



Research Article

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Experimental Study of Bulk Water Removal in Two Phase Flow

Weiwei E*, Kevin Pope and Xili Duan

Memorial University of Newfoundland, Canada



Abstract

The improvement of oil-water separation efficiency has become increasingly important in the oil and gas industry, as well as for environmental protection. This study uses both experimental and numerical methods to investigate the effects of flow rate (v), oil volume fraction (vof), and temperature (T) on oil-water separation efficiency. Design Expert software is used to analyzing data of the experiments. Experimental results show that the oil volume fraction and temperature are significant factors for separation efficiency. Also the interaction effects between flow rate and oil volume fraction, and that between flow rate and temperature are significant for oil-water separation efficiency. The oil concentration in separated water decreases significantly as the oil volume fraction increases.

Keywords

Oil-water separation, Multiphase flow, Design of experiment

Introduction

Oil/water separation is important due to increasing industrial oily-waste water in the oil and gas industry [1, 2]. The traditional way to separate oil-water in the industry is by using a gravity-based separator [3,4]. Oil and water separate in the separator because of the difference in specific gravity; oil will move to the surface of the water, while water will move to the bottom of the separator. Keller [5] devised a method to study multiphase flow with oil density between 11 to 70 API gravity. In the study, multiphase flow was injected into the separator, passing through a filter media system designed to collect oil droplets. Lars Schlieper, et al. [6] conducted an experiment in 2004 to investigate the separation behavior of a horizontal gravity separator with three different inner components. This study mainly focused on how inflow to the plate, the plate material, and the distance between the plates influenced the separation length of the separator. They proved that separators with inner components, like plates, can significantly reduce separator length compared to other separators. In 2009 Fitnawan, et al. [7] introduced a new design in gravity separators: the inclined gravity down hole oil-water separator. They found that using this new structure, they were able to increase separation efficiency up to 82%. Krebs, et al. [8] used a kinetic analysis to estimate the relationship between coalescence time and mean droplet diameter in the oil and water multiphase fluid system. They stated that the growth of separated oil and mean droplet diameter followed as a function of time ex-situ to quantify the kinetics of coalescence. In the oil-water two-phase

RSM model Liu, et al. [9] tested the velocity, pressure, and oil concentration distribution of the cyclone separator. The results of this simulation provided the basis for improvements and optimizations to the design of the cyclone separator structure.

Separation efficiency relies on the design of the separator and the operating conditions. This research examines the relationship between flow rate, oil volume fraction, temperature, and oil concentrations. The objective of this paper is to determine three operating factors, which is flow rate, oil volume fraction and temperature, and their effects on oil-water separation efficiency in a gravity separator.

Experimental Apparatus and Design

An American Petroleum Institute (API) separator was designed using Stokes' Law [10]. The API separator is designed based on the specific gravity difference between the oil and water, which is designed standards published by the American Petroleum Institute. Stokes' Law (Eq.1) is used

***Corresponding author:** Weiwei E, Memorial University of Newfoundland, 230 Elizabeth Ave, St. John's, NL A1C 5S7, Canada

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to calculate the rising velocity of oil droplet from the bottom of a separator to the surface of the water.

$$v_v = \frac{2}{9} \left(\frac{\rho_w - \rho_o}{\mu} \right) g R^2$$

$$v_h = 15 v_v$$

where, v_v is oil droplet rising velocity in m/s, v_h is oil droplet horizontal velocity in m/s, g is gravitational acceleration in m/s^2 , ρ_o is density the of oil in kg/m^3 , ρ_w is the density of water in (kg/m^3) , μ is dynamic viscosity in $N \frac{s}{m^2}$, R is oil droplet radius in m.

Figure 1 presents a 3D Solid Works image of the experimental setup. The properties of oil and water in this study are given in (Table 1). Both oil and water were transferred from the storage tanks with a pump to the test section made of 1-inch PVC pipe. Oil and water entered the test section from two pipes via a T-junction. Two pressure sensors and flow meters with a maximum capacity of 10 GPM were located in each of the flow lines (water and oil). After the pumps, each fluid had a bypass pipe to control the flow rate in the main line. The multiphase fluid flowed into the separator tank, where the oil and water were separated.

