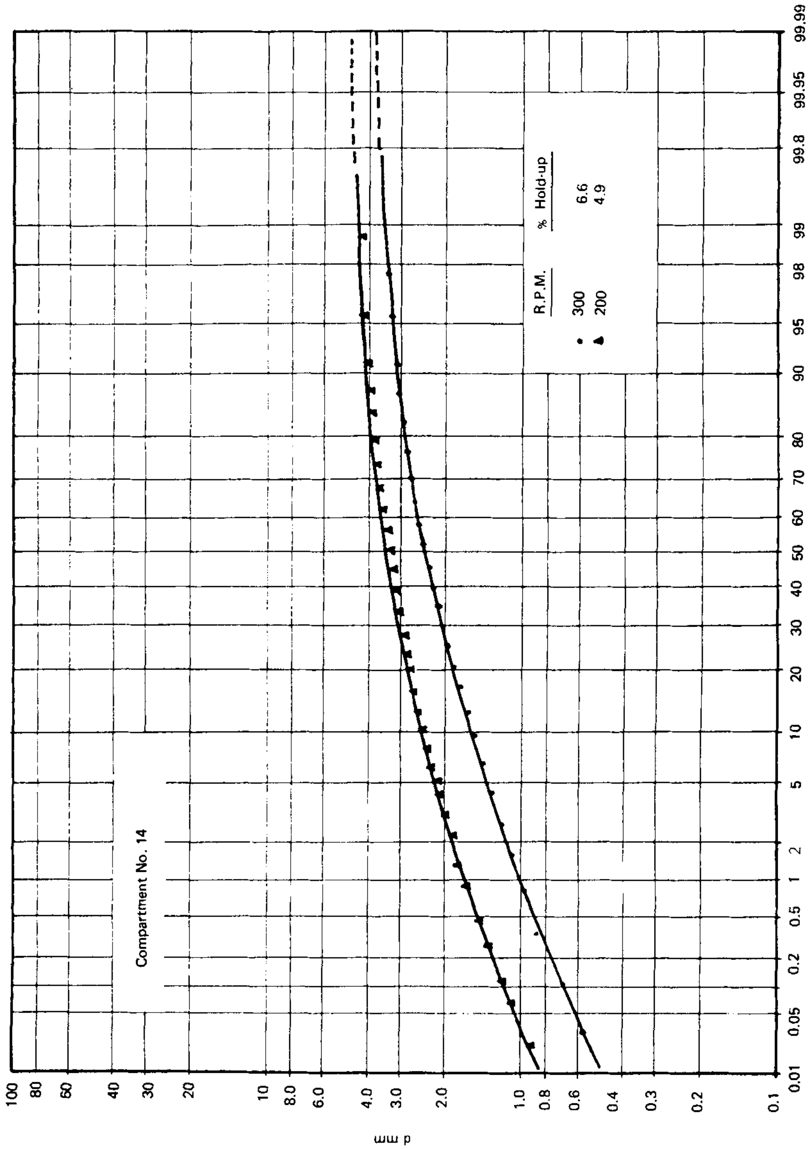

FIGURE 6. Drop Size Distribution for Compartment 14 at Different Rotor Speeds.

