International Journal of Technology (2015) 1: 31-43
ISSN 2086-9614

MEAN DROP DIAMETER IN A ROTATING SIEVED DISC CONTACTOR

Fatemeh Behzad[1*], Hossein Bahmanyar[1], Hoda Molavi[2], Setareh Manafi[1]

[1]*Surface Phenomena and Liquid-Liquid Extraction Research Laboratory, School of Chemical engineering, University College of Engineering, University of Tehran, Enghelab Ave, 11365-4563, Iran*
[2]*Niroo Research Institute, Shahid Dadman St., Tehran, 1468617151, Iran*

(Received: March 2013 / Revised: March 2014 / Accepted: September 2014)

ABSTRACT

A correlation has been proposed for mean drop diameter in a Rotating Sieved Disc Contactor (RSDC) considering drops break up, as well as drops coalescence with static holdup in the case of no mass transfer. The proposed correlation is a function of a number of stages, rotating speed in the form of Reynolds number, static hold-up and mother drop size. The effects of the last two terms have not been considered by other researchers. Therefore, the results are compared with two reported correlations to show how these two important terms influence the size of drops. Distilled water was used as a continuous phase and toluene was applied as a dispersed phase in the experiments. The absolute average relative error and standard deviation for the correlation were 14.74% and 10.08%, respectively.

Keywords: Hold-up; Mean drop diameter; Rotating sieved disc contactor

1. INTRODUCTION

The rotating disc contactor is a mechanically agitated column that was first invented by the Royal Dutch/Shell group (Reman & Olney, 1955). In comparison with the other types of columns like packed and spray column, its preference is because of low power consumption, high flexibility in operation and easy maintenance (Kamath & Subba, 1985; Laddha & Degaleesan, 1976). In fact, most of the countercurrent flow models were not applicable in the design of Rotating Sieved Disc Contactor in an industrial scale (Wang et al., 2002).

Krishnaiah et al. (1967) suggested that sieved discs were more suitable for systems of low interfacial tension. Further analysis shows how perforations on discs break the drops and disperse them in a RSDC. It seems that the RSDC has better mass transfer efficiency and controllability in comparison with the Rotating Disc Contractor (RDC) (Soltanali & Ziaie-Shirkolaee, 2007). Determination of mean drop size has an important role on the design of liquid-liquid extraction columns. As the studies have revealed, many determining parameters are dependent upon the drop size including the capacity of the RDC (Laddha & Degaleesan, 1976), velocity of the drop, interfacial area and mass transfer coefficient (Chang-Kakoti et al., 1985; Pratt & Stevens, 1992; Kumar & Hartland, 1996).

Kirou et al. (2004) have surveyed the effects of rotating speed on the mean drop diameter in a water-toluene system and showed that it has a great influence on the drop size and drop distribution. Besides the above mentioned parameters, it seems that number of stages (Kagan et al., 1964) and hold-up (Kadam et al., 2009) should be taken into consideration. Static hold-up can affect the droplet size, which is a key variable in liquid–liquid extraction affecting both

[*] Corresponding author's email: fatemeh_behzad1387@yahoo.com, Tel. 00982161112213, Fax. 00982166967788
Permalink/DOI: http://dx.doi.org/10.14716/ijtech.v6i1.779

hydrodynamics and mass transfer rate. In fact, drops may have coalescence with static hold-up which result in drops with bigger sizes (Molavi et al., 2011). As a matter of fact, the precise calculation of drop size distribution would help define a proper design and performance for the RDC. There are various devices for measuring the drop size in the extraction column. Two of these instruments are Laser particle analyzer (Ibrahim & Maloka, 2003; Al-Rahawi, 2007; Simmons et al., 2000) and photographic techniques with high speed camera which are applied by Cruz Pinto et al. (1983). The second technique is used in this research work just to measure the drop size.

1.1. Drop Size Measurements

As mentioned in the previous section photographic techniques are more precise than the other techniques, so this technique was used for measuring drop diameter in the column. Drop diameters were recorded at different positions of the column (the space between two valves) and different rotational speeds for available chemical systems. From these photographs the reading of the diameter of the drops was commenced with the software Autocad2007. Using an optional reference on the picture like the shaft axis diameter, a simple proportional relationship between these two values would be produced and then the relative real size of the drops would be achieved. An amount of 6–13 drops were monitored for each position in order to increase the accuracy. A total amount of 60 drops were read in the experiment. Since the drops in the middle and top of the column were exposed to major changes in diameter, the data were analyzed from the second valve to the top. The drops were of elliptical shape. The area for the elliptical drops was calculated from the following equation (Laddha & Degaleesan, 1976):

$$A = \frac{\pi}{2}\left[d_H{}^2 + \frac{d_V d_H}{\left(e^2 - 1\right)} \ln\left(e + \sqrt{e^2 - 1}\right)\right] \quad (1)$$

$$e = \frac{d_H}{d_V} \quad (2)$$

where A is the drop area, e is the drop inertia; d_v and d_H are the vertical and horizontal diameter of the drop, respectively. In order to find an equivalent drop area, a modified equation, was applied:

$$\frac{A}{A_e} = \frac{1}{2}\left[e^{\frac{2}{3}} + \frac{1}{e^{\frac{1}{3}}\sqrt{e^2 - 1}} \ln\left(e + \sqrt{e^2 - 1}\right)\right] \quad (3)$$

Finally, the equivalent drop diameter was calculated from the following equation:

$$A_e = \pi d_e{}^2 \rightarrow d_e = \left(\frac{A_e}{\pi}\right)^{\frac{1}{2}} \quad (4)$$

The mean drop diameter was calculated from Equation (7) (Chakra borty et al., 2003).

$$d_{32} = \frac{\sum n_i d_i^3}{\sum n_i d_i^2} \quad (5)$$

where n_i is number of drops with a diameter of d_i in a certain experiment.

1.2. Holdup

There are three types of holdup. 1) Static holdup is the ratio of the volumes of the dispersed phase trapped under rotors and stators to the column's active volume consisting of the volume of the dispersed phase plus the continuous phase. 2) Dynamic holdup is the ratio of the volume of the dispersed phase that crosses the column active height and is gathered during the continuous phase of the column active volume. 3) Total holdup is the sum of static and dynamic holdups.

Since the static holdup is available throughout the column especially under stators, it has the most influence on the size of the crossing drops and this kind of holdup is used in this research for presenting the correlation.

Dispersed phase holdup can be expressed by volumetric fraction of two phases as follows (Treybal, 1963):

$$\Phi = \frac{\nu_d}{\nu_d + \nu_c} \tag{6}$$

In this research, the sauter means the drop diameter that is reported for one chemical system in a Rotating Sieved Disc Contactor. It is correlated as a function of the rotational speed, the number of stages, the dispersed phase hold-up and mother drop size. The results are discussed and compared with two available correlations proposed by other researchers in which none of them have considered the effects of holdup and mother drop size on the mean drop diameter.

Sprough (1967) proposed the following correlation for d_{32} in the RDC:

$$d_{32} = \frac{\gamma^{0.6}}{\rho_c^{\ 0.6} D_R^{\ 0.8} N^{1.2}} \tag{7}$$

Kagan et al. (1964) correlated the mean drop size based on Reynolds and Froude numbers:

$$d_{32} = 16.7\,\mathrm{Re}^{-0.3}\, Fr^{-0.3} n^{-0.23} \left(\frac{\gamma}{g\rho_c} \right)^{0.5} \tag{8}$$

2. EXPERIMENTAL

2.1. Chemical System

One chemical system, including the distilled water as the stagnant continuous phase and toluene as the dispersed phase, was used in this work. Table 1 shows the physical properties of the system.

Table 1 Physical properties of the chemical systems at T=25 ºC

Materials	Name	ρ_c $\left(Kg/m^3\right)$	ρ_d $\left(Kg/m^3\right)$	$\mu_c \times 10^{-3}$ $(pa.s)$	$\mu_d \times 10^{-3}$ $(pa.s)$	$\gamma \times 10^{-3}$ $\left(N/m\right)$
Toluene-water	W-T	996	860	0.87	0.55	28

2.2. Device

A schematic diagram of the rotating sieved disc contactor is depicted in Figure 1. The central rotating shaft equipped with sieved discs is arranged at an equal distance. The discs are located in the middle of each compartment which is defined as the space between two stators. The column, rotors and stators are made of glass and stainless steel, respectively. Tables 2 and 3 show the main dimensions and sampling positions of the RSDC which are used in this work, respectively.

