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Hydrodynamics and mass transfer of oil–water micro-emulsion in a three phase internal airlift reactor

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ABSTRACT

In this article, the impacts of liquid properties, loading of solid phase and operating conditions on the hydrodynamic and mass transfer coefficient in a split-cylindrical airlift reactor sparged by air were investigated. The various oil-in-water micro-emulsion systems containing light naphtha, heavy naphtha, kerosene and diesel were used as the liquid phase with oil concentrations of 5% and the solid phase with the loading of 0, 0.25 and 0.5 wt.%. The experimental results showed that a micro-emulsion with the lowest density, viscosity and surface tension had maximum mass transfer and gas hold-up and minimum liquid circulation velocity. The gas hold-up and mass transfer decreased and liquid circulation velocity increased by solid particles addition. Further, solid loading enhancement had a dramatic effect on the mentioned parameters. Moreover, a proper correlation based on dimensionless numbers was used to predict mass transfer in this process. A very good agreement was observed between the correlated data and the experimental ones.

1. Introduction

Airlift bioreactors are among the most important classes of the modified bubble columns. They are structurally divided into two sections by a baffle split or draft tube. They have suitable heat and mass transfer and shorter reaction time; the reason is due to having closer contact between the phases, low shear rate, high mixing performance, and high and flexible capacity [1]. So they widely are use in gas–liquid contacting applications like wastewater treatment, biological processes, aerobic fermentation and chemical industries [2].

Oil in water micro-emulsion is one of the worst by-products of oil refinery, chemical and petrochemical companies [3]. It was reported that the European countries oil refineries produce more than 2000 million tons of wastewater per year [4]. According to the literature some of the wastewater systems can be treated by airlift bioreactors equipped with membrane, bacteria, microorganism and biomass [5].

Solid particles usually are used as microorganism carriers [6] and catalysts [7]. So their influences on hydrodynamic and gas–liquid mass transfer are so important. The solid loading enhancement caused gas hold-up and liquid velocity reduction although it increased the circulation time [8].

Liu et al. [9] studied the liquid dispersion behavior and mass transfer in three-phase external-loop reactor with large particles. They found that large particles loading enhancement decreased mass transfer and dispersion. Hatta et al. [10] studied three-phase flow in a vertical pipe and they found that solid particles motion strongly depends on the gas-phase volumetric flux.

Kassab et al. developed a theoretical model for predicting the airlift-pump performance in the air–water–solid three-phase flow [11]. The mass flow rate of solid particles increased with decreasing particles size although the submergence ratio increased at the same air flow rate.

Sun et al. developed a hydrodynamics model for the prediction of liquid circulation and gas hold-up in the riser of an air–water-silica sands three-phase annulus airlift reactor [12]. They reported, gas hold-up in riser increased with increasing the superficial gas velocity and decreasing solids concentration although liquid circulation velocity increased with the solids concentration reduction.

Talvy et al. used the particles with the density of less than water and with diameter close to the bubbles diameter (with the loading of 20% and 40% v/v) [13]. They found that at the superficial gas velocity of 0–2.5 cm/s, the gas hold-up in the three-phase airlift reactor is similar to the two-phase airlift reactor however at higher superficial gas velocities, a lower gas hold-up may be observed. They also reported that the liquid velocity decreased at various solid particles loadings [13].

The aim of this research is to investigate the impacts of aeration velocity, liquid properties and solid concentration on the hydrodynamics parameters and volumetric mass transfer coefficient in a split-cylinder airlift reactor. The various micro-emulsion systems

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were chosen with the similar concentrations in the wastewaters of petroleum industries. Therefore, hydrodynamic and mass transfer characteristics were studied during the petroleum wastewaters treatment in a gas–liquid–solid contactor such as the applied airlift reactor. To this end, oil-in-water micro-emulsions with oil concentration of 5% (v/v) are prepared and polyamide 6 is used as the solid phase with loading of 0, 0.25 and 0.5 wt.%. According to our experimental data a new correlation was developed and examined for Sherwood number ((Sh) as a symbol of mass transfer) based on the dimensionless numbers (such as Schmidt (Sc), Reynolds (Re) and Bond (Bo) numbers).

2. Experiment

2.1. Materials and method

Different petroleum fractions containing kerosene, heavy naphtha, light naphtha and diesel were purchased from Shazand Oil refinery Company (Iran) and their various solutions with various concentrations (3%, 5% and 7% (v/v)) were locally prepared.

The micro-emulsions were prepared from tap water and petroleum fractions (kerosene, diesel, light naphtha and heavy naphtha) and Nonil Phenol (with purity: 99.5% purchased from Isfahan Copolymer Company) was added as the emulsifier. This emulsifier was obtained from the reaction of Nonil Phenol and ethylene oxide. The number of products with different Hydrophilic Lipophilic Balance (HLB) values which change product application were obtained according to the number of ethylene oxide adducts. Therefore, an appropriate concentration of NF_{60} was gradually added to the mixture of tap water and petroleum for about 20 min until a stable micro-emulsion was obtained. The petroleum fractions and emulsifier properties are summarized in Tables 1 and 2, respectively. Solid phase consists of particles with density of 0.28–0.30 gr/cm^3 and size of 15–20 micron.

2.2. Apparatus set up

The split-cylinder airlift reactor has been explained in detail in the previous publication [14]. The reactor is a glass column with 1.3 m height and is 0.136 m in diameter. It has a rectangular baffle with 0.129 m of width, 1.0 m of height and 0.005 m of thickness. Also, the gas-free liquid height in the column was about 1.23 m for all experiments. A regulating valve and a calibrated rotameter control the volumetric flow rate of air in the riser zone. The inverted U-tube manometers were used to measure the gas hold-up.

2.3. Measurement methods

The gas hold-up in the riser zone was measured using the well-known manometric method [1].

Zuber and Findlay's method [15] was used to find the flow regimes.

The volumetric oxygen transfer coefficient (k_La) was measured by the well-known dynamic gassing-in method [16].

The steady state bubbles diameter size was determined with photographic technique by a digital camera (CANON S51S, with resolution of 8 M pixels).

The Moving Average method was used to estimate the number of bubbles (more than 300). They were randomly chosen in ten pictures which were captured at the middle of the reactor (0.6 m above the bottom). Then, bubbles diameters were measured by WINDIG software (version 2.5). In spherical bubbles, d_1 is equal to d_2 ($d_v = d_1 = d_2$) while elliptical bubbles were measured according to the maximum and minimum diameters of bubbles as the following:

$$d_v = \sqrt[3]{d_1^2 d_2} \quad (1)$$

where d_v, d_1 and d_2 are equivalent, maximum and minimum diameters, respectively. Average of bubbles diameter is calculated through:

$$d_{ave} = \frac{\sum_1^N d_i^3}{\sum_1^N d_i^2} \quad (2)$$

where d_i is the bubble diameter of number i (from 1 to N).

The surface tensions were measured by the Ring method using a tensiometer (Model K10ST, KRUSS GmbH, Germany) for various fluids and the densities of the solutions were calculated from the density law for mixtures. The relevant data are summarized in Table 3.

3. Results and discussion

3.1. Gas hold-up

Fig. 1 shows the overall gas hold-up for four different water micro-emulsions with oil concentration of 5% (v/v) and solid particles with volume fractions of 0, 0.25 and 0.5 wt.% versus superficial gas velocity. Also, the obtained results were compared with pure water data. The gas hold-up increased with increasing superficial gas velocity. Schafer et al. posited that high values of superficial gas velocity increased the bubble collision frequency which caused more coalescence and larger bubbles production [17]. The release of larger bubbles may result in smaller bubbles portion enhancement in the fluid and consequently in gas hold-up increment [18].

The rate of increase in light naphtha based micro-emulsion without solid particles is higher than it in the other fractions (about 131% at the highest superficial gas velocity in comparison with pure water). As shown in Table 3, surface tension, kinematic

Table 1
Material physical properties emulsifier at 20 °C.

Trade name	Avg. EO mole	Appearance	Avg. (Mw)	Water (wt.%)	Density at 20 °C (g/cm^3)	Cloud point (°C)	pH	HLB
NF-60	6	Oily liquid	484	0.5 Max	1.045 ± 0.01	60 ± 4	5–7	10.9

Table 2
Material physical properties oil fractions at 20 °C.

Trade name	SP gravity 15.5/15.5 (°C)	IBP	FBP (°C)	Flash point	Pour point	H_2S	RSH (ppm)
L. naphtha	0.668	47	89	–	–	FREE	<10
H. naphtha	0.7495	95	157	–	–	FREE	<10
Kerosene	0.8035	161	257	49	–	FREE	<10
Diesel	0.8265	239	380	111	3	FREE	<10