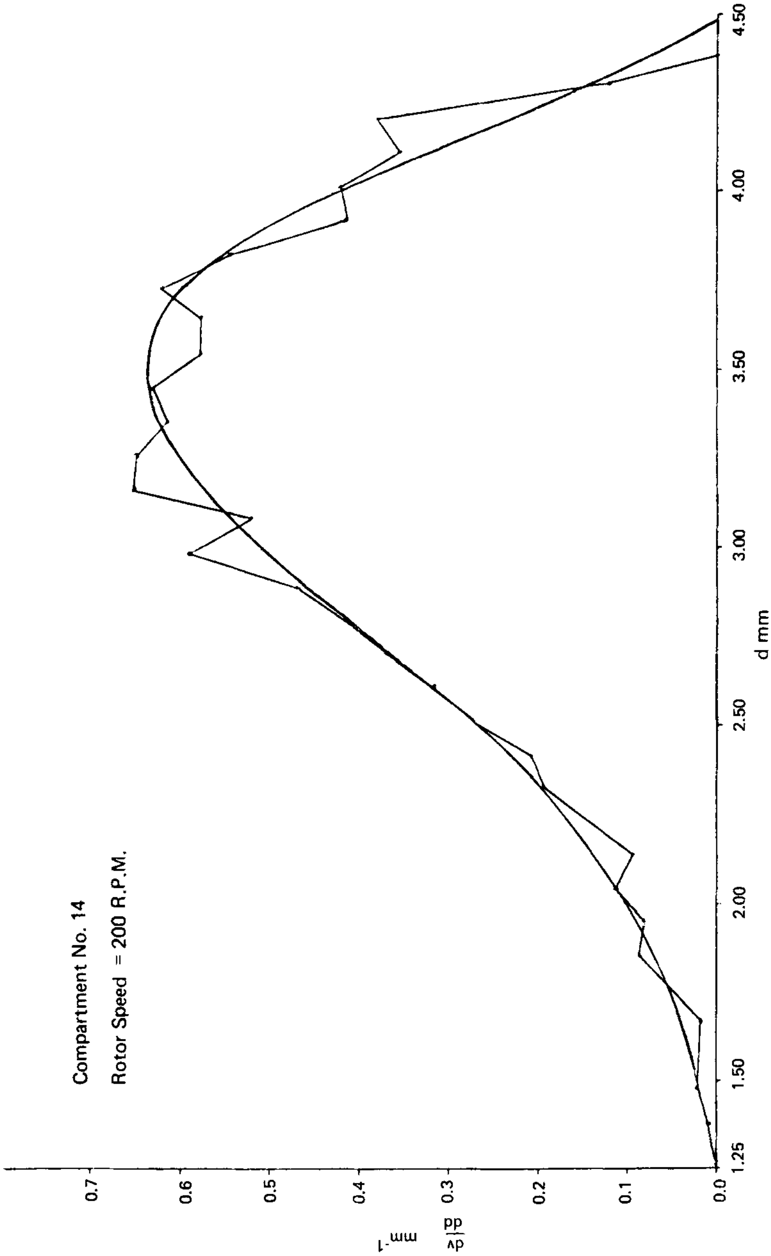

FIGURE 7. Comparison of Experimental Drop Size Distribution at 200 r.p.m. with Density Distribution.

