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Determining Effective Parameters on Hydrodynamic Characteristics of Pulsed Packed Column Using ANOVA Method: Determining Optimum Conditions with Maximum Extraction Efficiency

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ABSTRACT

Using nanoparticles can lead to an increase in mass transfer rate in liquid–liquid extraction systems. Increasing the concentration of nanoparticles in liquids results in the deposition of nanoparticles and thus limits its use in extraction systems. In this paper, the effect of adding a surfactant to nanoparticle in liquid-liquid extraction systems on extraction efficiency is investigated. The effect of surfactant concentration on the extraction efficiency has been investigated both separately and in the presence of nanoparticles. In this research, the effect of continuous and dispersed phase velocity, and pulsation intensity on the hydrodynamic characteristics of the system has been investigated for the first time with the simultaneous use of silica nanoparticles and SDS surfactant in the vertical pulsed packed column.

Using hydrodynamic system and in the presence of nanoparticles and surfactant, this research article provides optimum conditions to obtain maximum efficiency with minimum additives and pulsation intensity. ANOVA analysis (three-level Box–Behnken experimental design) has been used to investigate the effective parameters and sensitivity analysis. The results showed that pulsation intensity is the most effective factor on response. With increasing pulsation intensity from 1 to 2.5, the droplet size decreases and hold-up is increased from 0.02 to 0.05 (at Q_d=Q_c= 2 lit/s) in the system. Also, the effects of adding SiO_2 nanoparticles and Sodium dodecyl sulfate (SDS) surfactant into a chemical system on the hydrodynamic characteristics were studied. The results showed that by adding nanoparticles the droplet size decreases while hold-up increases. Finally, a semi-empirical correlation has been proposed to predict the droplet size in terms of operational parameters, the system chemical properties and the nanoparticle volume fraction. It was found that when pulsation intensity, nanoparticle concentration and surfactant concentration were 1.75, 0.1, and 0.05 respectively, extraction efficiency increased to 0.98.

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1. Introduction

Using nanoparticle idea was first proposed by Maxwell and named nanofluid on fluids including these particles. Nanofluids have been considered because of their ability to improve the heat transfer and are used in many applications of heat transfer augmentation theoretically and experimentally [1-4]. Nanoparticles can improve conductivity of the base fluid and increase heat transfer. Heat and mass transfer are the same process; accordingly, nanoparticles can improve mass transfer function [5-7]. In an experimental study, the influence of nanoparticles on the dye droplet diffusion was investigated in the base fluid [8]. The results showed that dye droplet diffusion occurs more quickly in the nanofluid. Higher mass transfer augmentation in nanofluids compared to base fluids is attributed to Brownian motion of the nanoparticles. This model suggested that Brownian motion increases mixing and thereby increases mass transfer. Many researches have been done to analyze the effects of nanoparticles such as Al_2O_3, Fe_2O_3 and etc on the mass transfer coefficient [6,9-15] The results showed that using nanoparticles improves

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mass transfer coefficient strikingly. Furthermore, the type of nanoparticle is effective too. Lee et al. experimentally investigated the effect of Al_2O_3 and CNT nanoparticles on heat transfer [15]. The results indicated that heat transfer coefficient is more effective by using CNT than Al_2O_3. However, the Al_2O_3 nanoparticle has better effect than the CNT nanoparticle in mass transfer process. Although the exact cause of mass transfer enhancement due to the use of nanoparticles has not been determined, it has been recommended that CNT nanoparticle is less effective on mass transfer coefficient compared to circular nanoparticles because of its less Brownian motion [8,16-17]. There are a few researches done to analyze the effects of nanofluids on mass transfer and most investigators have focused on mass transfer in gas absorption process [6,18-19]. A few studies have been done in field of using nanofluids in liquid-liquid extraction systems [10,16,20-25]. Due to an extensive use of liquid-liquid extraction systems in chemical and petroleum industries, hydrometallurgy, nuclear technology, food industries, waste management and other fields, it is essential to produce reliable experimental data and propose reliable mechanisms for the explanation of nanoparticles effects on this process. In liquid-liquid extraction systems, hold up is a significant parameter which is an effective parameter in designing these systems [26]. Dispersed phase hold up is effective on residence time of dispersed phase, drop coalescence and interfacial area [27,28]. The research review indicated that adding nanoparticles in liquids increases liquid surface tension and reduces base fluid viscosity. These changes influence the system hydrodynamic characteristics. The results showed that the droplet size is an important parameter in these systems. Surfactants are another parameter which affect hydrodynamic characteristics in these systems. Surfactants are compounds that lower the surface tension (or interfacial tension) between two liquids, between a gas and a liquid, or between a liquid and a solid. In this study, the influence of five parameters included: continuous and dispersed phase flow rates, pulsation intensity, nanoparticles and surfactants in the base fluids on the mean drop size, and hold up in pulsed packed column systems. At first, using Design Experts software, sensitive analysis of the system by using pure water in terms of continuous and discontinuous phase speed and pulsation intensity has been analyzed and the most effective parameter on responses has been predicted. Then, the effect of nanoparticles and surfactants on hydrodynamic characteristics of the system has been analyzed. Moreover, a semi-empirical correlation has been proposed to calculate the droplet size and hold up in pure water system including surfactants and nanoparticle. Finally, Extraction efficiency was investigated in different concentrations of nanoparticles and surfactant.

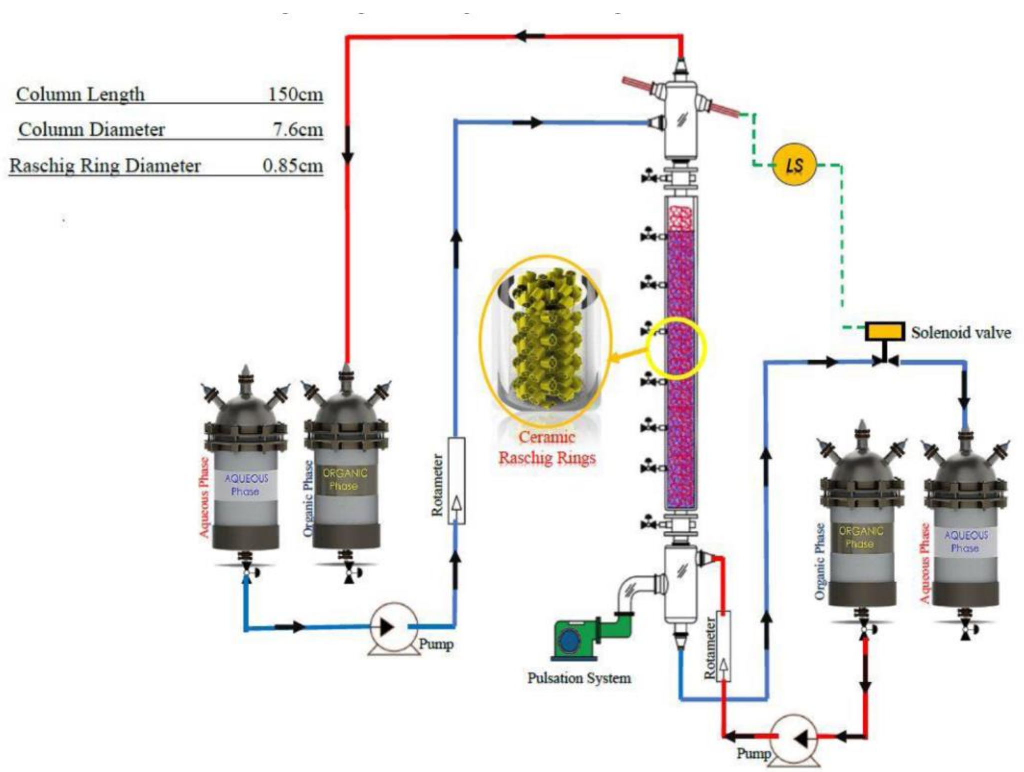


Figure 1. Experimental system

Table 1. Physical properties of liquid systems at 20 °C and nanoparticles [29].

Physical property	Toluene/water
ρ_c[kg/m^3]	994.4-995.7
ρ_d[kg/m^3]	864.4-865.2
η_c[mPa.s]	1.059-1.075
η_d[mPa.s]	0.574-0.584
σ[mN/m]	26.5-36.0
Diameter of nanoparticle(nm)	20-30
$\rho_{nanoparticle}$[kg/m^3]	2200

2. Experimental section

Fig.1 indicates the experimental setup used in this study. The experimental systems were water- toluene-acetone. Acetone with 3.5wt% was used as solute in mass transfer conditions. Distilled water was used as the continuous phase and toluene (99.5wt% purity) was used as the dispersed phase. This system has been accepted by the European Federation of Chemical Engineering (EFCE) [29]. The physical properties of the systems used in these experiments are presented in Table. 1. The experiments have been done in a pulsed packed column with 7.6 cm diameter and 150 cm height. A circular ring with 0.85 cm diameter as a packing has been applied and the filled part is 68% column. The pulsation system has been used and two tanks for inlet flow and two tanks for outlet flow with 100-liter capacity have been considered. Flow rate has been measured by flow meter. The interface location of two phases was controlled by an optical sensor automatically. Optical sensor sends a signal to the solenoid valve if the interface location is changed and the aqueous phase leaves the column. In this article, SiO_2 nanoparticle and Sodium dodecyl sulfate (SDS) surfactant have been used to determine droplet size modification and hold up in the base fluid.

2.1. Determining hydrodynamic characteristics

Droplet size and hold up have been determined in different flows of continuous and discontinuous phases, different pulse intensity in the present of nanoparticles and surfactants. For droplet size and hold up determination, the system must operate in a steady state condition. To do so, the column should operate in recycle model until no changes are detected in the phase interface.

In each experiment, after reaching the steady state, a digital camera (Canon-Power Shot A490, 10 mega pixels resolution Japan) was placed perpendicular to the column to take pictures from rising droplets. Photographs were taken at different positions along the column. Then, droplet size has been measured by photographic technique and using AutoCAD software which have been indicated by d_1 and d_2 for no circular droplets. The equivalent diameter has been determined as follow [30]:

$$de = (d_1^2 d_2)^{\frac{1}{3}} \qquad (1)$$

Sauter mean diameter was then calculated from Eq. (2).

$$d_{32} = \frac{\sum_{i=0}^{n} n_i d_i^3}{\sum_{i=0}^{n} n_i d_i^2} \qquad (2)$$

Where n_i and d_i are the total number of droplets (the number of droplets with equivalent diameter of d_i) and the equivalent diameter of i_{th} droplet, respectively. In each photo, to ensure the statistical significance of the drop diameter 300 drops have been analyzed approximately.

Hold-up was determined by displacement method. In this method, at the end of each test, inlet and outlet flows were closed simultaneously and the dispersion phase was allowed to join at the interface. Hold up has been determined from total volume and dispersed phase volume as follow:

$$\varphi = \frac{V_d}{V_d - V_c} \qquad (3)$$

Where V_d and V_c [m^3] are the volume of the dispersed and continuous phases, respectively.

The extraction efficiency can be calculated by the below equation:

$$E = \frac{C_0 - C}{C_0 - C^*} \qquad (4)$$

Where, C_0, C, and C^* are defined as initial concentration in primary droplets before contact, solute concentration in droplet after t seconds at discontinuous outlet, and concentration of solute in equilibrium with continuous phase, respectively.

2.2. Design of experiments (DOE)

For further investigation of the effects of input variables on drop size and hold up, design of experiments has been done. DOE provides a systematic way to explore the relation between input variables and responses. Using DOE, much information can be obtained with a limited number of tests. For example, for one case with three factors and three levels, 27 tests are needed by full-factorial method, whereas by Box–Behnken method, just 13 tests are needed. The number of tests using Box–Behnken method has been calculated as follow:

$$N = 2k(k-1) + C_0 \qquad (5)$$

Where k and C_0 are the number of factors and center point repetition respectively.

Using DOE technique, a set of numerical experiments is performed for a permitted set of design points to construct a measured response level in the design space, i.e. a function $\eta(x_1, x_2, \ldots, x_n)$, where $x_1, x_2, x_3, \ldots, x_n$ are variables affecting the process and are considered in design within a certain range. When a second-order polynomial equation is used, the response surface equation is written as follows:

$$f = a_0 + \sum_{j=1}^{n} a_j x_j + \sum_{j=1}^{n} a_{jj} x_j^2 + \sum \sum_{i \neq j}^{n} a_{ij} x_i x_j \qquad (6)$$

Where a_{ij} is unknown coefficient of polynomial equation and f is related to quadratic model. In this study, three independent parameters including continuous and discontinuous rate flow and pulsation intensity on the hydrodynamic of liquid-liquid extraction system have been analyzed. Range of effective parameters are listed in Table 2.

Table 2. The range of three independent variables expressed in coded and real units

	parameter	Level of factor -1	0	+1
1	Q_d [A]	2[lit/hr]	4[lit/hr]	6[lit/hr]
2	Q_c [B]	2[lit/hr]	4[lit/hr]	6[lit/hr]
3	Af [C]	1	1.75	2.5

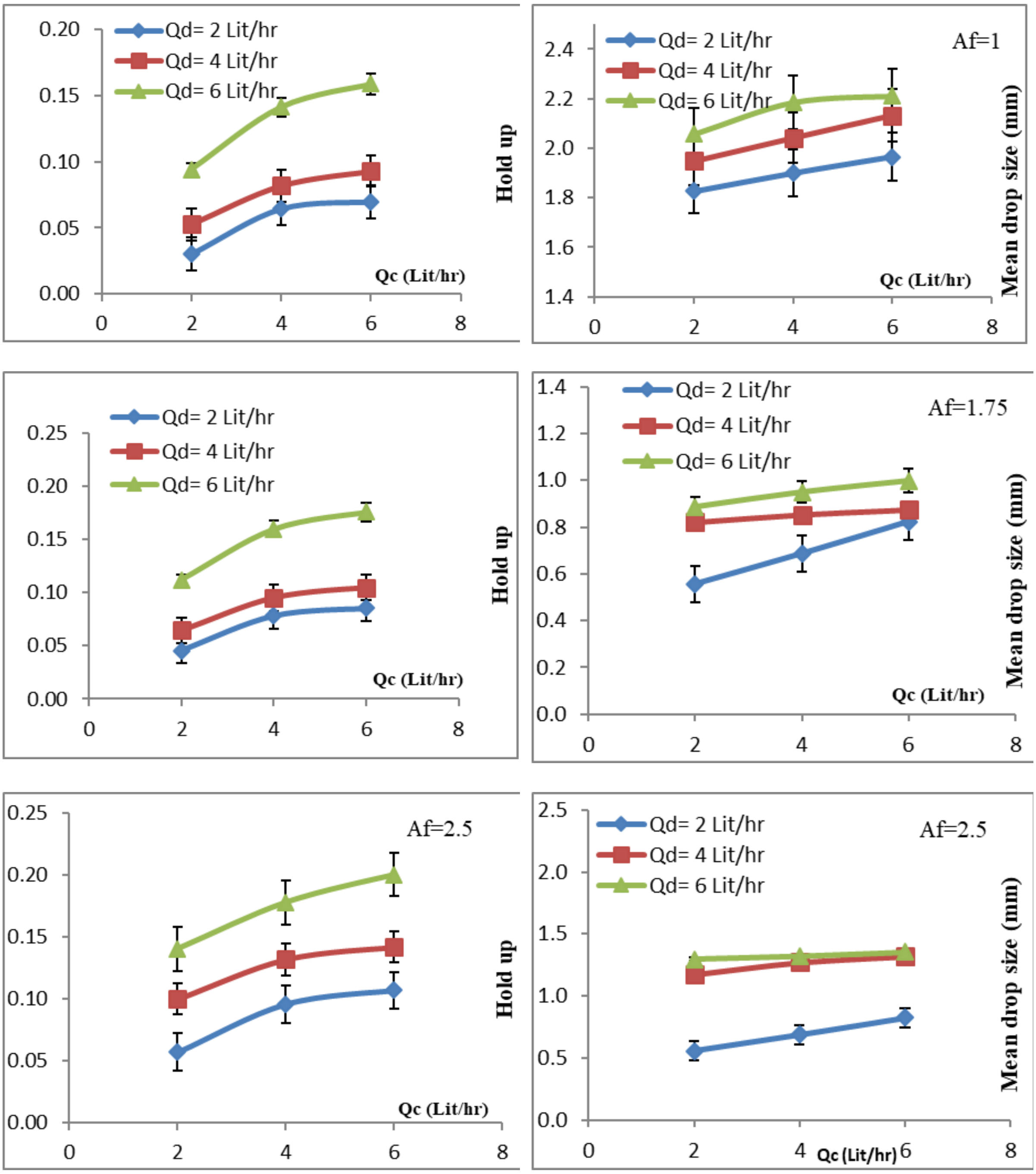


Figure 2. Effect of pulsation intensity on mean drop size and hold up

3. Result and discussion

Operating parameters that affect droplet size include phase flow rates (continuous and dispersed) and pulsation intensity. Fig. 2 shows the effect of higher pulsation intensities and continuous and discontinuous phase flow rate on drop size and hold up. As seen in the figure, with increasing higher pulsation intensities at a constant flow rate, the drop size decreases, as with increasing higher pulsation intensities, the drops are broken and Sauter mean diameter decreases. Also, the effect of phase flow rate on drops diameter has been analysed. Results showed that by increasing the flow rate of continuous phase, drops diameter, has increased due to the increase of droplet coalescence. Moreover, increasing the dispersed phase flow rate increases the holdup because the ratio of dispersed to continuous phase in the system has increased and thereby, droplet size has increased. So, droplet size and hold up in the system have increased. To determine the most effective factor on two analysed responses, sensitive analysis has been done. The range of variable parameters are listed in Table.1. The main responses are hold up and droplet size which are calculated in equations 1 and 3 respectively. The total designed points and responses are listed in Table 3.

The Normal diagram has been shown in Fig. 3. Using this diagram can be assessed to see whether the results are normally distributed or not. As seen in the figure, residual normal graph is a straight line that does not show anything abnormal.

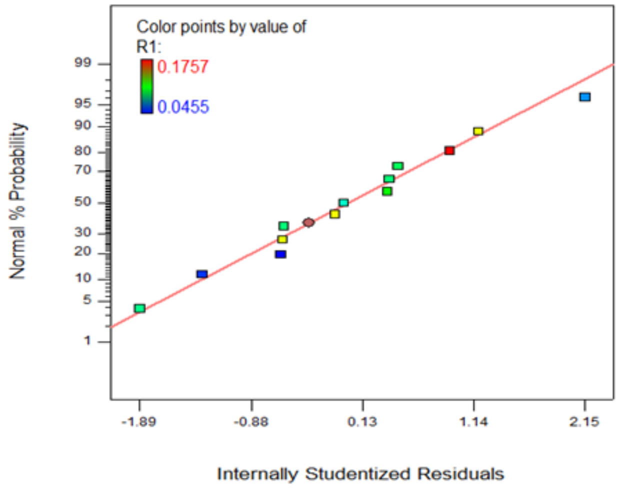


Figure 3. The normal probability plot of residuals

Table 3. Box–Behnken design matrix with three independent variables expressed

run	A=Q_c	B=Q_d	C=Af	R_1=hold up	R_2=mean drop size
1	+1	-1	0	0.0853	1.0648
2	0	+1	-1	0.1412	2.185
3	+1	0	-1	0.093	2.1320
4	0	-1	-1	0.0643	1.8997
5	+1	+1	0	0.1757	1.354
6	0	0	0	0.0952	1.2705
7	+1	0	+1	0.1415	0.8736
8	0	-1	+1	0.0955	0.6873
9	-1	-1	0	0.0455	0.8591
10	-1	0	+1	0.0996	0.8216
11	0	+1	+1	0.1399	0.8869
12	-1	0	-1	0.0526	1.9481
13	-1	+1	0	0.1117	1.2971

Table 4. ANOVA Table for the prediction of (R_1) purpose function

Source	Sum of Squares	Mean Square	F_value	P_value Prob>F	
Model	0.016	2.728E-003	13.81	0.0028	significant
A-A	4.357E-003	4.357E-003	22.06	0.0033	
B-B	9.654E-003	9.654E-003	48.87	0.0004	
C-C	1.947E-003	1.947E-003	9.86	0.0201	
AB	1.464E-004	1.464E-004	0.74	0.4224	
AC	1.103E-006	1.103E-006	0.00558	0.9429	
BC	2.641E-004	2.641E-004	1.34	0.2916	
Residual	1.185E-003	1.975E-004			
Cor Total	0.018				

Table 5. ANOVA Table for the prediction of (R_2) purpose function

Source	Sum of Squares	Mean Square	F_value	P_value Prob>F	
Model	3.22	0.54	13.87	0.0027	significant
A-A	0.031	0.031	0.80	0.4048	
B-B	0.18	0.18	4.74	0.0722	
C-C	3.00	3.00	77.40	0.0001	
AB	5.535E-003	5.535E-003	0.14	0.7183	
AC	4.349E-003	4.349E-003	0.11	0.7489	
BC	1.836E-003	1.836E-003	0.047	0.8348	
Residual	0.23	0.039			
Cor Total	3.45				

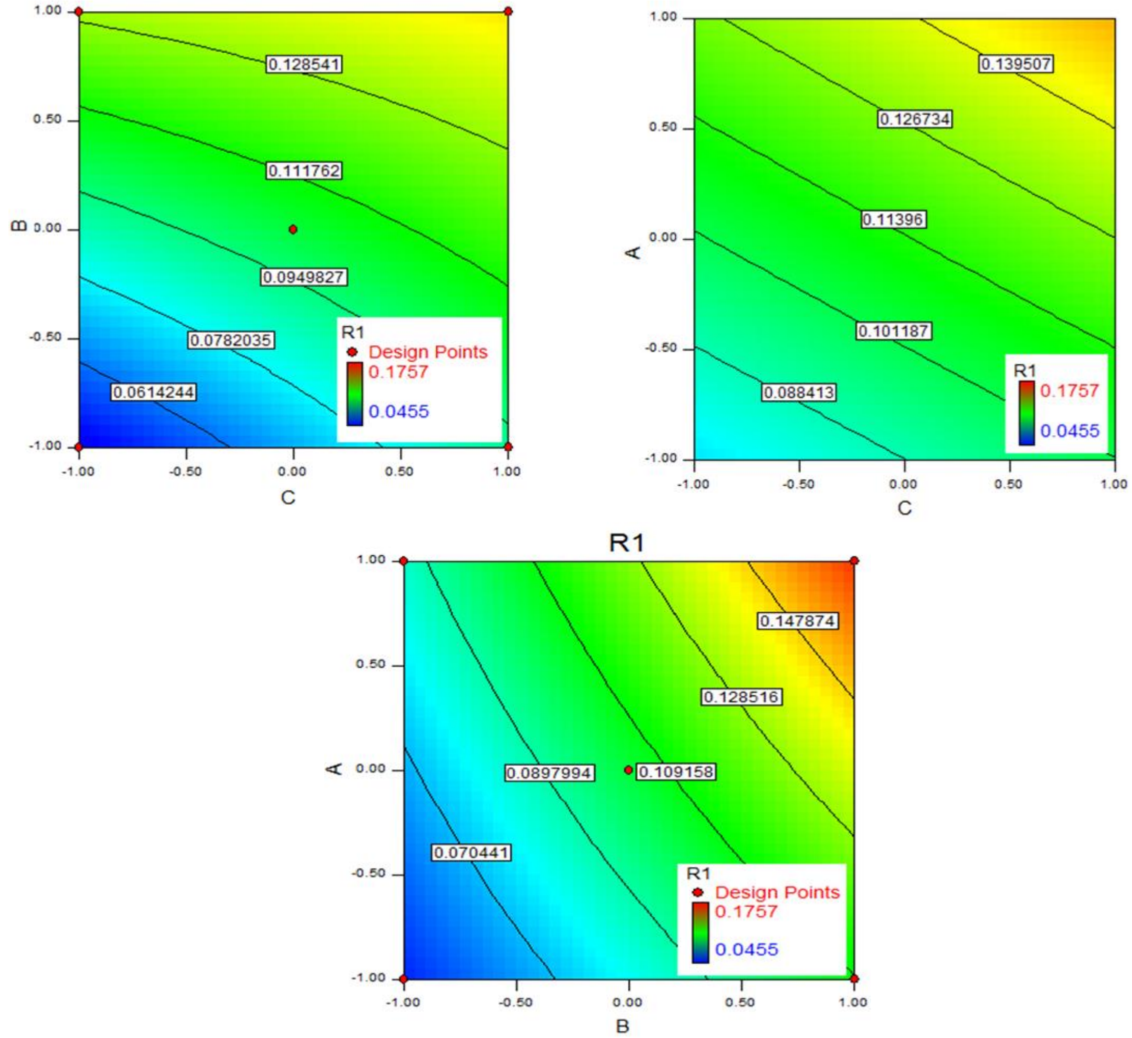


Figure 4. Contour plots exhibiting the interactive effects between two independent variables (other variables were held at their respective center levels for R_1

To analyze the importance of model two parameters, P-value and F-value can be used. The larger F-value and the lower P-value indicate the more important model. As seen in tables 4 and 5, in this model, F-value has a higher amount for both two responses and accordingly, the model is important. To check the suitability and importance of the model, the determination coefficient and adjusted determination coefficient have been used. In this case, R for two models are 0.98 and 0.99, which indicates that variables by regression model have been explained. The correlation coefficient near to one indicates a good relation between the predicted variables and experimental results. In this model, R=0.99. To analyze the importance of the main effects and factors interaction on responses, values of F-value and P-value in the ANOVA table were investigated. Parameters which have high F-value and low P-value are effective factor on responses.

According to ANOVA analysis, A and B factors are the most effective on hold up, and B and C factors are the most effective on the droplet size. In addition to the amounts of

P-value and F-value, two-dimensional and three-dimensional response interface graph can be used to analyze the main and interaction effects of factors on the response. Figures 4 and 5 show the response surface diagram as the function of two variables at another variable central level. Considering the effects of three independent factors on analyzed responses, one constant parameter has been considered in each graph. The nonlinear nature of the response surface graphs and related contours shows the importance of the interaction effect of the two factors on the response (drop size and hold up) which confirms the results derived from ANOVA analysis. According to ANOVA analysis, pulsation intensity is the most effective factor on both two responses. With increasing pulsation intensity, the droplet size decreased and hold up increased. So, the pulsation intensity is the most effective factor on hydrodynamic in this system.

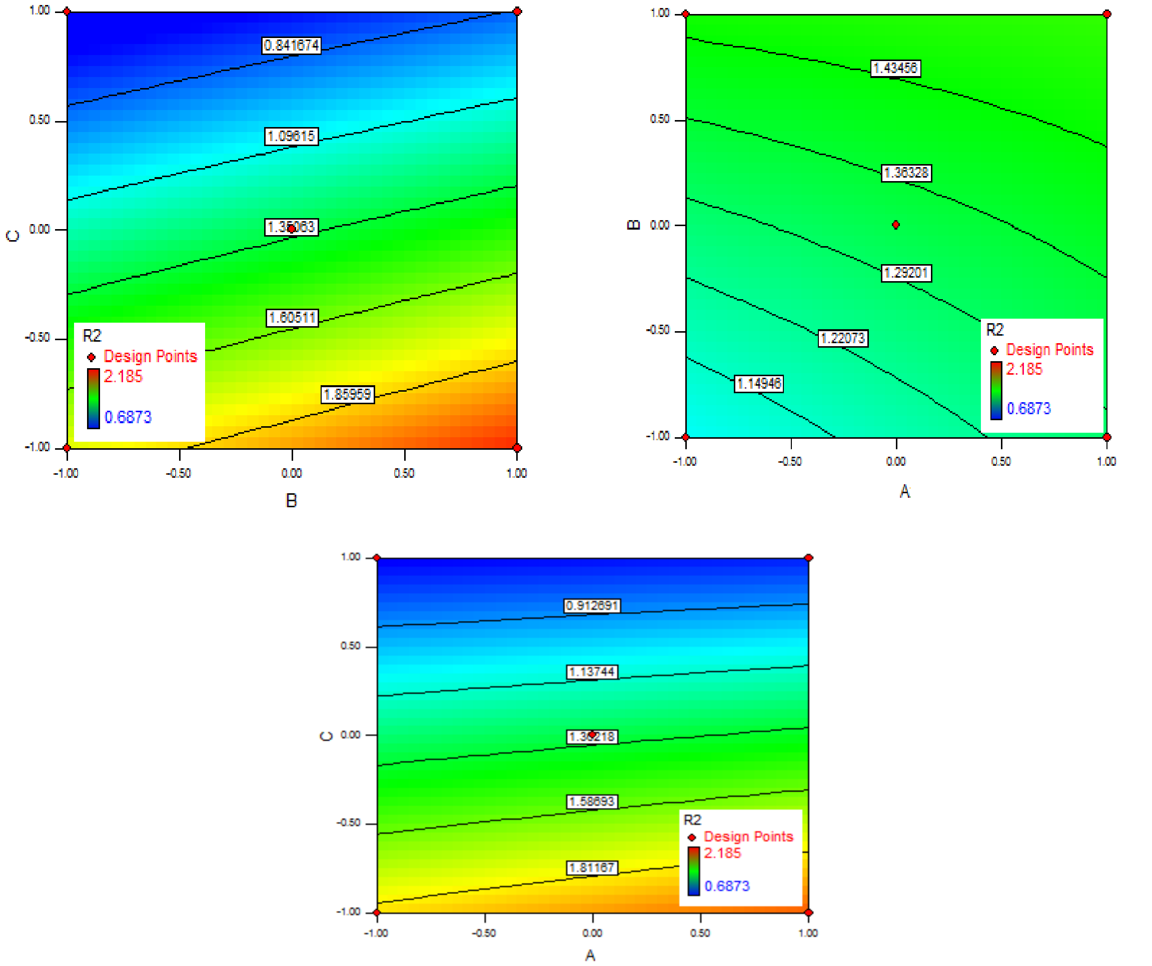


Figure 5. Contour plots exhibiting the interactive effects between two independent variables (other variables were held at their respective center levels for R_2

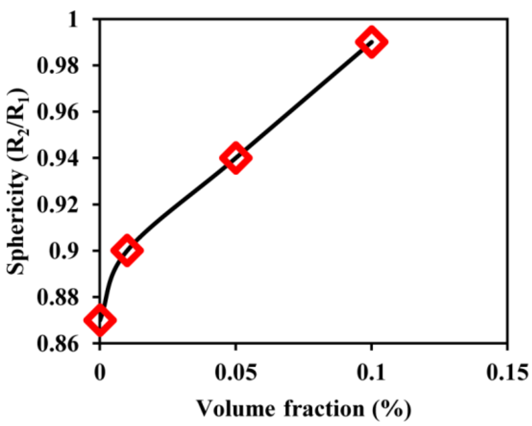


Figure 6. The sphericity of droplets versus volume fraction of nanoparticles

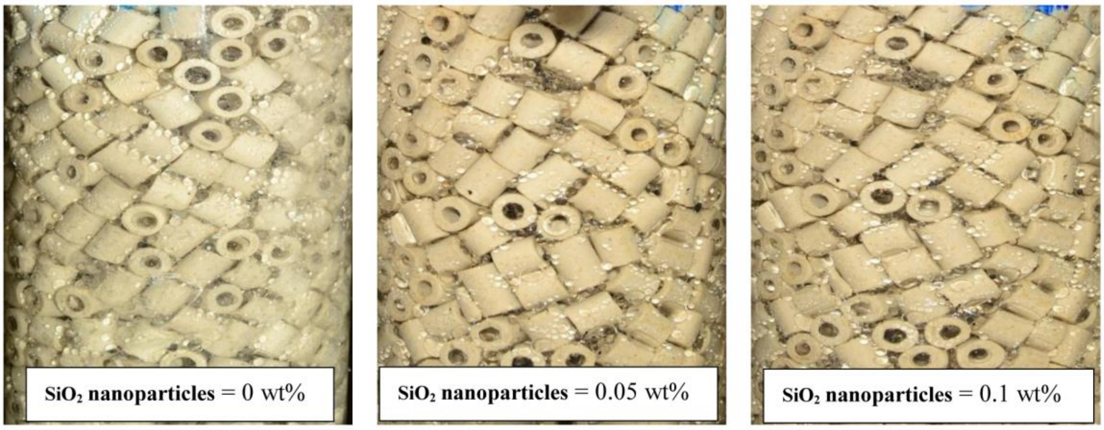


Figure 7. Illustration of the influence of SiO_2 nanoparticles content on the geometrical shape of droplets

3.2. The Influence of adding nanoparticles and surfactant

In the previous part, the influence of operational factors on hydrodynamic characteristics of the system was studied. According to the results, pulsation intensity is the most effective factor on hydrodynamic characteristic of the system. In this part, the main aim is changing fluid thermophysical properties of the system using nanoparticles and surfactant for changing the system hydrodynamic characteristics. Experimental results indicated that addition of nanoparticles had a marked influence on the geometrical shape and size of the droplets.

Fig. 7 shows formed droplets in the same operating conditions (Pulsation 0.2 and flow 0.3) at various nanoparticle contents including 0, 0.05, and 0.1wt%. As can be seen from the figure, the samples containing 0 and 0.01% nanoparticle weight fraction have elliptical droplets. By increasing the nanoparticle content, the droplet forms change to circular shapes. In nanoparticle weight fraction 0.1%, the droplets form spherical shapes. This implies that by adding nanoparticle, the elliptical shaped droplets would change to the circular forms. The same results have been reported for the systems in the presence of nanoparticles. Generally, surface tension alteration makes the droplet forms change from elliptical to the circular. Thus, surface tension alteration can explain the droplet deformation due to increased nanoparticle content in fluid. Appropriate explanations on increasing the spherical of droplets using surface tension change could be find in some references. In Fig. 6, the spherical form of droplets is indicated in each concentration. Spherical form was measured for about 100 droplets and for all nanoparticle concentrations. As shown in figure, in 0.1 nanoparticle weight fraction, almost complete spherical droplets are observed. In addition to the shape of droplets, the presence of nanoparticles also affects the droplet size.

In Fig. 8, the effect of nanoparticle concentration on droplet size in two different pulses and at different speeds of continuous and discontinuous phases has been shown. As seen in the figure, the droplet size has decreased by increasing nanoparticle concentration. Usage of nanoparticles decreases interfacial tension of two chemical systems and thereby droplet size is decreased due to drop breakage. Furthermore, the effect of nanoparticle concentration in the base fluid on hold up has been analyzed and the results showed that hold up increased by increasing nanoparticle concentration. Since the presence of nanoparticles in the system leads to a decrease in the droplet size of the dispersed phase, and droplet size distribution is more uniform. So, with the droplet size reduction, droplet velocity related to continuous phase decreases and with increasing the droplet number, hold up increases.

3.3. The effect of surfactant on hold up and droplet size

The experimental results indicated that using surfactant can reduce the droplet size. Fig. 9 exhibits a picture of droplet formation in system due to adding various surfactant contents. As it can be seen in the figure, by adding surfactant, the droplet diameter decreases compared to the fluid without any surfactant. To investigate the size of droplets, the size of almost 200 droplets was measured. The observations showed that the droplets are bigger in fluid without surfactant, so the reason for drop size reduction by adding surfactants to the system is to change the surface tension between the continuous and discontinuous phases. Fig. 10 indicates the effect of surfactant percentage in the base fluid on hold up and the droplet size. As seen in the figure, by increasing surfactant content from 0.003 to 0.005wt%, the droplet size decreases. Since surface-active substances have profound effects on the droplet behaviour, the interface tension decreases by adding surfactant and thereby causes drop breakage and consequently the droplet size reduction. Also, in the range of added surfactant concentration, it is observed that with increasing surfactant, hold up decreases. Since reducing surface tension decreases the droplet union, by increasing the surfactant concentration from 0.005wt% to 0.01wt%, the drop size and holdup increase due to the reduction of fluid viscosity and surface tension and leads to an increase in the coalescence.

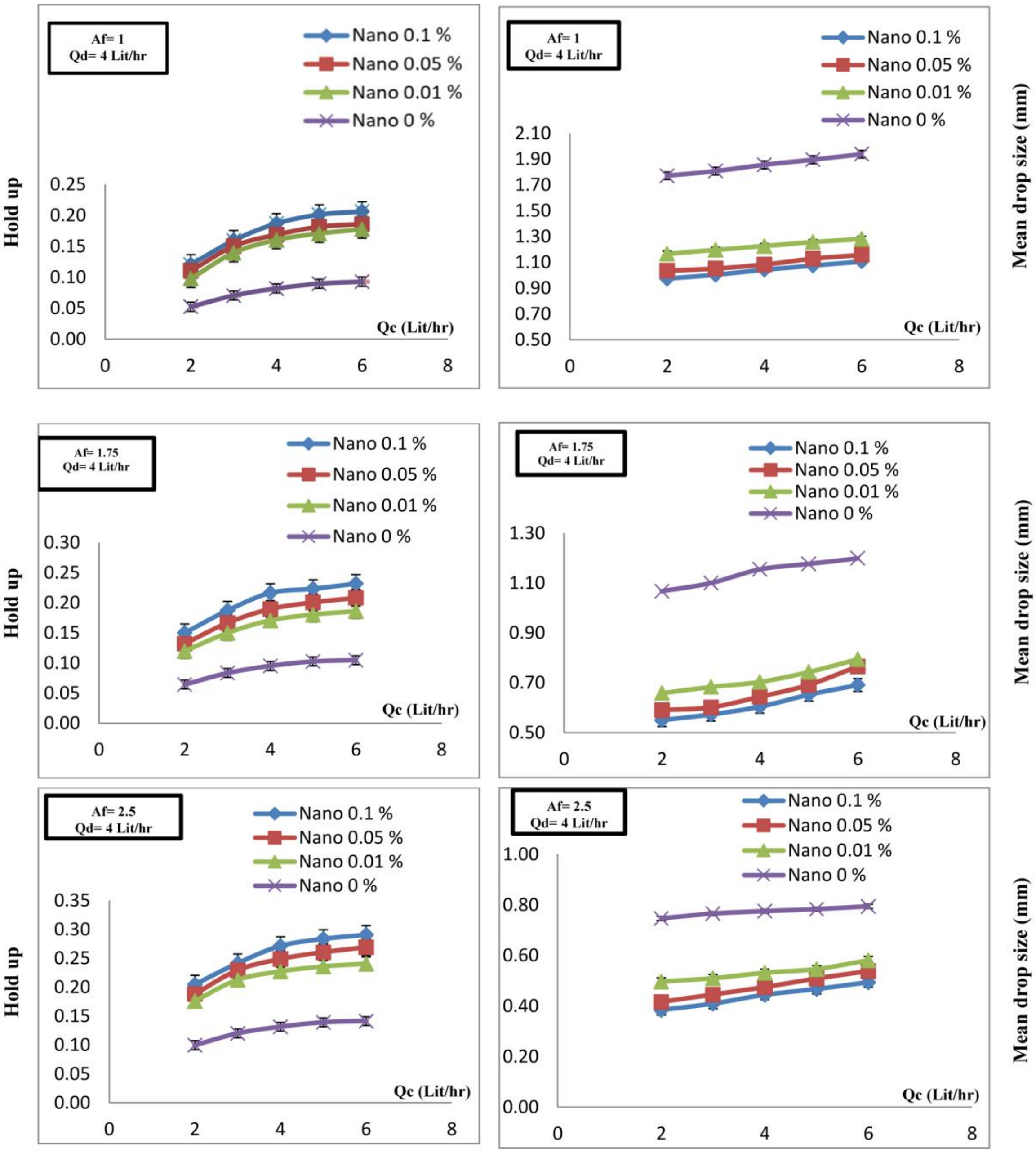


Figure 8. Influence of nanoparticles concentration in the base fluid on hydrodynamic characteristic of the system

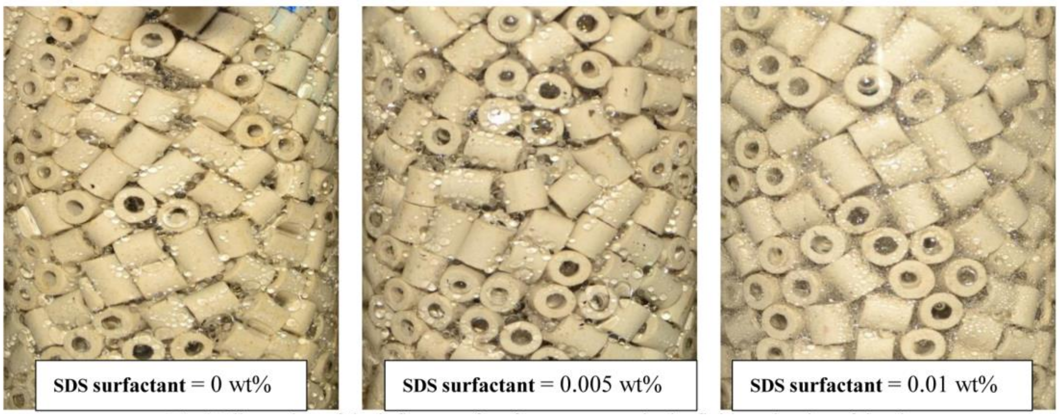


Figure 9. Illustration of the influence of surfactant content in the fluid on the size of droplets

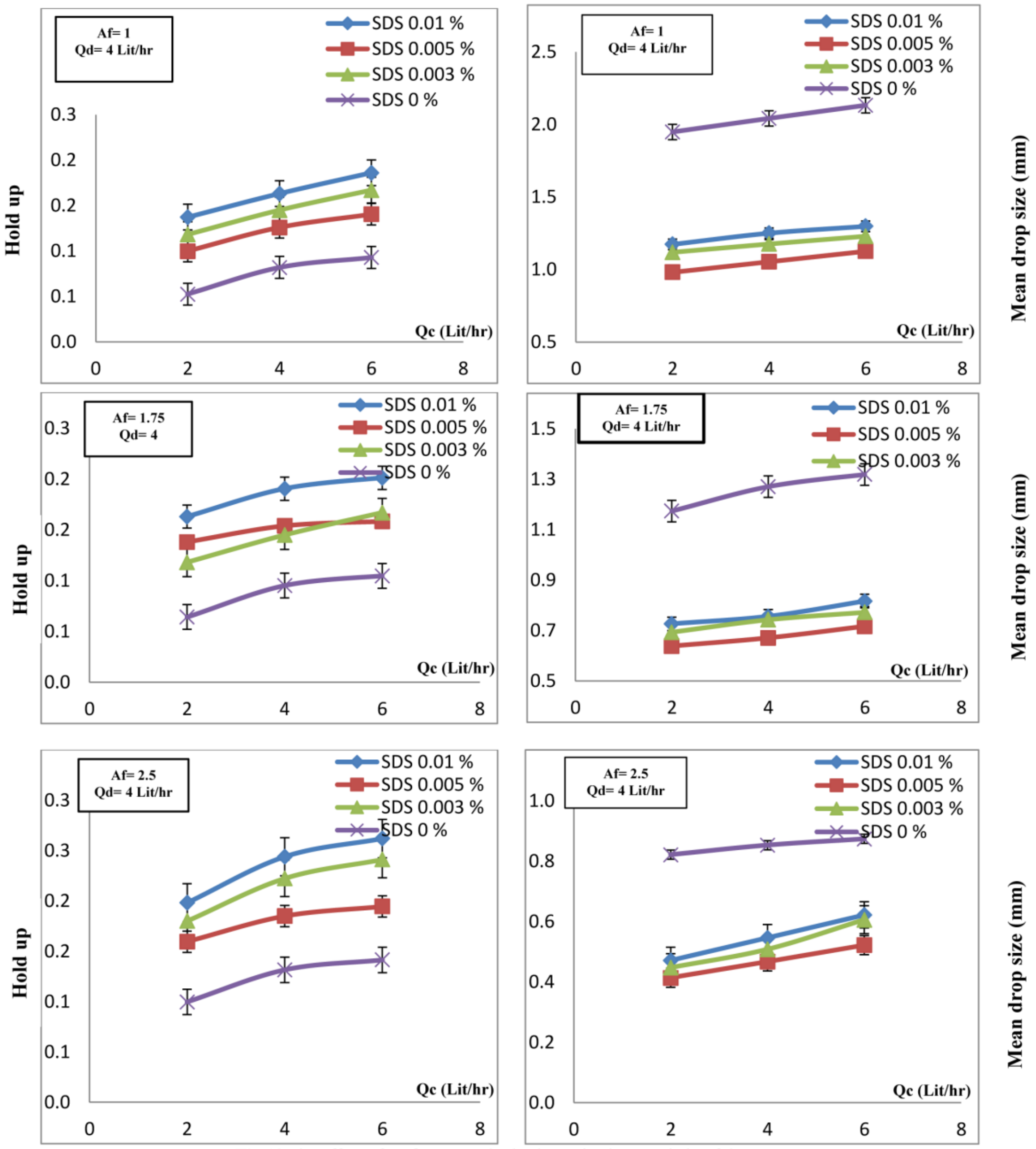


Figure 10. the effect of surfactant on hydrodynamic characteristic of the system

Fig. 11 shows the effect of adding 0.1wt% nanoparticle and 0.01wt% surfactant in the chemical system simultaneously on hydrodynamic characteristics of the system. According to the results, adding nanoparticle and surfactant separately causes the droplet size reduction and increases hold up. According to Fig. 8, by adding nanoparticle and surfactant simultaneously, hold up based on the system increases only by adding nanoparticle or surfactant. Also, the droplet size decreases

3.4. Prediction of Sauter mean drop diameter and average holdup:

One of the purposes of this article is presenting experimental results for the droplet size and proposing an equation to predict the droplet size and average hold up in the pulsed packed column. A function based on operational parameters includes: pulse intensity, continuous and discontinuous phase velocity and thermo physical properties of the chemical system. According to dimensionless analysis, SPSS software was used to determine mean drop diameter and average hold up. Equations 7 and 8 indicate mean drop diameter and average holdup in the column respectively based on nanoparticle percentage in the chemical system.

$$\frac{d_{32}}{\sqrt{\frac{\gamma}{\Delta\rho g}}} = 3.41 \times 10^{-5} \left(\frac{Af}{U_d}\right)^{-0.243} \left(\frac{\Delta\rho}{\rho_c}\right)^{-1.637} \left(\frac{\mu_c}{\mu_d}\right)^{0.112} \left(\frac{\mu_d \cdot U_d}{\gamma}\right)^{-0.152} \times \left(1 + \frac{U_d}{U_c}\right)^{-0.074} (1 + w)^{-0.565} \quad (7)$$

$$\varphi = 0.441 \times \left(1 + \frac{V_c}{V_d}\right)^{0.159} \left(\frac{A_f^4 \cdot \rho_c}{g\sigma}\right)^{-0.12} \left(\frac{V_d^4 \cdot \rho_c}{g\sigma}\right)^{0.82} \left(\frac{\Delta\rho}{\rho_c}\right)^{-0.187} \left(\frac{\mu_d^4 \cdot g}{\sigma \cdot \rho_c}\right)^{-0.0051} \times \left(1 + 0.22 w^{0.042}\right)^{0.54} \quad (8)$$

Where g is related to gravity, Af is pulse intensity, μ and ρ are viscosity and density respectively, U is superficial speed in each phase and w is weight percentage of nanoparticles. Fig. 12 compares the experimental and calculated results from Eq. 7. The mean error in this analysis is 5.4%.

The results indicate that as nanoparticles are added, holdup increases and droplet diameter within the column decreases. Moreover, increasing the surfactant content helps to a higher holdup increase and more reduction in the droplet size. Under both conditions, mass transfer rate increases. Figure 13 indicates the effects of different nanoparticle and surfactant concentrations on extraction efficiency. But as the findings indicate and as seen in figure 13, the effects of nanoparticles concentration on extraction efficiency have some optimum points, and as the concentration exceeds these points, extraction output decreases. Studying the effect of surfactant content on extraction efficiency indicates that increasing surfactant concentration increases extraction efficiency in a way that a 0.01 increase leads to a 0.90 increase in extraction efficiency. However, a 0.05 increase in nanoparticle concentration leads to 0.91 percent increase in extraction efficiency and as nanoparticle concentration increases, extraction efficiency decreases.

Therefore, simultaneous addition of surfactant and nanofluids not only changes the properties of base fluid but also increases mass transfer rate which leads to higher

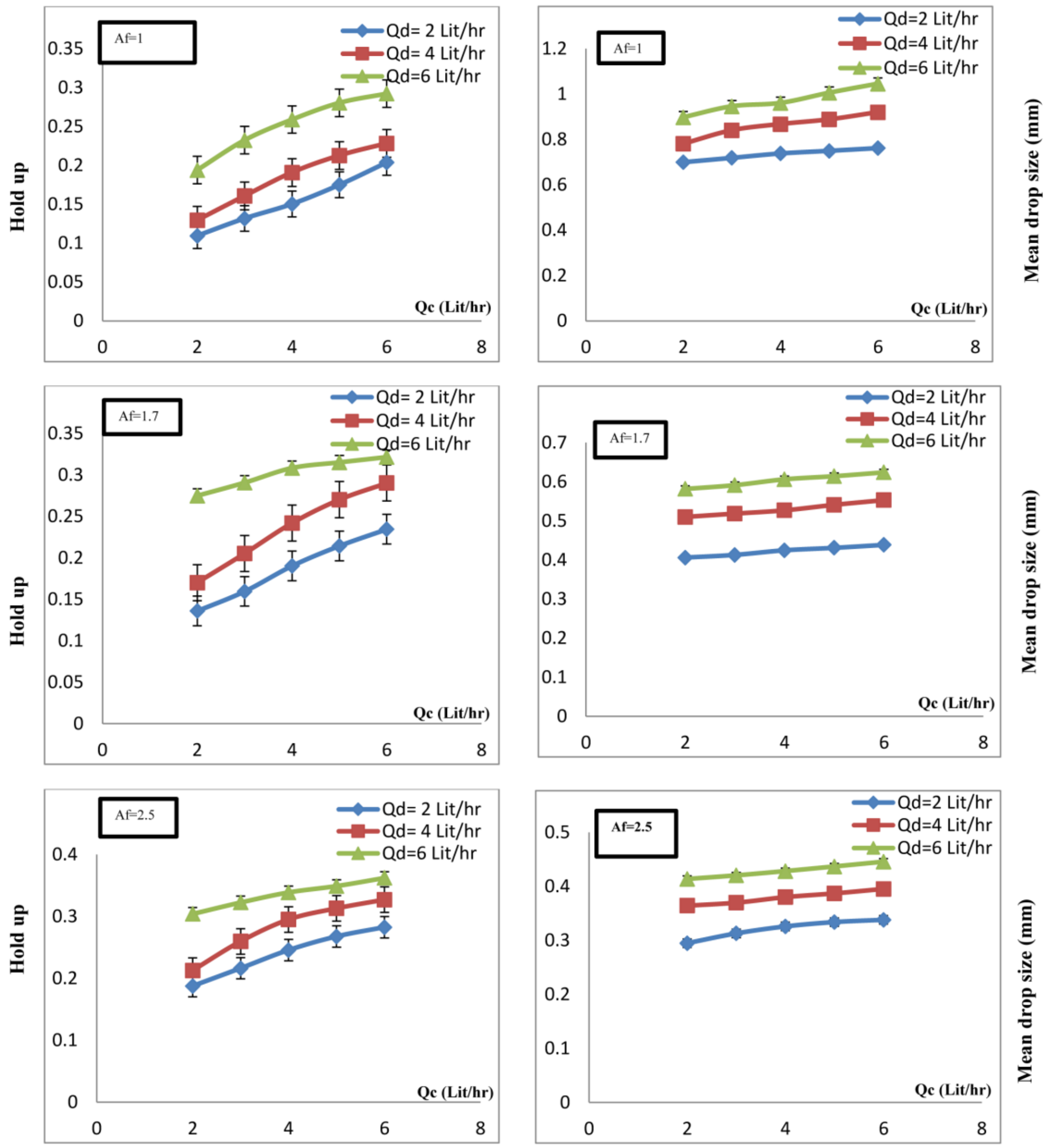


Figure 11. Effect of adding 0.1% nanoparticle and 0.01% surfactant in chemical system on hold up and droplet size

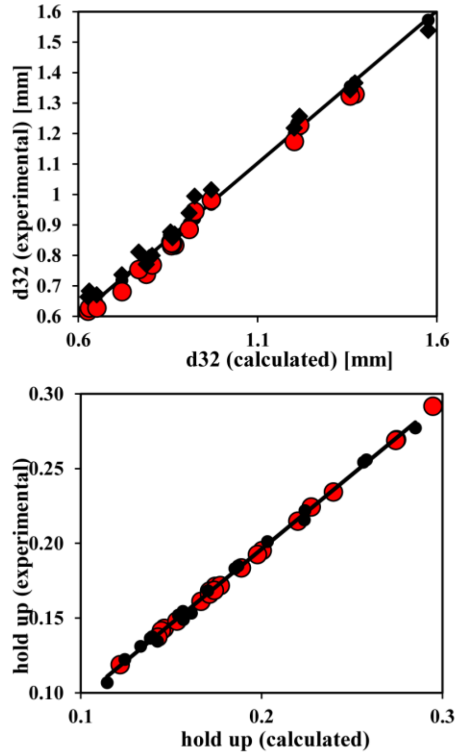
stability of fluid and the prevents from aggregation of nanoparticles in the system in the long time.

Figure 14 shows the effects of simultaneous use of nanoparticles and surfactant on the extraction efficiency in different pulsation intensities. Each graph indicates fixed pulse intensity in different concentrations of nanoparticles and surfactant. As can be seen, under different pulsation intensities and fixed nanoparticle concentrations (0.01wt %), extraction efficiency increases by increasing the surfactant concentration, but there is no dramatic increase in extraction output between 0.05wt% and 0.01wt%. Increasing the surfactant and nanoparticle concentration increases holdup and decreases droplet size. It is expected that under fixed pulsation intensity and nanoparticle concentration, the extraction output also increases, but as surfactant level increases the extraction output remains almost constant. This behaviour is mostly noticeable at higher pulsation intensities. As the figure indicates, the same results are obtained for 1.75 and 2.5 pulsation intensities, 0.1 nanoparticle concentration, and 0.01 surfactant concentration. Surfactant concentration decreases surface tension and nanoparticle concentration increases Brownian motion, and both of them can improve convection mass transfer mechanism and penetration. However, higher surfactant and nanoparticle concentration induced lower mass transfer resistance in the continuous phases. In this study, the dispersed phase controls mass transfer level and addition of any additive will not have a significant effect on the extraction output.

4. Conclusion

The effects of operational parameter including continuous and discontinuous phase flow rate and pulse intensity on hydrodynamic characteristic of liquid- liquid extraction system have been investigated experimentally. Using ANOVA analysis, the most effective operational factor on hydrodynamic characteristic has been determined. The results showed that pulse intensity is the most effective factor on hydrodynamic characteristic and continuous phase velocity factor has the minimum effect on the system operation. Also, the effects of nanoparticles and the surfactant on droplet size and Hold up have been analyzed. The results showed that droplet size reduces by adding nanoparticle and surfactant and hold up increase in the system. Also, by adding nanoparticles and surfactant simultaneously, droplet size decreases and hold up increases impressively. Finally, a semi-empirical equation has been proposed to predict droplet size based on operational parameters and chemical properties of the system.

In the second phase, the effects of adding nanoparticles and surfactant on extraction output were investigated. The results indicated that increasing nanoparticle and surfactant concentration increases extraction output, but increasing nanoparticle concentration alone results in an insignificant increase in the extraction output. Adding surfactant levels resolves the problem. It was also found that lower nanoparticle concentration and pulsation intensity maximized extraction output.



Figuer 12. experimental and calculated results comparison

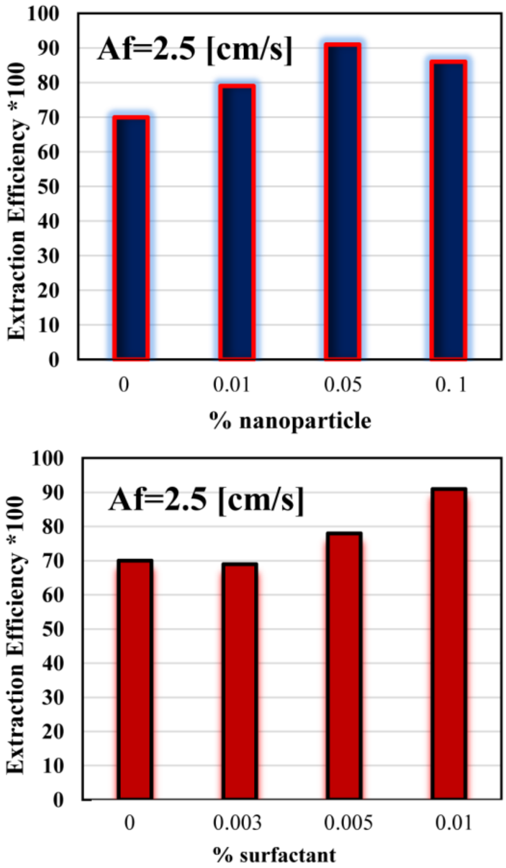


Figure 13. The effects of nanoparticle and surfactant on extraction efficiency

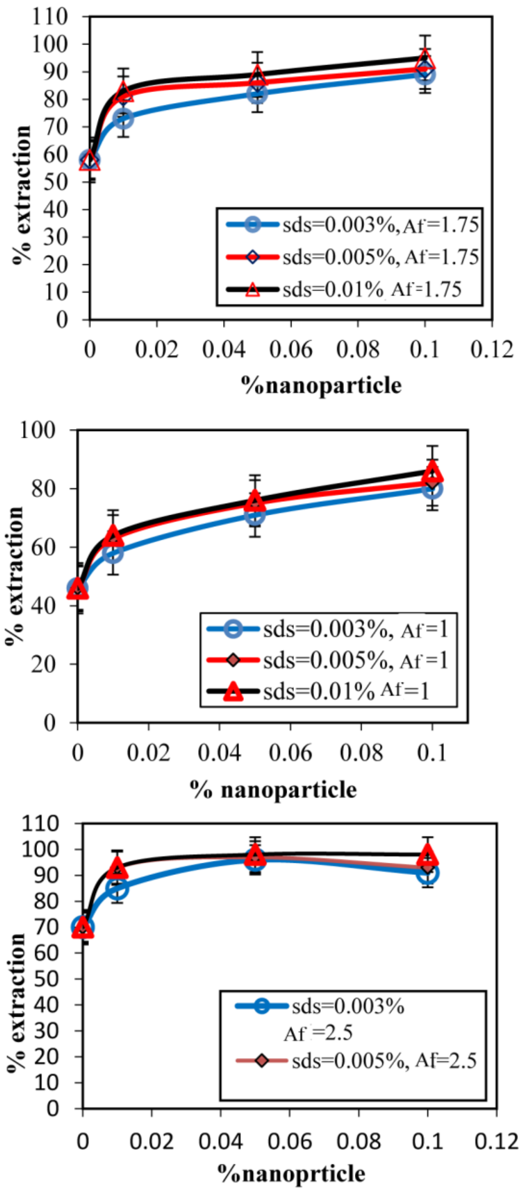


Figure 14. The effects of simultaneous use of nanoparticles and surfactant on extraction

Nomenclature

A	Amplitude of pulsation (m)
D_d	Molecular diffusivity (m2/s)
λ	The viscosity ratio of the phases (dimensionless)
μ_c	Continuous phase viscosity (pa.s)
G	Gravitational acceleration (m/s2)
ρ_c	Continuous phase density (kg/m3)
Δρ	Density difference between phases (kg/m3)
Q_c	Flowrate of continuous phase (m3/s)
L	Column length (m)
Af	Pulsation intensity (cm/s)
ω	Mass fraction of nanoparticles (dimensionles
φ	Dispersed phase hold up (dimensionless)
d32	Sauter mean drop diameter (mm)
μ_d	Dispersed phase viscosity (pa.s)
F	Frequency of pulsation (1/s)
ρ_d	Dispersed phase density (kg/m3)
γ or σ	Interfacial tension (N/m)
Qd	Flowrate of dispersed phase (m3/s)
P_e	Peclet number (dimensionless)
E	Extraction efficiency (dimensionless)

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Appendix

There are no appendices.

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