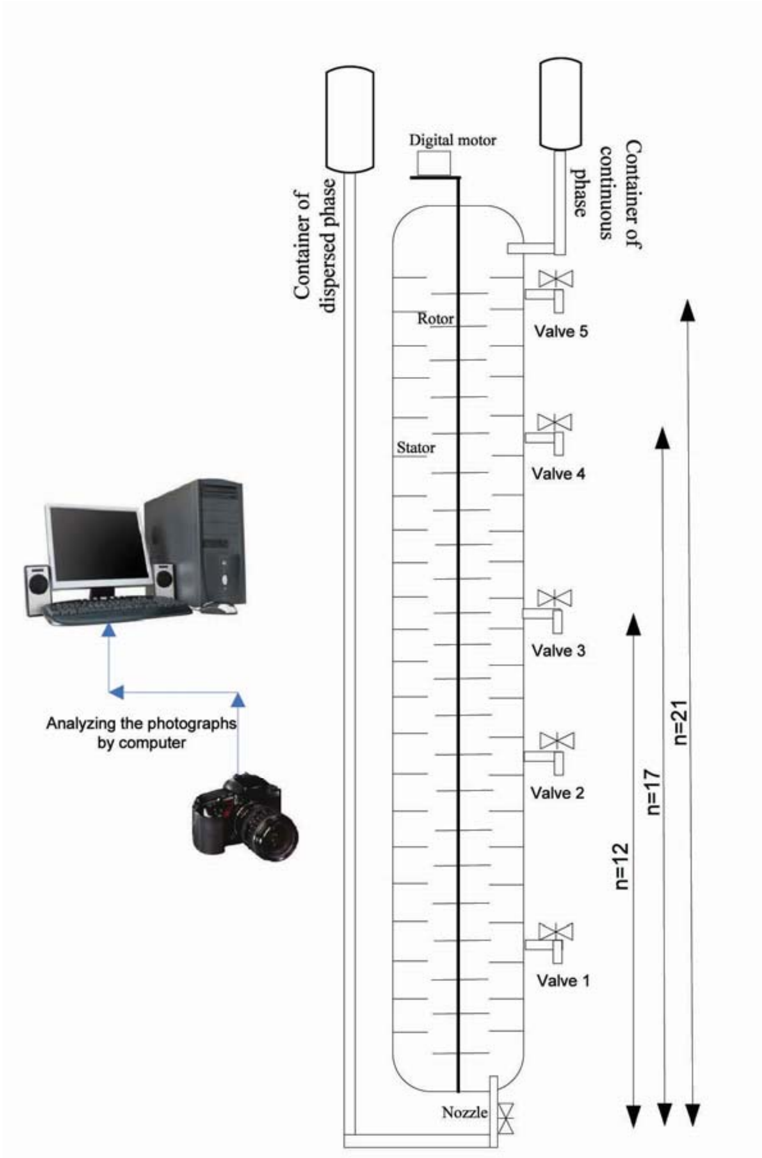

Figure 1 Schematic diagram of RSDC

Table 2 Main dimensions of the RSDC

Component	Value
Inner diameter of column (mm)	91
Inner diameter of stator (mm)	61
Outer diameter of rotor (mm)	45.5
Hole diameter on rotor (mm)	3
Compartment High (mm)	27.8
Disc thickness (mm)	1
Shaft diameter (mm)	14
Column height (m)	1.20

Table 3 Sampling positions of the RSDC

Number of stages	Column active height (mm)	Number of valves
Up to the fifth valve	685	21
Up to the forth valve	545	17
Up to the third valve	405	12

2.3. Methods

In the first step and in order to ensure no mass transfer between phases, distilled water saturated with toluene is used as a continuous phase and toluene saturated with distilled water is used as a dispersed phase. Then, after filling the entire column with the continuous phase, single droplets of the dispersed phase were fed to the column through a nozzle which was installed at the bottom of the column. Afterward, the motor was turned on to rotate the rotary discs and induce turbulence in the system. The experiment was repeated at 3 different rotating speeds, 1.25, 2.5, 3.75 rps, respectively. Droplet movement was monitored with photographs. At the end of each experiment the motor was turned off, the nozzle was closed and samples of the dispersed phase which had accumulated below the rotors and stators (holdup) were collected through the sampling valves.

3. RESULTS AND DISCUSSION

There are two phenomena which affect the size of drops: Breakage and Coalescence. Some factors such as rotating speed and number of stages cause the drops to break. Also there are two other parameters, namely mother drop size and holdup which could lead to the formation of the drops with bigger sizes and moderate the effects of breakage phenomena.

3.1. Proposed Correlation

In order to reach accurate correlations, the dimensionless ratio of the mean drop size to rotor diameter has been outlined as a function of the number of stages, rotating speed in the form of Reynolds number, liquid static hold-up and dimensionless ratio of mother drop diameter to compartment height using datafit9 software.

$$\frac{d_{32}}{D_R} = 1.9 \times 10^6 \times \left(\frac{d_{320}}{H_S}\right)^{2.86} n^{-0.73}\,\mathrm{Re}^{-0.7}\,\Phi^{0.93} \tag{9}$$

The mother drop diameter is a drop exactly exiting from the nozzle. In Figure 2 the dimensionless mean drop diameter is shown for the proposed correlation of the calculated values versus experimental data. The Absolute Average Relative Error (AARE) and standard deviation (σ) are 14.74% and 10.08% respectively.

$$AARE = \frac{1}{N'}\sum_{i=1}^{N'}\left|\frac{y_{\exp}(i) - y_{pred}(i)}{y_{\exp}(i)}\right| \tag{10}$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N'}\left[\left|\frac{y_{\exp}(i) - y_{pred}(i)}{y_{\exp}(i)}\right| - AARE\right]^2}{N' - 1}} \tag{11}$$

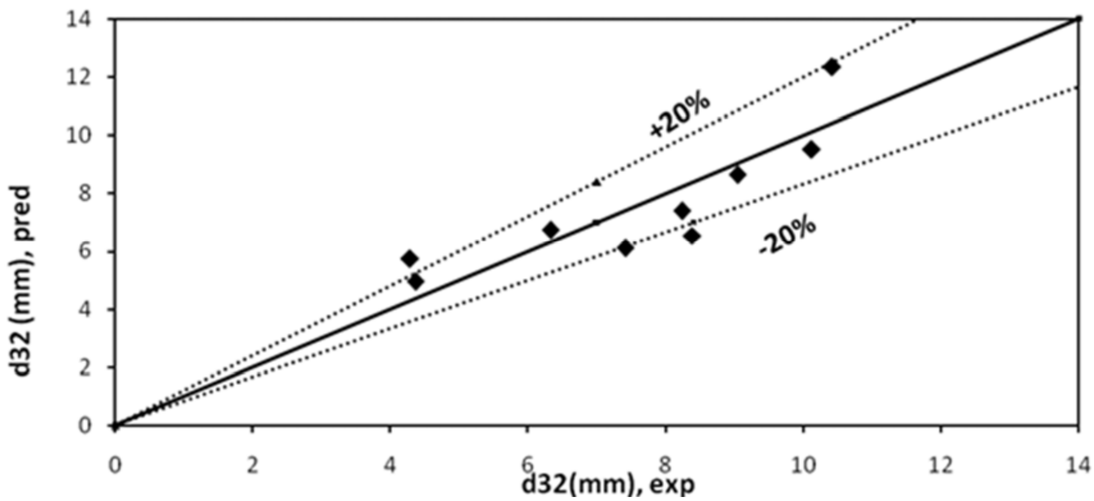

Figure 2 Predicted mean drop diameter versus experimental mean drop diameter for water-toluene system

3.2. The effect of rotating speed and number of stages on mean drop diameter

Figure 3 depicts the mean drop size versus rotating speed at three different stages of the column for experimental and predicted data. As the figure shows in the constant stages the drops show a decreasing trend with an increase in the rotating speed. On the other hand, as the rotating speed increases, the probability of drops contact with obstacles like rotors and stators increases and then the size of drops decreases as a result of the breakage phenomena. The second factor that causes the drops to break is the number of stages which is defined as the number of rotors up to each valve. Figure 4 shows the mean drop diameter versus the number of stages at three constant rotating speeds and mother drop sizes for experimental and calculated values. Increase in the number of stages cause the drops to cross longer distances throughout the column and consequently the probability of their contact with obstacles and formation of the smaller drops increases as well.

3.3. The effect of holdup and mother drop size on mean drop diameter

The presence of static holdup in the column means drops would coalesce with the trapped liquids under rotors and stators and make bigger drops. Figure 5 shows one drop in two cases: 1) a drop coalesces with the holdup gathered on the stator 2) after coalescing with holdup the creation of a separate drop occurs. The mother drop is the drop that is generated from the nozzle.

Due to its high velocity during exiting from the nozzle, its changes in diameter are almost negligible up to the second valve and the main changes in its diameter happen from the second valve on. A bigger mother drop diameter after coalescence with holdup would produce drops with bigger diameter. Figures 6 and 7 show the effects of holdup and mother drop diameter on mean drop diameter, respectively. In addition, the experimental and predicted data for mean drop diameter for three constant numbers of stages versus mother drop diameter, holdup and rotating speed have been shown at the end of the paper.

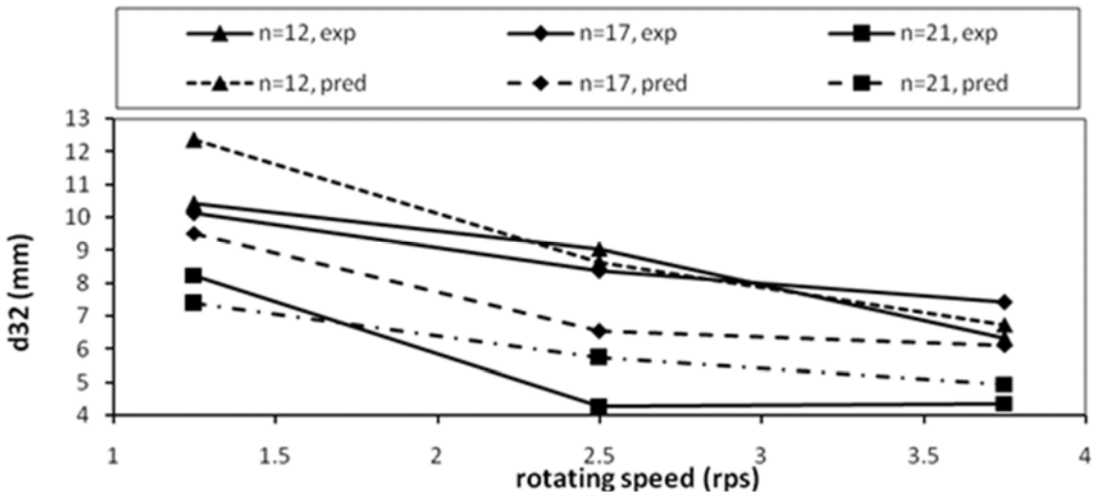

Figure 3 Mean drop diameter versus rotating speed for experimental and predicted values