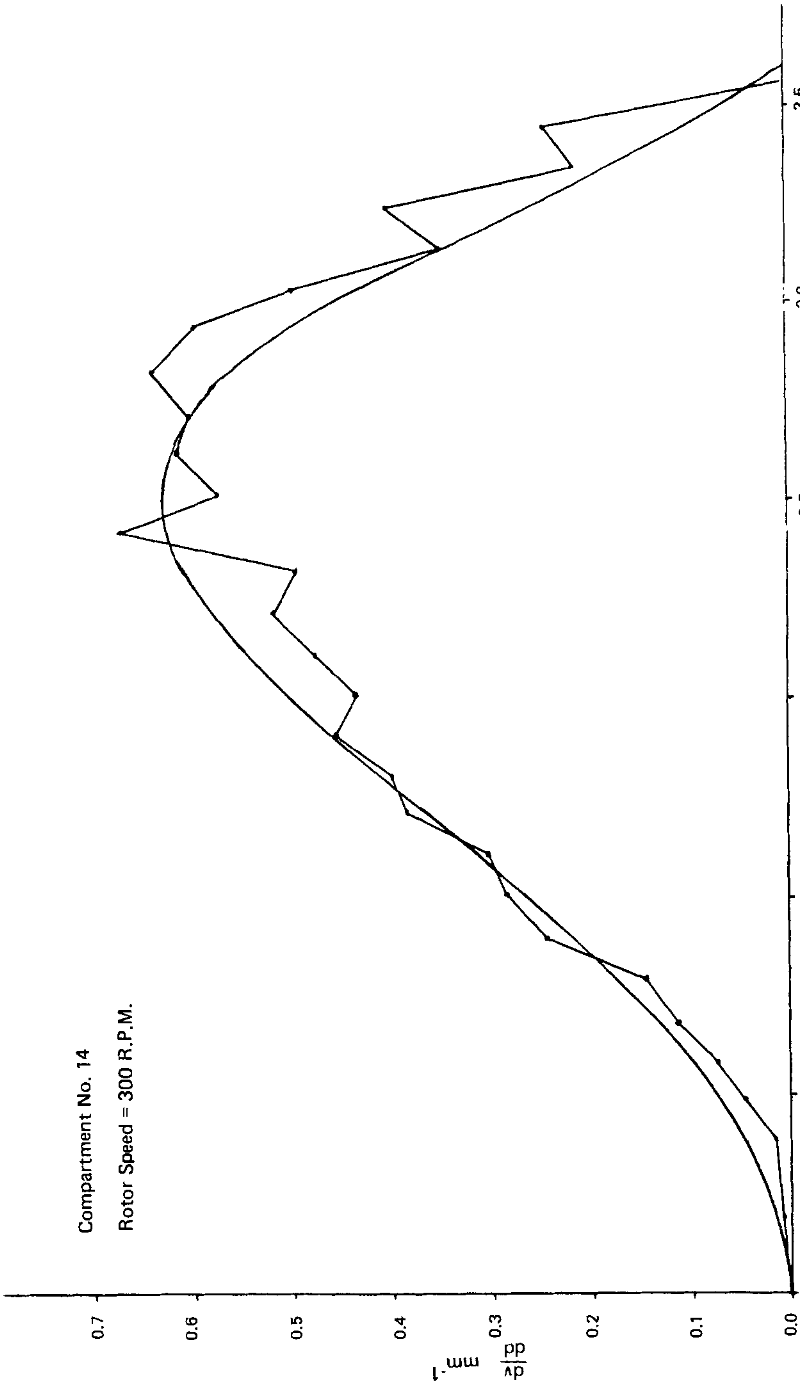

FIGURE 8. Comparison of Experimental Drop Size Distribution at 300 r.p.m. with Density Distribution.