The traditional one-factor-at-a-time (OFAT) method has very limited ability when there are many factors for an experiment. Using OFAT method to examine the interactions between flow rate, oil volume fraction and temperature requires a large number of experiments, and it is also hard to find interactions between the factors [11,12]. Therefore, the Design of Experiment (DOE) method has been used. DOE is a methodology for systematically and statistically design experiments and analyzes data. The analysis of variance (ANOVA) method is used to analyze the data [13]. DOE is more efficient and capable and is able to reduce the number of experiments significantly without losing the desired data points.

The main purpose of this paper is to study the interaction between variables, therefore, a two-level, three-factor, face-centered composite design (2^3) from the response surface methodology (RSM) was used to investigate the effects of three factors: flow rate (v), oil volume fraction (vof), and temperature (T) on the response of the oil concentration. The RSM method is the most popular mythology in DOE to design three variables with maximum information and minimum experimental tests. The factors and levels are shown in Table 2. A specific run sheet was generated by the Design Expert

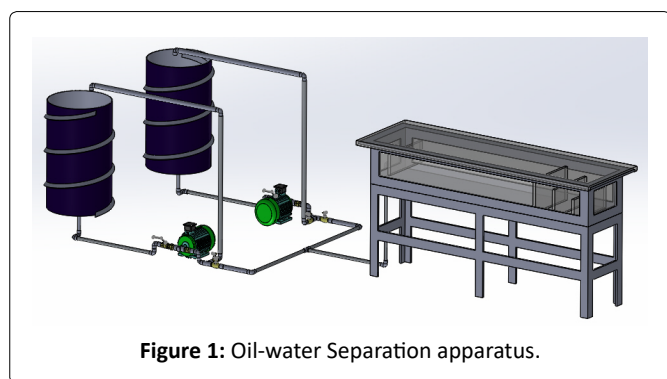


Figure 1: Oil-water Separation apparatus.

Table 1: Properties of oil and water.

Parameters	Mineral oil	Water
Density (kg/m^3)	859	992
Viscosity (cSt)(@40°C)	15	0.6579
Interfacial tension (mN/m)	20.1	20.1

Table 2: Summary of design factors and levels.

Factor	Name	Low Actual	High Actual
v	Flow Rate	1 GPM	2.5 GPM
Vof	Oil Volume Fraction	0.2	0.5
T	Temperature	20°C	32°C

Software. The oil concentration was calculated by taking nine 25 ml samples for each run, then an analytical balance was used to weigh the samples, W_{total} . A centrifuge separator was used to separate the oil and water samples completely. The separation operated at 8500 rpm, for 25 min for each sample. After the second separation process, water was removed from the bottom of the samples with a syringe pump. Then the analytical balance was used to measure the weight of oil, W_{oil} .

In most of the real cases, the oil volume fraction is less than 0.5 in the oil-water multiphase flow. The minimum oil volume fraction 0.2 was designed according to the measurement range of flow meter, which is from 0.1 to 10 GPM. Base on the temperature limitation of glue which is used to connect the pipeline of this experimental setup, temperature range from 20°C to 32°C was selected in this study. In this study, the oil-water separation efficiency is represented by oil concentration.

$$C_{oil} = \frac{W_{oil}}{W_{total}}$$

According to Kline and McClintock [14], in general, if n measurements v_n are being made, each with a measurement tolerance of w_n , and a function R is calculated using the measured values, then the uncertainty or tolerance in the calculation can be determined as:

$$w_R = \left[\left(\frac{dR}{dv_1} \right)^2 (w_1)^2 + \left(\frac{dR}{dv_2} \right)^2 (w_2)^2 + \dots + \left(\frac{dR}{dv_n} \right)^2 (w_n)^2 \right]^{1/2}$$

Based on Eq. (4), for the oil concentration uncertainties of this experiment, Eq. (3) only has one variable, therefore, w_R is determined by the accuracy of the analytical balance, which around 0.0001.

Results and Discussion

After completing the experiments based on the run sheet (a total of 20 runs), an ANOVA result was generated by Design Expert. The ANOVA table is shown in Table 3. Sum of square (SS) means variability of all the experimental data. The smaller value of SS likely indicates the better the model's estimation will be. df represents the degree of freedom. Mean square is a sum of square divided by its df . A p-value less than 0.0500 indicates the factor is significant. Based on this result, some significant factors are as follows: flow rate, oil volume fraction, the interaction effects between flow rate

and oil volume fraction, the interaction effects between flow rate and temperature, and the interaction effects between oil volume fraction and temperature.

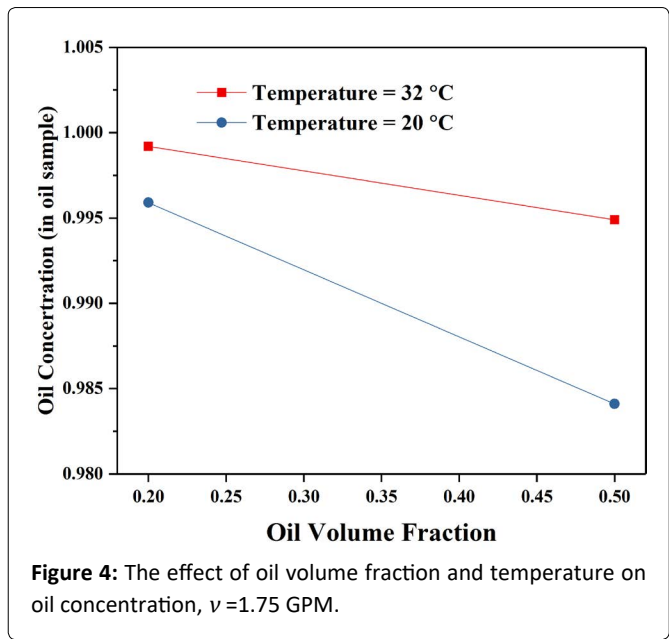
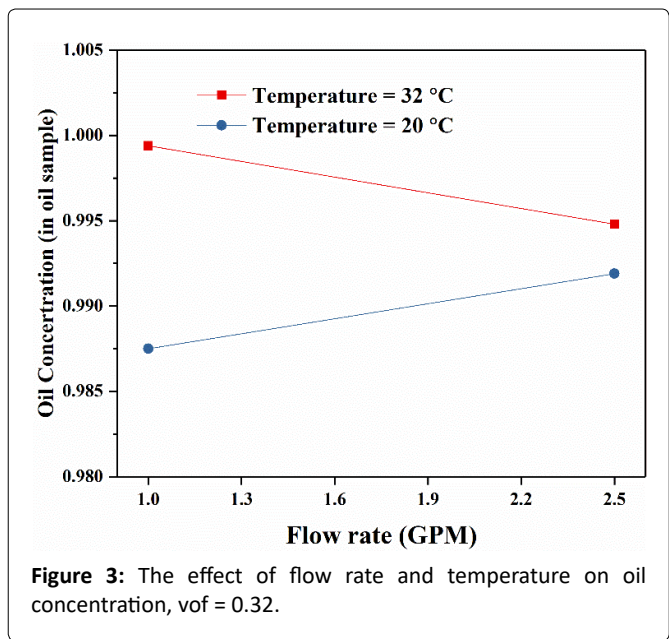
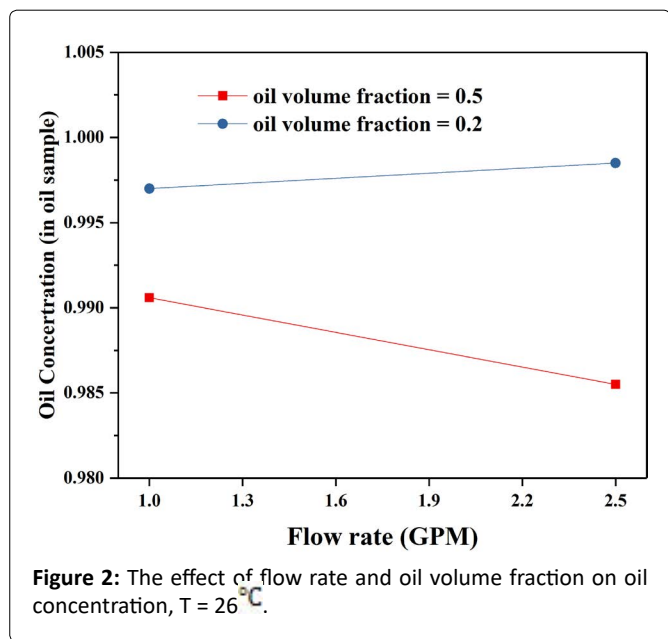
According to Figure 2, when the oil volume fraction = 0.5, the oil concentration decreases as the flow rate increases. However, when the oil fraction = 0.2, oil concentration increases slightly with the increases of the flow rate. With the increase of oil volume fraction, the oil concentration decreases.

Figure 3 indicates that flow rate and temperature have complex effects on oil concentration. When temperature T= 32°C, oil concentration decreases significantly with the increase of flow rate. However, when the temperature is 20°C, the flow rate has positive impacts on oil concentration. With the increase of temperature, the oil concentration decreases.

As shown in Figure 2 and Figure 3, under lower oil volume fraction and lower temperature, separation efficiency improved with the increase of flow rate. The possible reasons for this result were explained by Carlos, et al. [15] in 2001.

Table 3: The ANOVA data analysis.

Source	Sum of Square	df	Mean Square	F Value	p-value Prob > F
Model	6.767×10^{-4}	6	1.128×10^{-4}	15.19	< 0.0001
v-flow rate	1.563×10^{-6}	1	1.563×10^{-6}	0.21	0.0001
vof-oil volume fraction	2.890×10^{-4}	1	2.890×10^{-4}	38.93	< 0.0001
T-temperature	2.176×10^{-4}	1	2.176×10^{-4}	29.31	0.6540
v&vof	1.980×10^{-5}	1	1.980×10^{-5}	2.67	0.0148
v& T	9.025×10^{-5}	1	9.025×10^{-5}	12.16	0.0040
vof& T	5.852×10^{-5}	1	5.852×10^{-5}	7.88	0.1264
Residual	9.651×10^{-5}	13	7.424×10^{-6}		
Lack of Fit	3.470×10^{-5}	2	1.735×10^{-5}	3.09	0.0862
Pure Error	6.181×10^{-5}	11	5.619×10^{-6}		
Cor Total	7.732×10^{-4}	19			



One reason is a higher flow rate means shorter residence time but higher acceleration forces. However, lower flow rates mean longer residence times but lower acceleration forces. In addition, Jiang, et al. [16] and Liu, et al. [17] found that when the flow rate is lower than 20 GPM, the separation efficiency increases with the flow rate. As they explained, another reason is that large flow rate breaks oil droplets into smaller ones, and this increases the emulsification degree of the multiphase fluid. This discourages the separation. On the other hand, a higher flow rate improves the motion of the liquid inside a separator, which is beneficial for oil-water separation.

Figure 4 shows that oil volume fraction has negative effects on oil concentration. With the change of the oil volume fraction from 0.1 to 0.5, oil concentration decreases sharply. Increasing temperature also results in the increase of oil concentration. Reyes, et al. [18] proved a similar oil volume

fraction influence on the separation efficiency trend by using both the simulation and experimental methods in 2006.

Both Figure 3 and Figure 4 show that higher temperature leads to better separation efficiency. The same result is found by Kokal and Al-Ghamdi in 2005 [19]. One of the factors that influence the oil-water separation efficiency is the stability of the emulsion. Based on their study, the oil-water emulsion stability decreases with the increase of temperature. Therefore, higher temperature helps better separation efficiency.

Conclusions

An API designed separator was used to investigate the effects of flow rate (v), oil volume fraction (vof), and temperature (T) on oil concentration. By using the statistical design of experiments, a two-level, three-factor, face-centered composite method was used to investigate the effect on separation efficiency. Based on the ANOVA results, the oil volume fraction (vof) is one of the most important factors on separation efficiency. Oil concentration decreases as the oil volume fraction increases. The interaction effects of flow rate and temperature on oil concentration are complex. Under a higher temperature, the oil concentration decreases with flow rate. However, for a lower temperature, the oil concentration increases with flow rate. This result is consistent with other previous studies.

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