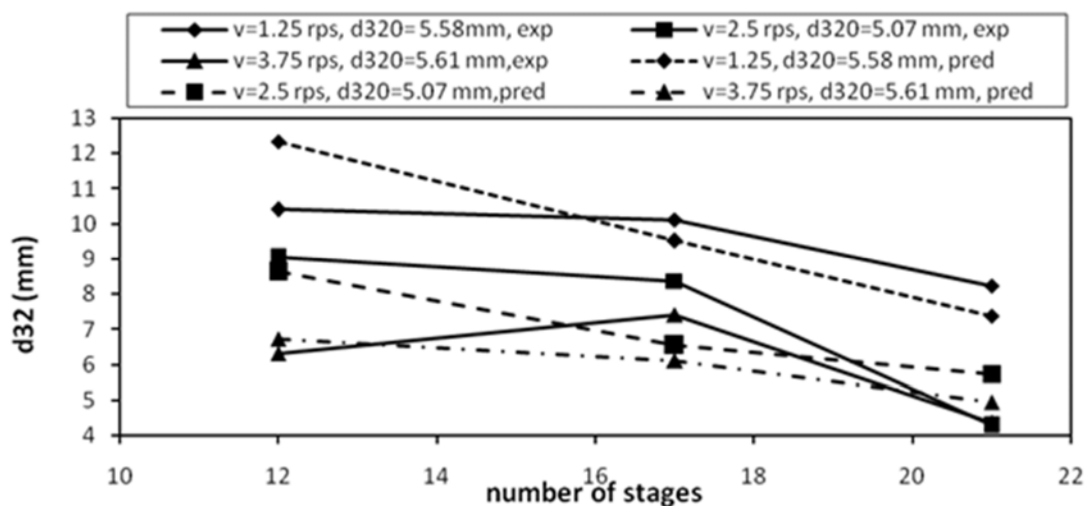

Figure 4 Mean drop diameter versus number of stages for experimental and predicted values

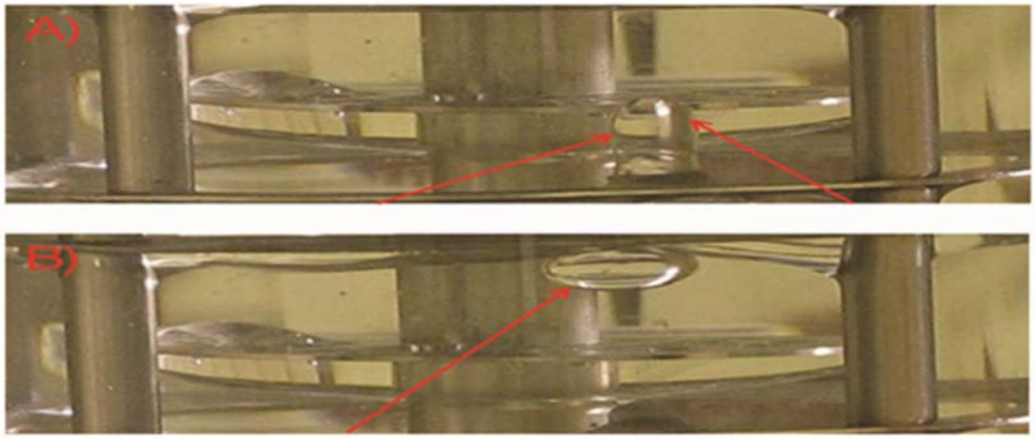

Figure 5 Drop in two cases: a) Coalescing with holdup; b) After coalesce with holdup

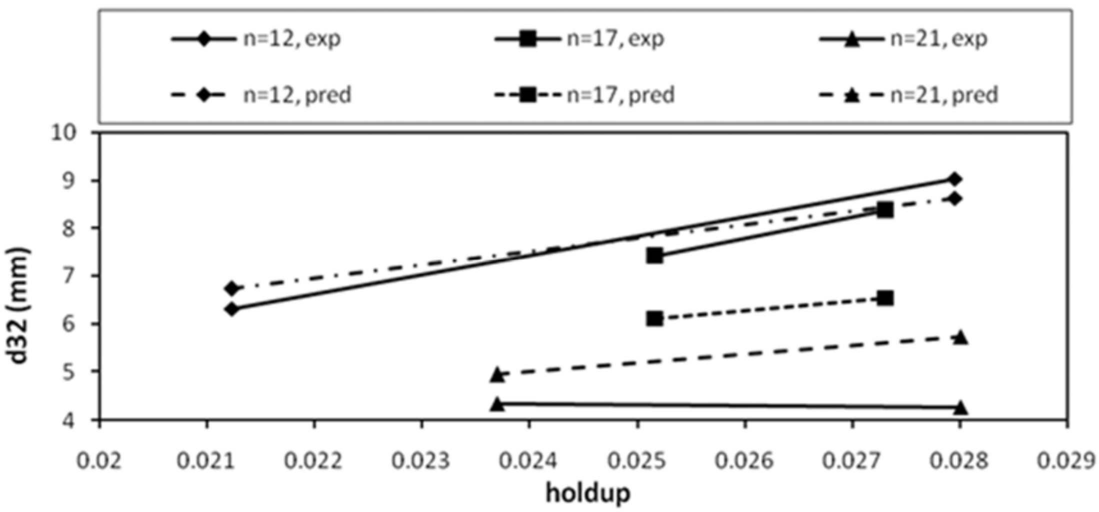

Figure 6 Mean drop diameter versus holdup

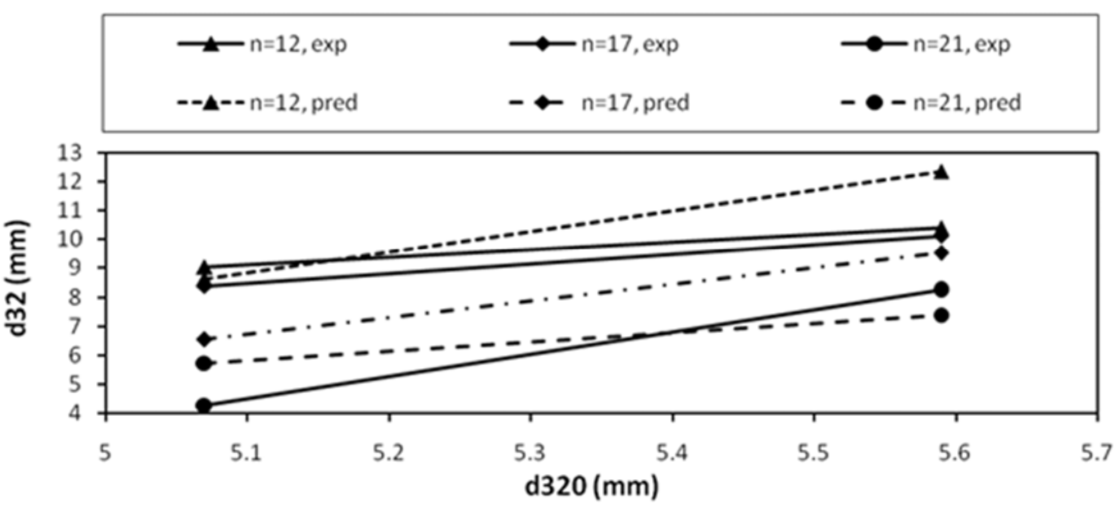

Figure 7 Mean drop diameter versus mother drop size

3.4. Comparison of the New Correlation with Two Reported Correlations

Two reported correlations have been chosen to be compared with the new correlation. Both researchers have worked on the Rotating Disc Contactor which is similar with the device used by the present work. The results of this comparison have been shown in Figures 8 and 9. The predicted mean drop diameter versus rotating speed for two different mother drop sizes through the correlations proposed by Sprough and Kagan occur, as well as the experimental mean drop diameters that have been delineated in these two figures. All diagrams have a decreasing trend. The experimental drops are bigger in size than those predicted by the other correlations. None of the previous works has taken into account the effects of holdup and mother drop diameter on their correlations, so they are not in agreement with our experimental data. The relation between the mother drop, the mean drop size and the holdup is taken into account in our previous works (Molavi et al., 2011). As it was stated before, the holdup and mother drop size would enhance the diameter of drops and moderate the effects of the breakage phenomena.

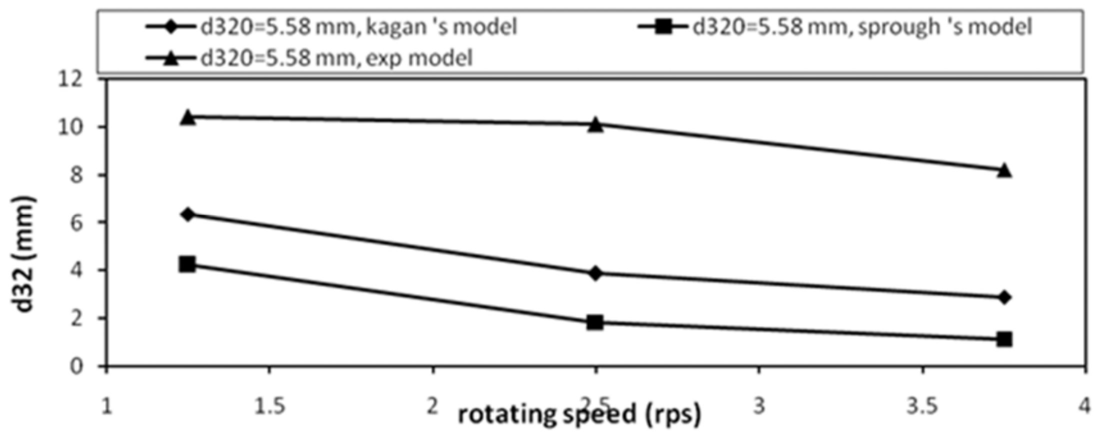

Figure 8 Mean drop diameter vs. rotating speed compared with other correlations for mother drop size=5.58 mm

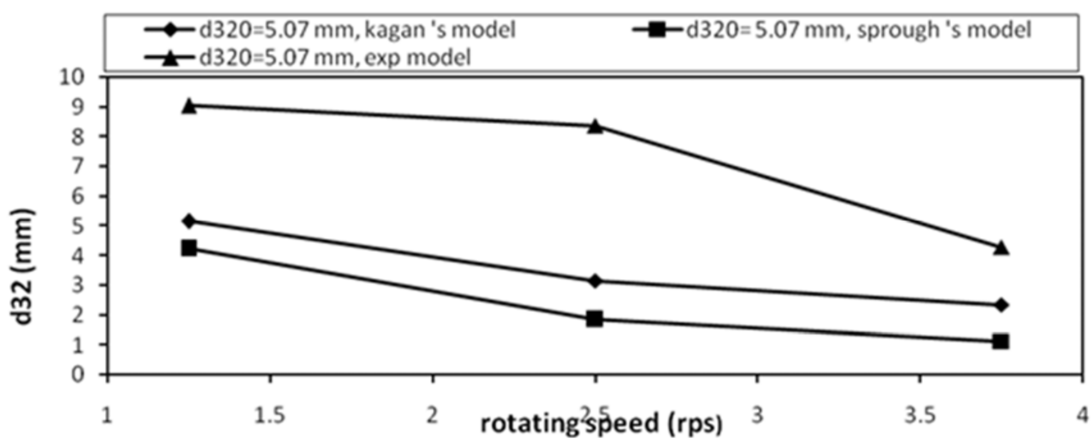

Figure 9 Mean drop diameter vs. rotating speed compared with other correlations for mother drop size=5.07 mm

Table 4 The effects of the mother drop diameter on predicted and experimental mean drop diameter in the constant number of stages (n)

n	d320 (mm)	d32, exp	d32, pred
12	5.07	9.03	8.63
	5.58	10.41	12.34
17	5.07	8.37	6.54
	5.58	10.11	9.51
21	5.07	4.28	5.73
	5.58	8.23	7.38

Table 5 The effects of holdup on predicted and experimental mean drop diameter in the constant number of stages (n)

n	Φ	d32, exp	d32, pred
12	0.021	6.32	6.73
	0.028	9.03	8.63
17	0.025	7.41	6.12
	0.027	8.37	6.54
21	0.023	4.36	4.95
	0.028	4.28	5.73

Table 6 The effects of rotating speed on predicted and experimental mean drop diameter in the constant number of stages (n)

n	Rotating speed (rps)	d32, exp	d32, pred
12	1.25	10.41	12.34
	2.5	9.03	8.63
	3.75	6.31	6.73
17	1.25	10.11	9.51
	2.5	8.37	6.54
	3.75	7.41	6.12
21	1.25	8.23	7.38
	2.5	4.28	5.73
	3.75	4.36	4.95

4. CONCLUSION

The effects of mother drop diameter, liquid static hold-up, number of stages and rotating speed (in the form of Reynolds number) on mean drop diameter were studied experimentally in a rotating sieved disc contactor for one chemical system: Water-Toluene system. Toluene as dispersed phase and water as continuous phase was used in this research. Holdup and mother drop size enhanced the size of drops and caused the drops to coalesce with liquids gathered under rotors and stators in contrast to the number of stages and rotating speed which caused the drops to break due to contact with obstacles inside the column. According to the figures in the constant number of stages, the drops show a decreasing trend with an increase in the rotating speed. In addition, an increase in the number of stages causes the drops to cross longer distances throughout the column and the probability of their contact with obstacles and the formation of the smaller drops increases as well. Bigger mother drop diameter after coalescence with holdup would produce drops with a bigger diameter. As a result, one correlation has been proposed for the dimensionless form of the mean drop diameter and the effects of all the above factors have been taken into consideration in the form of dimensionless numbers. The results were discussed and compared with two correlations proposed by Sprough and Kagan which has the same condition with the present work. Since none of the researchers have considered the effects of static holdup and mother drop size in their correlations, the diagrams relevant to the experimental values are superior to the two predicted diagrams. It implies that static holdup and mother drop diameter moderate the effects of the breakage phenomena.

5. ACKNOWLEDGEMENT

Special thanks to Mr. Mohammad Oliayee and Ms. Melody Dehdasht and Ms Ezzat Zahedi for their help in correcting and editing the language of the manuscript.

Nomenclature

A	Area of elliptical drop	(mm^2)
A_e	Equal sphere area	(mm^2)
AARE	Absolute average relative error	(-)
D_R	Rotor diameter	(mm)
d_{320}	Average mother drop size	(mm)
d_{32}	Mean drop diameter	(mm)
d	Drop diameter	(-)
e	Drop inertia	(-)
$Fr = \frac{N^2 D_R}{g}$	Froude number	(-)
g	Acceleration due to gravity	(m/s^2)
H_s	Compartment height	(m)
n	Number of stages	(-)
N	Rotating speed	(rps)
N'	Numerator in Eq 10,11	
$Re = \frac{N D_R^2 \rho_C}{\mu_C}$	Reynolds number	(-)
Greek letters		
Φ_L	Liquid static holdup	(-)
ρ	Density	(kg/m^3)
$\Delta\rho$	Density difference	(kg/m^3)
γ	Interfacial tension	(N/m)
μ	Viscosity	(Pa.s)
σ	Standard deviation	(-)
Subscripts		
c	Continuous phase	
d	Dispersed phase	
e	Equal	
H	Horizontal	

V	Vertical
exp	Experimental value
pred	Predicted value

6. REFERENCES

Al-Rahawi, A.M.I., 2007. New Predictive Correlations for the Drop Size in a Rotating Disc Contactor Liquid-Liquid Extraction Column, *Chemical Engineering & Technology*, Volume 30(2), pp. 184–192

Chakra borty. Bhattacharya, M.C., Datt S., 2003. Effect of Drop Size Distribution on Mass Transfer Analysis of the Extraction of Nickel (II) by Emulsion Liquid Membrane, *Physicochemical & Engineering Aspects*, Volume 224, pp. 65–74

Chang-Kakoti, D.K., Fei, W.Y., Godfrey. J.C., Slater, M.J., 1985. Drop Sizes and Distributions in Rotary Disc Contactors Used for Liquid-Liquid Extraction, *Separation and Processing Technology*, Volume 6(27), pp. 40–48

Cruz-Pinto, J.J.C., Korchinsky, W.J., Al-Husseini, R., 1983. Mass Transfer to Non-uniform Dispersions in Countercurrent Flow Liquid-Liquid Extraction Columns, *In Proceedings of ISEC 83*, American Institute of Chemical Engineering, Denver, Conference, USA

Ibrahim, S.Y., Maloka, I.E., 2003. Physical Properties of Aqueous N-Methyl Pyrrolidone at Different Temperatures, *Petroleum Science & Technology*, Volume 22(11–12), pp. 1571–1579

Kadam, B.D., Joshi, J.B., Koganti, S.B., Patil, R.N., 2009. Dispersed Phase Hold-up, Effective Interfacial Area and Sauter Mean Drop Diameter in Annular Centrifugal Extractors. *Chemical Engineering Research & Design*, Volume 87(10), pp.1379–1389

Kagan, S.Z., Aerov, M.E., Volkova, T.S., Trukhanov, V.G., 1964. Calculation of the Drop Diameter in Rotary Disc Extractors. *Journal of Applied Chemistry*. USSR (Engl. Transl.), Volume 37, pp. 67–73

Kamath, M.S., Subba Rau, M.G., 1985. Prediction of Operating Range of Rotor Speeds for Rotary Disc Contactors, *Canadian Journal of Chemical Engineering*, Volume 63(4), 578–584

Kirou, V.I., Tavlarides, L.L., Bonnet, J.C., 2004. Flooding, Holdup & Drop Size Measurement in Multistage Column Extractor, *Tsouris, AIChE J*. Volume 34(2), pp. 283–292

Krishnaiah, M.M., Pai, M.U., Rao, M.V.R., Sastri, S.R.S., 1967. Performance of a Rotating Disk Contactor with Perforated Rotors. *British Chemical Engineering*, Volume 12, pp. 719–721

Kumar, A., Hartland, S., 1996. Unified Correlations the Prediction of Drop Size in Liquid-Liquid Extraction Column. *Industrial & Engineering Chemistry Research*, Volume 35(8), pp. 2682–2695

Laddha, G.S., Degaleesan, T.E., 1976. *Transport Phenomena in Liquid-Liquid Extraction*, McGraw Hill Company, New York.

Molavi, H., Hoseinpoor, S., Bahmanyar, H., Shariaty-Niasar, M., 2011. Investigation on Local and Average Static Hold-ups in Liquid-Liquid Systems in a Rotary Disc Contactor. *Canadian Journal of Chemical Engineering*. Volume 89(6), pp. 1464–1472

Pratt, H.R.C., Stevens, G.H., 1992. *Science and Practice of Liquid-Liquid Extraction*, Clarendon Press, Oxford, U.K.

Reman, G.H., Olney, R.B., 1955. The Rotating Disc Contactor a New Tool for Liquid-Liquid Extraction, *Chemical Engineering and Processing*, Volume 51(3), pp. 141–146

Simmons, L., Mark, J.H., Ziad Sohial, H., Azzopardi, B.J., 2000. Comparison of Laser-based Drop-size Measurement Techniques & Their Application to Dispersed Liquid-liquid Pipe Flow, *Optical Engineering Journal*, Volume 39(2), 505–509

Soltanali, S., Ziaie-Shirkolaee, Y., 2007. Comparative Study on Experimental Correlation of Mean Drop Size in Liquid–liquid Extraction Columns. *Asian Journal of Biochemical and Chemical Engineering*, Volume 1, pp. 23–25

Sprough, F.B., 1967. Hydrodynamic Behavior of Rotating Disc Contactor under Low Agitation Conditions, *Chemical Engineering Science*, Volume 22, pp. 435–440

Treybal, R.E., 1963. *Liquid Extraction*. McGraw-Hill, New York

Wang, Y.D., Fei, W.Y., Sun, J.H., Wan, Y.K, 2002. Hydrodynamics and Mass Transfer Performance of a Modified Rotating Disc Contactor (MRDC), *Chemical Engineering Research and Design*, Volume 80(4), pp. 392–400