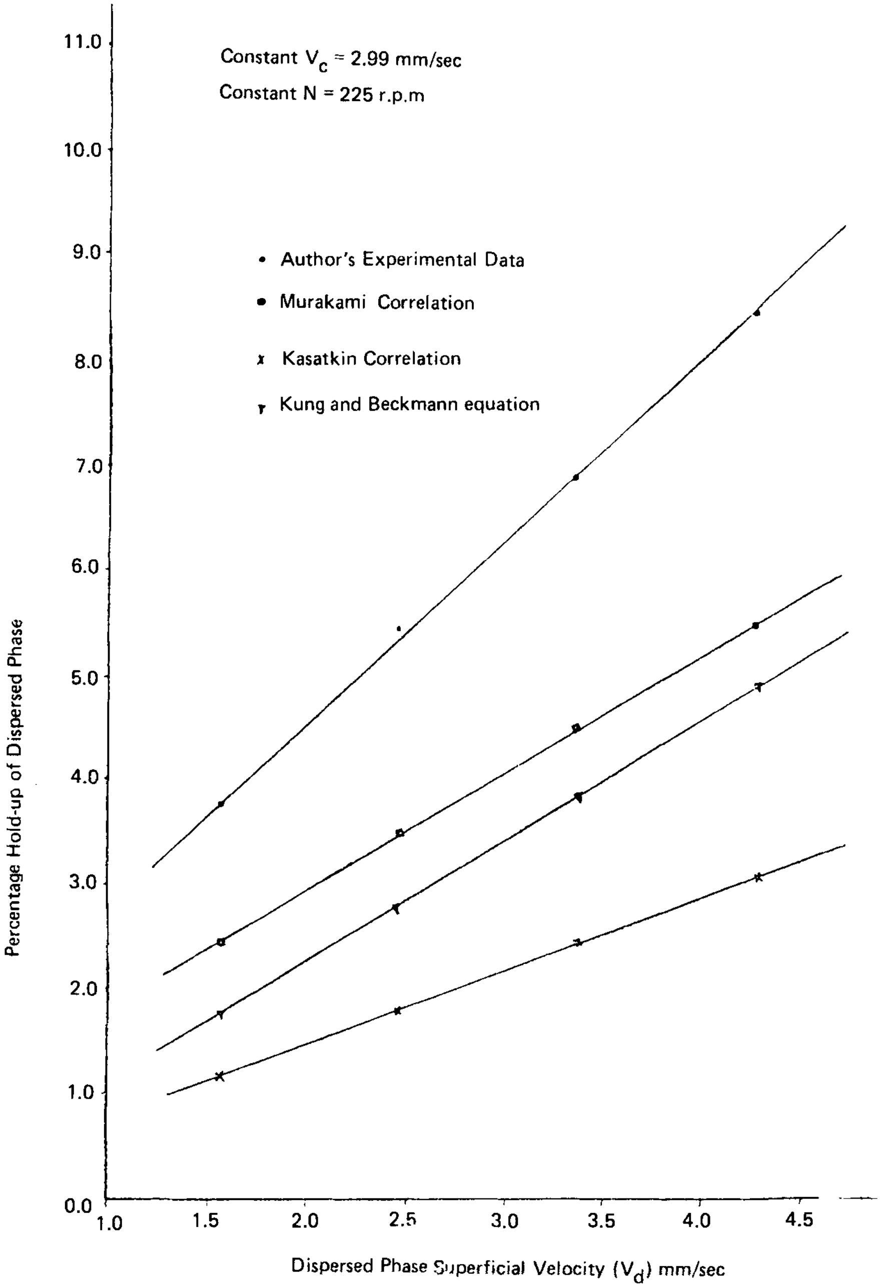

FIGURE 9. Experimental and Predicted Values of Hold-up. (Predicted values by substitution in equations - Table 3.)

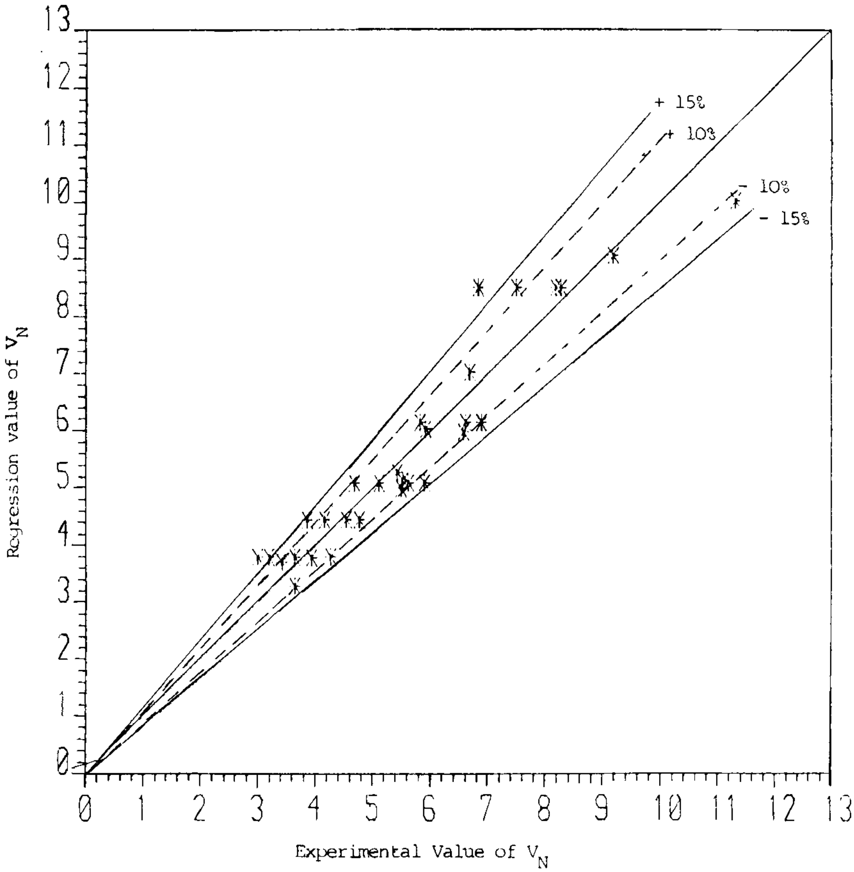

FIGURE 10. Correlation of Experimental V_N Data with Equation 15.

$$d_{32} = \frac{d_m}{1 + a\dot{e}} 0.25^{\delta^2} \qquad (13)$$

The deviation of d_{32} from that of d_{32} is 5.2% at 200 r.p.m. and 3.6% at 300 r.p.m.

ii) Dispersed Phase Hold-up

All the correlations proposed to calculate the dispersed phase hold-up in an RDC have been compared with the experimental data of this study and great divergences have been found as shown in Figure 9.

The dispersed phase hold-up has in the past been analysed in one of two ways. In the first the hold-up is considered to be a function of the characteristic velocity V_N; secondly the hold-up has been correlated by dimensional analysis.

In the first method it was assumed that equation 14 (1, 12, 15)

$$\frac{V_d}{X} + \frac{V_c}{1 - X} = V_N\ (1-X) \tag{14}$$

is applicable to an RDC, and studies were directed to the production of a more accurate correlation for V_N as a function of the physical properties of the system and the column geometry. Since all the correlations previously published were based on results obtained from columns of small diameter the values of V_N obtained for the column used in this study were used to test equation 14. That is the characteristic velocities were calculated from the above equation for each measured value of the hold up X at set values of V_d and V_c. Then V_N was correlated by equation 15 obtained by dimensional analysis.

$$\frac{V_N \mu_c}{\sigma} = 6.24\times10^{-3} \left[\frac{\Delta\rho}{\rho_c}\right]^{0.783} \left[\frac{g_c}{D_r N^2}\right]^{0.234} \left[\frac{D_s}{D_r}\right]^{1.778} \left[\frac{H}{D_r}\right]^{1.362} \left[\frac{D_r}{D_c}\right]^{1.922} \tag{15}$$

Correlation of V_N for the data of this study shows an average percent error of only 8.8% between the experimental and predicted results, and 64.5% of the data were within ± 10% and 90.3% within ± 15%. The comparison between the predicted value of V_N and the experimental value is presented in Figure 10. Some of the published data (11,12) for small RDC's have again been analysed together with the results of this work and a correlation produced with an average percent error equal to 13.4%. The correlation is

$$\frac{V_N \mu_c}{\sigma} = 6.24\times10^{-3} \left[\frac{\Delta\rho}{\rho_c}\right]^{-0.941} \left[\frac{g_c}{D_r N^2}\right]^{0.205} \left[\frac{D_s}{D_r}\right]^{1.601} \left[\frac{H}{D_r}\right]^{0.689} \left[\frac{D_r}{D_c}\right]^{1.786} \tag{16}$$

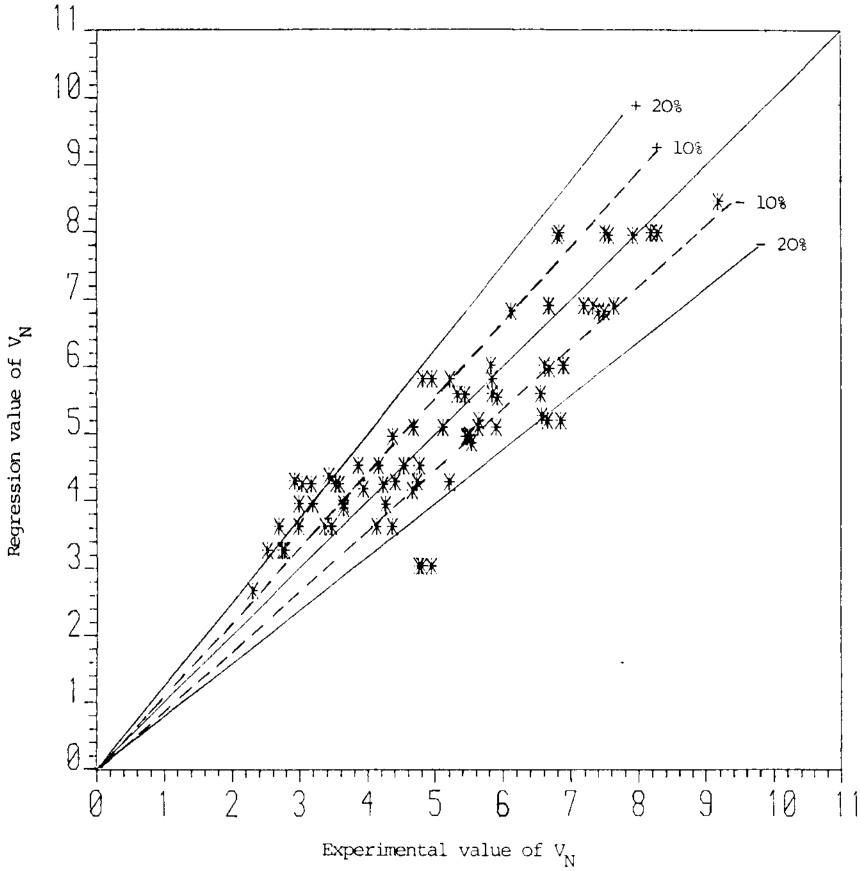

FIGURE 11. Correlation of Experimental V_N Data with Equation 16.

50.7% of the data were correlated within ± 10% and 81.8% of the data were correlated with ∓ 20%. The average percent error of the data of this work was within ± 10%. Figure 10 gives a comparison between the predicted value and the experimental value of V_N.

In the second method hold-up was correlated as a function of the physical properties of the system, the column geometry and the power input to the rotors and equation 17 has been derived by dimensional analysis (14,15)

$$X \alpha \left[\frac{ND_r}{V_c}\right]^a \left[\frac{V_d}{V_c}\right]^b \left[\frac{D_s^2-D_r^2}{D_c}\right]^c \left[\frac{H}{D_c}\right]^d \left[\frac{D_r}{D_c}\right]^e \left[\frac{\Delta\rho}{\mu_c}\right]^f \left[\frac{\rho_c D_c V_c^2}{\sigma}\right]^g \left[\frac{V_c^2}{gD_c}\right]^h \left[\frac{\rho_c V_c D_c}{\mu_c}\right]^i \qquad (17)$$

Multilinear least square computer regression was applied to estimate the values of the exponents using the data of this work as well as previous reported data. The resulting correlation is represented by equation 18 for which the average percent error was found to be 14.0%.

$$X = 1.05\times10^{14} \left[\frac{ND_r}{V_c}\right]^{0.521} \left[\frac{V_d}{V_c}\right]^{0.775} \left[\frac{D_s^2-D_r^2}{D_c}\right]^{-0.187} \left[\frac{H}{D_c}\right]^{-0.873} \left[\frac{D_r}{D_c}\right]^{-0.201} \left[\frac{\Delta\rho}{\sigma_c}\right]^{4.843} \left[\frac{\rho_c D_c V_c^2}{\sigma}\right]^{1.082} \left[\frac{V_c^2}{gD_c}\right]^{0.892} \left[\frac{\rho_c V_c D_c}{\mu_c}\right]^{-2.367} \qquad (18)$$

72.1% of the data were correlated within 15% and 81.7% within 20%. The average percent error of the data of this work only is 9.0% and a comparison between the predicted values of X and the experimental values is shown in Figure 12.

Conclusions

i) Drop Size and Drop Size Distribution

All the previously proposed equations and correlations to estimate drop size in small RDC's lead to wide divergences when applied to large diameter contactors. The equations proposed from this study extend the range of correlations for drop size up to industrial scale columns. In addition the drop size profile can be estimated by applying the correlations presented. The effect of rotor speed upon the drop size and upon the drop size distribution are clearly shown by Figures 3, 6, 7 and 8 and the experimental drop size

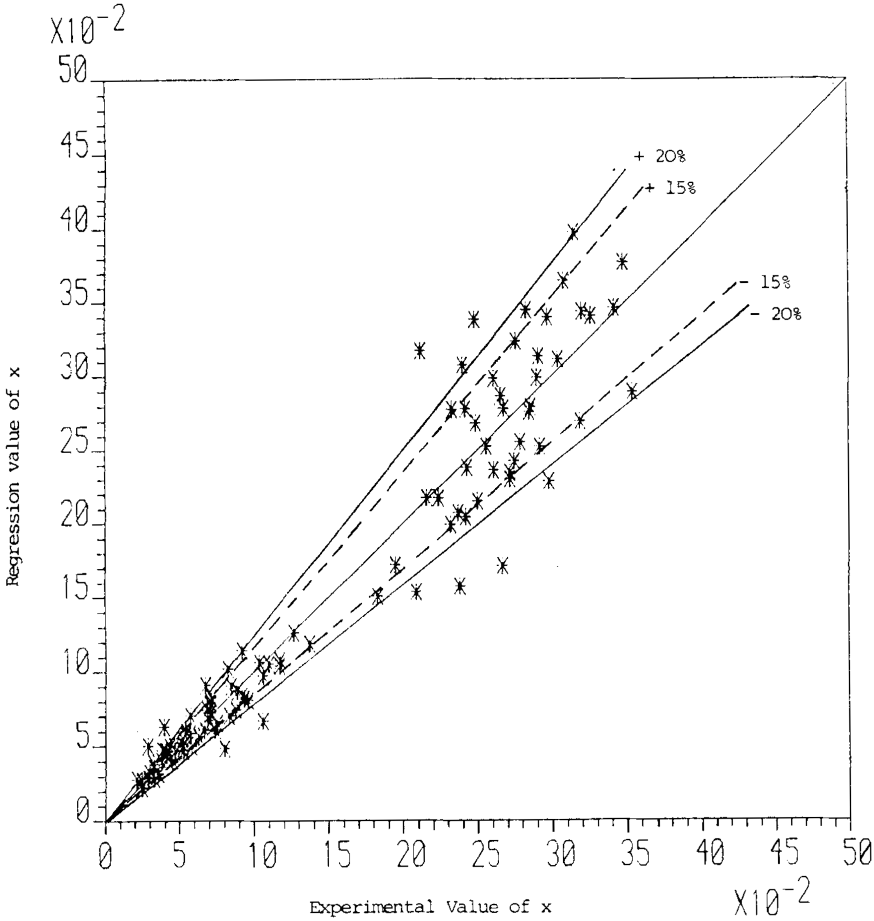

FIGURE 12. Correlation of Experimental Hold-up Data with Equation 18.

distributions are in excellent agreement with the upper limit log-normal distributions which should be used in preference to other functions.

ii) Dispersed Phase Hold-up

Comparison of the predicted values of the dispersed phase hold-up and the experimental values gave unsatisfactory results as shown in Figure 9 because most of the correlations proposed are derived from data obtained in small scale columns. The correlations proposed by this study to correlate the characteristic velocity, equations 15 and 16, give very good results irrespective of column size.

However the hold-up in any RDC is more accurately correlated by the dimensional analysis correlation, equation 18.

In conclusion the correlations presented should, when used as part of an established design procedure (30), result in more precise design of columns for commercial duties.

Nomenclature

a' = distribution parameter (skewness parameter)

C_1 = correlation constant

d_o, d = drop diameter

d_{max}, d_m = maximum drop size

d_{vg} = geometric mean drop diameter

d_{32} = volume-surface, or Sauter mean drop diameter

D_c = column diameter

D_r = disc diameter

D_s = stator ring opening

E = power input per unit mass

g_c = acceleration due to gravity

H = compartment height

L = characteristic dimension of turbulence

n = compartment number or number of drops

N = rotor speed

N_c = total number of compartments

P = power input

$r_{s.d}$ = radius of a stable drop

v = volume of fraction of drops

V = superficial velocity

V_N = characteristic velocity; i.e. the mean vertical droplet velocity at substantially zero flowrates ($V_c = 0$, $V_d \rightarrow 0$) and rotor speed N.

X = fractional hold-up of the dispersed phase

Greek Letters

γ = surface tension

δ = uniformity distribution parameter

μ_c = viscosity of continuous phase

ρ_c = density of continuous phase

σ = interfacial tension

Subscripts

c = continuous phase

d = dispersed phase

i = fraction of drops of size d_i

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