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Hydrodynamics of co-current downward liquid-liquid system with packing

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Abstract−The effect of packing and its voidage on the hydrodynamic characteristics of co-current downward liquid-liquid system (CCDLLS) was studied using water and three different oils (exxsol, kerosene and white oil). Two flow regimes, homogeneously dispersed oil regime and heterogeneously dispersed oil, were observed with the total pressure drop showing a minimum at the regime transition velocity. Depending on the packing, frictional pressure drop either shows a minimum or monotonically increases with water velocity. Low-density oil results in higher holdup and correspondingly higher frictional pressure drop. Higher dispersed phase holdup is obtained by using a low voidage packing. Semi-empirical/empirical equations are proposed to predict the frictional pressure drop and phase holdup.

Keywords: Liquid-liquid Flow, Co-current Downward, Packed Bed, Hydrodynamics, Pressure Drop

INTRODUCTION

Mass transfer operations involving two liquid phases, like extraction, show good performance in equipment with good contact between the two phases. This contact depends on the interfacial area between the two phases through which mass transfer takes place. High interfacial area can be achieved when one phase is dispersed in the other, the holdup of the dispersed phase is high and the size of the dispersed phase is small. Spray columns are one among the several liquid-liquid contacting equipment available for mass transfer operations, which have no moving parts and hence easy to operate. In a spray column, the continuous phase and the dispersed phase flow counter-currently to each other. In such a column, if the dispersed phase is lighter than the continuous phase, it rises quickly through the column, and hence the holdup of the dispersed phase is low. Further, in the counter-current mode of operation, the range of operating velocities is limited by flooding, restricting the maximum holdup that can be achieved. One way to increase the holdup is by sending the light dispersed phase downwards co-current to the continuous liquid phase. This contacting mode is termed as co-current downward liquid-liquid system (CCDLLS). Since both liquids are flowing downwards, the buoyancy force of the dispersed phase is resisted by the continuous phase drag resulting in a higher holdup [1].

Few studies have been carried out on the hydrodynamics of CCDLLS. Studies have been conducted on flow regimes, phase inversion, pressure drop and phase holdup. Different flow regimes which have been observed include core annular flow, slug flow, and dispersed flow [2]. In most of the studies, the frictional pressure drop was found to show a minimum at the phase inversion velocity [3]. The different parameters studied include phase velocities, oil viscosity and column diameter. Attempts have been made to predict the transition velocity, frictional pressure drop, and phase holdups, using different models like the homogeneous model and the drift flux model [4].

Most of the above studies on CCDLLS have used energy-intensive devices like ejector/nozzle for distribution of the liquids or have been performed in small diameter columns. The main application area of focus for these studies is on oil transportation through pipes to reduce the frictional energy loss while transporting. A low energy-intensive method of liquid distribution in CCDLLS was studied by Samdavid et al. [5] using a perforated type of distributor. Further, the hydrodynamic characteristics were studied in a large diameter column at low phase velocity focusing on extraction as an area of application. The authors observed oil continuous, and oil dispersed regimes and reported a holdup as high as ~60% near phase inversion velocities.

One of the disadvantages in the CCDLLS, similar to the counter-current liquid-liquid spray column, can be back mixing in the continuous liquid phase, as there are no moving parts in the column. Residence time distribution (RTD) studies carried out by Samdavid [6] in CCDLLS showed that the axial dispersion in the liquid phase is significant in the absence of packing. One of the ways to reduce this back mixing is to contact the two liquid phases in the presence of a packing. Unlike a counter-current liquid-liquid packed system, there is no limitation of operation due to flooding, in the CCDLSS with packing. A literature survey reveals that, to the best of the knowledge of the authors, the only study on co-current downflow of two immiscible-liquids through a packing is by Sallaly and Reynier [7]. These authors studied the phase holdup and dispersed phase flow behavior using tracer techniques. Heptane and water were used as the continuous and dispersed phase, respectively, with Pall rings as packing in a column of ID 5 cm. Exit age distribution of the dispersed phase was found using aqueous NaCl solution as

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Table 1. Properties of liquid

Properties	Water	Exxsol	Kerosene	White oil
Density (Kg/m^3)	1,000	765	800	846
Surface Tension (mN/m)	72.97	18.56	25.44	31.41
Viscosity (mPa s)	0.797	1.15	1.66	24

Table 3. Range of operating parameters

Liquid	Velocity range
Water	60-1,000 lph (0.59 cm/s-9.83 cm/s)
Oil	10-200 lph (0.098 cm/s-1.97 cm/s)

a tracer and fitted using a three-parameter RTD model accounting for mass exchange between static, and dynamic holdup. It was concluded that the total holdup consists of three parts: capillary, static and dynamic. RTD curves of the dispersed and the continuous phase were less skewed at high flow rates due to a decrease in stagnant zones.

Though the presence of packing can reduce the back mixing in the continuous phase, since the packing occupies a portion of the total column volume, the volume available for the flow of liquid phase is reduced. Considering the disadvantage (low available volume for liquid phase) and advantage (reduced back mixing) of adding packing in CCDLLS, hydrodynamic characteristics of CCDLLS with packing requires detailed investigation. Hence, the overall objective of the present work was to comprehensively study the hydrodynamics of CCDLLS with packing. