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An investigation on the Effect of Continuous Phase Height on the First and Second Critical Rotor Speeds in a Rotary Disc Contactor

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Abstract**—**A Rotary Disc Contactor with inner diameter of 9.1cm and maximum operating height of 40cm has been used to investigate break up phenomenon. Water-Toluene, Water as continuous phase and Toluene as dispersed phase, was selected as chemical system in the experiments. The mentioned chemical system has high interfacial tension so it was possible to form big drops which permit accurate investigation on break up phenomenon as well as the first and second critical rotor speeds.

In this study, Break up phenomenon has been studied as a function of mother drop size, rotor speed and continuous phase height. Further more; the effects of mother drop size and continuous phase height on the first and second critical rotor speeds were investigated. Finally, two modified correlations were proposed to estimate the first and second critical speeds.

Keywords**—**Breakage, First critical rotor speed, Rotary disc contactor, Second critical rotor speed

I. Introduction

LIQUID-liquid extraction is a separation process, which is based on different distribution of the separable components between two liquid phases. Liquid-liquid extraction processes are widely applicable in chemical and biochemical industries [1].

Many types of devices have been used over the years in solvent extraction processes, but the Rotating Disk Contactor (RDC) is the most widely adopted since it was developed by the Royal Dutch/Shell Group in the middle of the last century. Comparisons with other conventional contactor devices have been made showing that RDCs are more efficient, and provide increased yields over the others [1-4].

The RDC column consists of a series of stages separated by equally spaced horizontal stators, in which liquid dispersion is generated by mechanical agitation of horizontal discs mounted on a vertical rotor shaft [5]. An important application of these contactors is in the petroleum industry for furfural and sulfur dioxide extraction, propane deasphalting, solfolane extraction and for caprolactum purification [3].

Investigation on the first and second critical rotor speeds is very important. In fact, Kamath and Subba Rau showed that for good operation, the RDC should be operated between the lower and higher critical rotor speeds [2].

The performance of RDC depends largely on the geometry of the column internals and rotor speed [2]. Kung and Beckmann were the first to observe the existence of two regimes of RDC operations in terms of characteristic velocity of the dispersed phase droplets [6]. In the first regime, characteristic velocity remains approximately constant up to a certain rotor speed (the first critical rotor speed) and then decreases with further increase in the rotor speed (the second regime). Characteristic velocity varies rapidly with rotor speed after the first critical rotor speed up to the rotor speed that called second critical rotor speed. After that, the mentioned variation becomes moderate. The existence of the second critical speed was the first found in 1985 by Kamath and Subba Rau [2].

These critical rotor speeds could be defined base on breakage probability: the first critical rotor speed for a drop with specific size defines as the rotor speed at which the drop breakage starts. In fact, before the first critical rotor speed, the probability of break up for a drop with specific size is zero. Moreover, the second critical rotor speed (for a drop with specific size) is a rotor speed at which the probability of breaking that drop is equal 1.

There are several equations to estimate the first and second critical rotor speeds. Equation (1) was proposed by Kannappan [7] to predict the first critical rotor speed for any given liquid system and column geometry. This equation was modified as equation (2) by Khadivparsi [8] to calculate the second critical rotor speed.

$$\frac{g}{D_R N_{cr_1}^2}\left[\left(\frac{\gamma^3\rho_c}{\mu_c^4 g}\right)^{\frac{1}{4}}\left(\frac{\Delta\rho}{\rho_c}\right)^{\frac{3}{5}}\right]^{0.5} = 25 \qquad (1)$$

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$$\frac{g}{D_R N_{cr_2}^2}\left[\left(\frac{\gamma^3 \rho_c}{\mu_c^4 g}\right)^{\frac{1}{4}}\left(\frac{\Delta\rho}{\rho_c}\right)^{\frac{3}{5}}\right]^{0.5} = 9 \qquad (2)$$

In mentioned equations, the effect of drop size on critical rotor speed has not been considered. However, this parameter has important role on drop breakage as well as the first and second critical rotor speeds.

Correlation (3) was proposed in 1991 by Bahmanyar and Slater in which drop size was introduced to the equation [10].

$$\frac{d_{cr}}{D_R} = 3.586\times10^{-3}\times\left(\frac{\rho_c N^2 D_R^3}{\gamma}\right)^{-0.8}\left(\frac{\rho_c N D_R^2}{\mu_c}\right)^{0.7} = 3.586\times10^{-3}\times(We_D)^{-0.8}\times(\mathrm{Re})^{0.7} \qquad (3)$$

In none of the mentioned equations the effect of continuous phase height (in the other word, continuous phase weight) on the breakage has not been taken into account.

In this study, the effects of drop size as well as continuous phase height on the first and second critical rotor speeds have been considered and two modified equations based on equation (3) have been proposed to predict the first and second critical rotor speeds.

II. Experimental

A. Chemical System

Water-Toluene was chosen as chemical system due to its high interfacial tension. In all experiments, distilled water which was saturated of specified organic phase was used as continuous phase and toluene which was saturated of distilled water was applied as dispersed phase. In all experiments, dispersed phase was fed as single drops by using a nozzle, while there was no continuous phase flow. Physical properties of mentioned chemical system are shown in Table I [10].

TABLE I
Physical Properties of the Chemical System

Physical Property ($25^{\circ}C$)	Amount
$\rho_c (kg/m^3)$	996
$\rho_d (kg/m^3)$	860
$\mu_c (mPa.s)$	0.87
$\mu_d (mPa.s)$	0.55
$\gamma (mN/m)$	28

B. Experimental Setup

The RDC was made of glass and its rotors and stators were made of stainless steel. The column was outfitted with 13 stator rings and 12 rotating discs located in the middle of each compartment. The stators were supported by four rods and a central shaft held the rotor discs. Column inner diameter and height were 91mm and 60cm, respectively. More details on column dimensions are given in Fig. 1.

Two nozzles with different inner diameters (0.3 and 0.4mm) were used to form two different drop sizes (4 and 6 mm, respectively) by controlling formation time and flow rate. Drops of disperse phase were entered from the bottom of the column. It worth noting that, the distance between the nozzle tip and the first stator ring was mentioned at about 22mm to avoid the effect of rotor rotation on the drop size [9].

C. Experimental Procedure

At first, column was filled up to a specific height with saturated water. It should be noted that, three different continuous phase heights were used in the experiments: 40.5, 26.5 and 12.5 cm.

After that, dispersed phase (toluene) was entered (as single drops) from the bottom of the column by using a nozzle with definite internal diameter. The flow rate of organic phase was fixed in a specific value by use of a rotameter.

After ensuring to reach to stable conditions, some films were taken from the first six stages. In each experiment, the probability of mother drop breakage at third stage was determined. Finally, by using these films and disc thickness (1mm) as reference distance, drop sizes were determined.

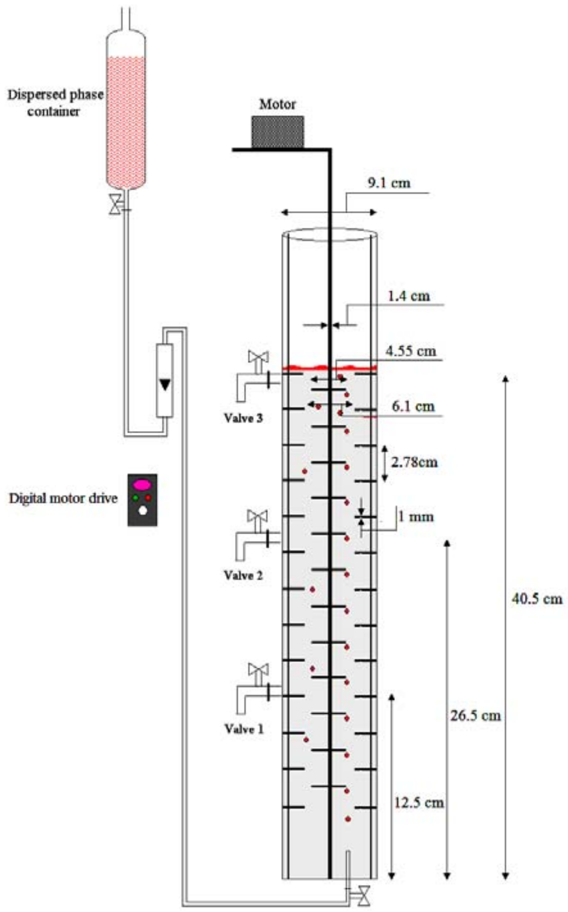


Fig. 1 Schematic feature of experimental setup

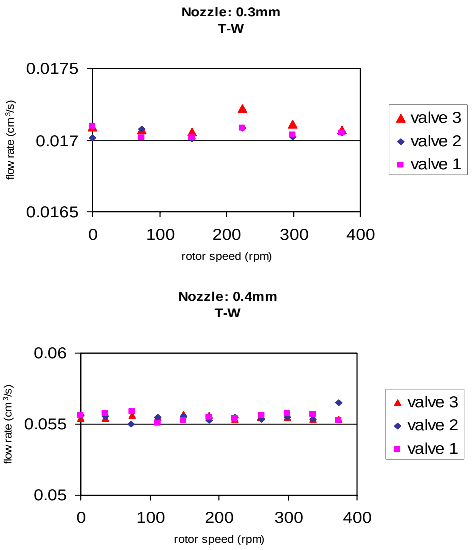


Fig. 2 Variation of flow rate versus rotor speed

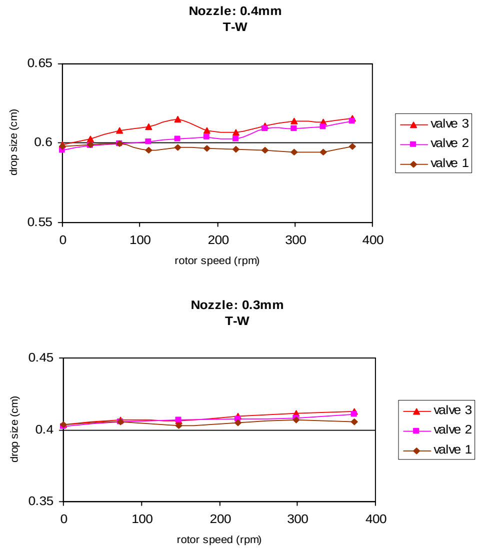


Fig. 3 Variation of drop size with rotor speed

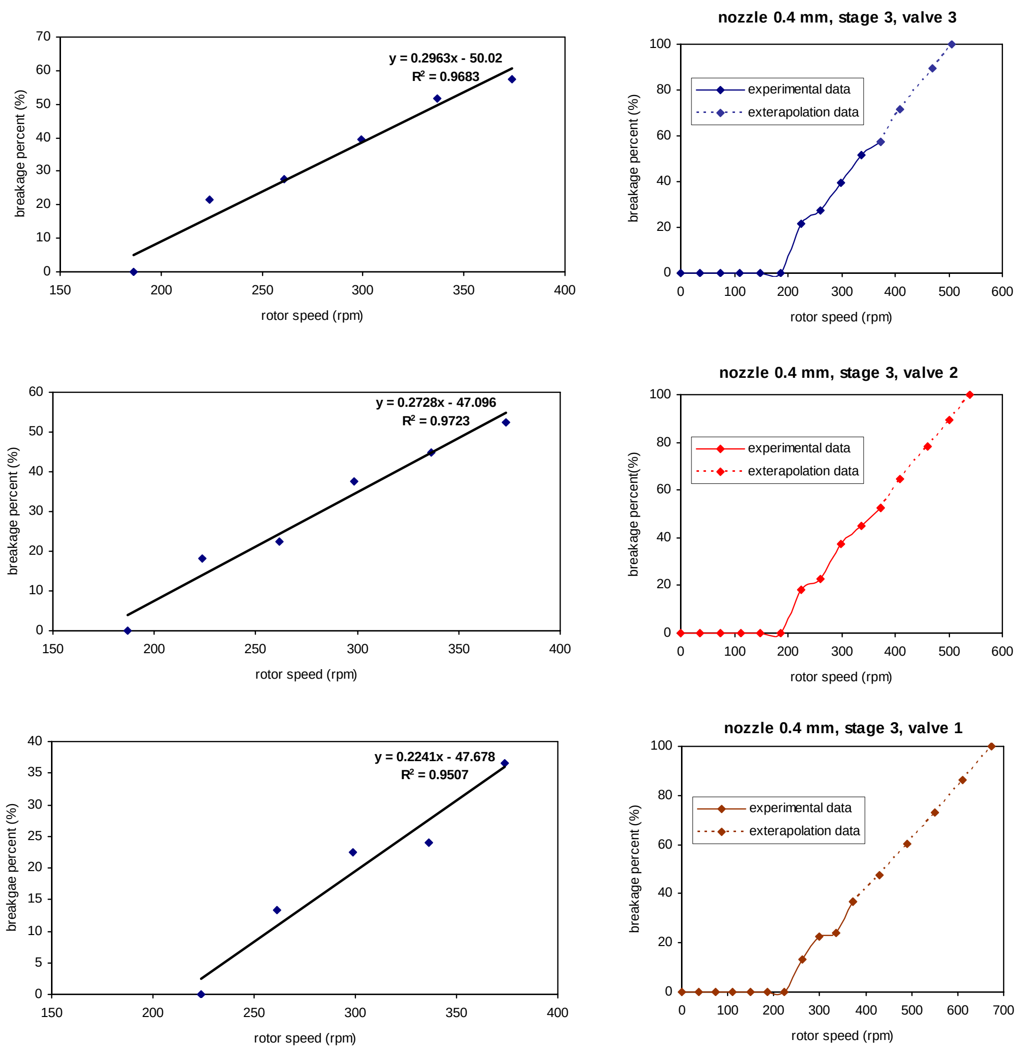


Fig.4 Variation of drop breakage percent versus rotor speed for 6mm drop size

III. Experimental Results

As mentioned before, two nozzles with different inner diameters were used: 0.3 and 0.4 mm, which were applied to form drops with 4 and 6mm diameter, respectively. Variations of flow rate versus rotor speed for drops formed in mentioned nozzles are shown in Fig. 2 which are almost constant.

Further more, the charts which are indicated in Fig. 3 show the variation of drop size versus rotor speed. As it is obvious the variations are negligible.

Results of experimental and extrapolated data for breakage percent versus rotor speed for two different drop sizes are presented in Figs. 4 and 5. These results are related to three different continuous phase height.

It should be noted that, since it was not possible to reach to the second critical rotor speed by use of mentioned setup; the breakage probability of 1 was estimated by extrapolating the experimental data of breakage probability versus rotor speed.

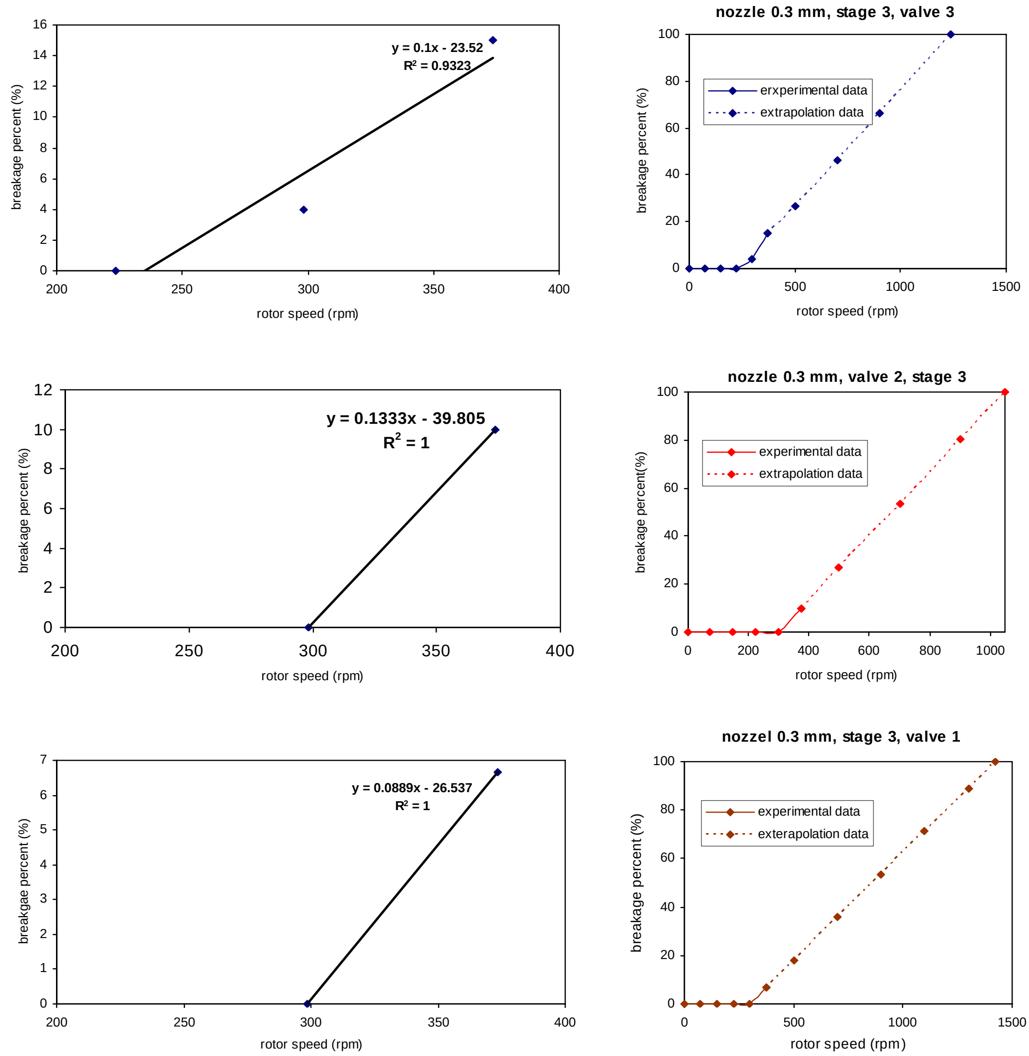


Fig. 5 Variation of drop breakage percent versus rotor speed for 4mm drop size

IV. Discussion

Fig. 6 presents the effect of continuous phase height on the first and second critical rotor speeds for two drops with different size. Regarding to these graphs, the height of continuous phase- in fact, weight of the water above the mother drop- has effect on the first and second critical rotor speeds. Indeed, with increment in continuous phase height, drops can break in lower rotor speeds. In addition, the probability of drop breakage in a specific rotor speed is higher when continuous phase height is up to the third and second valve comparing to the condition that this height is up to the first valve.

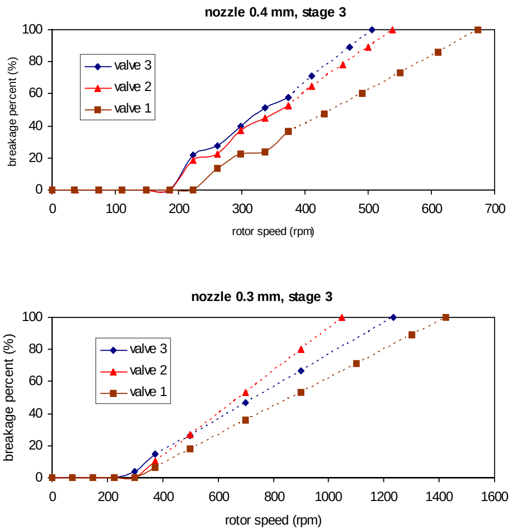


Fig. 6 The effect of continuous phase height on the first and second critical rotor speeds for two different mother drop sizes

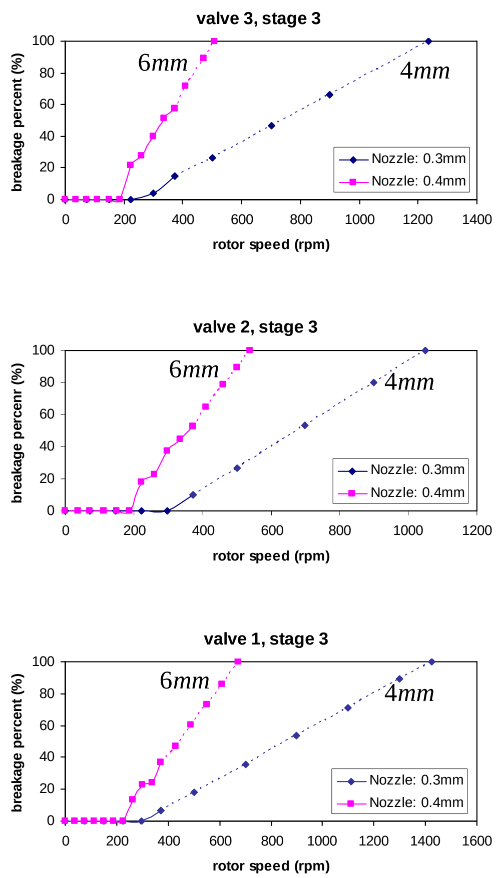


Fig. 7 Comparison of the effect of mother drop size on the breakage percent versus rotor speed, for different continuous phase heights

Fig. 7 shows comparison of the effect of mother drop size on the breakage percent versus rotor speed, for different continuous phase height. As indicated in this Fig. for drops with smaller size (4mm), the first and second critical speeds is bigger comparing to that of the drops with bigger diameter (6mm).

The results of the first and second critical rotor speeds as well as their ratio (N_{cr_1}/N_{cr_2}) are tabled in TABLE II. This ratio is about 0.2-0.35 in all cases.

TABLE II
AMOUNT OF THE FIRST AND SECOND CRITICAL ROTOR SPEEDS

Drop size	Valve	N_{cr_1} (rpm)	N_{cr_2} (rpm)	N_{cr_1}/N_{cr_2}
6mm	3	186.5	506.31	0.368
	2	186.5	539.2	0.345
	1	223.8	674.03	0.332
4mm	3	223.8	1235.2	0.178
	2	298.53	1048.8	0.279
	1	298.53	1423.36	0.209

V. PROPOSED CORRELATIONS

Rearranging equation (3) for N_{cr_1} leads to:

$$N_{cr_1} = \left(3.856\times10^{-3}\frac{\gamma^{0.8}}{\mu_c^{0.7}\rho_c^{0.1}}\right)^{\frac{10}{9}} \times d_{cr}^{-\frac{10}{9}} \qquad (4)$$

We proposed a modified correlation (by using experimental data) to predict the first critical rotor speed by introducing continuous phase height into equation (4):

$$N_{cr_1} = 0.59\times\left(3.856\times10^{-3}\frac{\gamma^{0.8}}{\mu_c^{0.7}\rho_c^{0.1}}\right)^{\frac{10}{9}} \times d_{cr}^{-\frac{10}{9}} \times h^{-0.22} + 1.1 \qquad (5)$$

Further more, correlation (6) is proposed to estimate the second critical rotor speed:

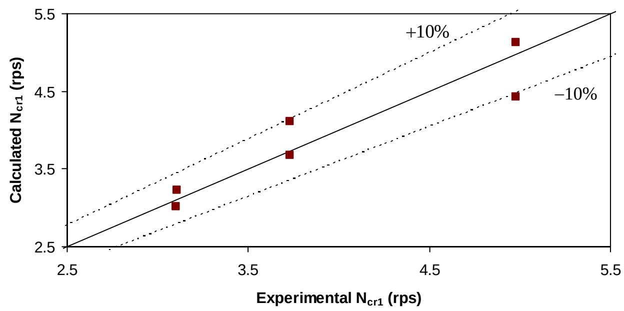
$$N_{cr_2} = 6.33\times\left(3.856\times10^{-3}\frac{\gamma^{0.8}}{\mu_c^{0.7}\rho_c^{0.1}}\right)^{\frac{10}{9}} \times d_{cr}^{-\frac{10}{9}} \times h^{-0.1} - 9.88 \qquad (6)$$

The correlations (5) and (6) yield to an absolute average relative error (AARE) of 5.4 % and 5.5%, respectively. Furthermore, the standard deviations (σ) between predicted and experimental values are 4.1% and 5.5%, respectively. Absolute average relative error and standard deviation can be calculated by following equations:

$$AARE = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{y_{\exp}(i) - y_{pred}(i)}{y_{\exp}(i)}\right| \qquad (7)$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}\left[\left|\frac{y_{\exp}(i) - y_{pred}(i)}{y_{\exp}(i)}\right| - AARE\right]^2}{N-1}} \quad (8)$$

In Fig. 8 calculated N_{cr_1} and N_{cr_2} from correlations (5) and (6) versus experimental data of the first and second critical rotor speeds are presented.



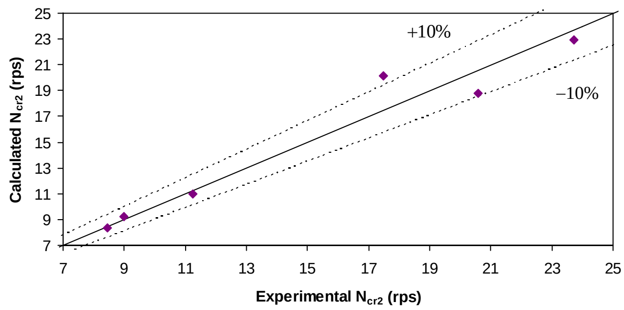


Fig. 8 Calculated N_{cr_1} and N_{cr_2} versus experimental data

VI. Conclusion

Breakage phenomenon as well as the first and second critical rotor speeds were studied as a function of continuous phase height in a RDC by using water-toluene chemical system.

It was observed that by increasing continuous phase height, the first and second critical rotor speeds will decrease. In addition, for a drop with prescribed size, in a specific rotor speed, breakage probability shows increment when the mentioned height increases.

Two modified correlations were proposed to estimate the first and second critical rotor speeds. These correlations yield to an absolute average relative error (AARE) of 5.4 % and 5.5%, respectively. Moreover, the standard deviations (σ) between predicted and experimental values are 4.1% and 5.5%, respectively.

Nomenclature

AARE	Absolute average relative error	(-)
d_{cr}	Critical drop size	(m)
D_R	Rotor diameter	(m)
g	Gravity acceleration	(m/s)
h	Continuous phase height	(m)
N	Rotor speed	(rps)
N_{cr_1}	First critical rotor speed	(rps)
Re	Reynolds number	(-)
We	Weber number	(-)

Greek Symbols

μ_c	Viscosity of continuous phase	(Pa.s)
μ_d	Viscosity of dispersed phase	(Pa.s)
ρ_c	Density of continuous phase	(kg/m^3)
n	Density of dispersed phase	(kg/m^3)
$\Delta\rho$	Density difference	(kg/m^3)
γ	Interfacial tension	(N/m)
σ	Standard deviation	(-)

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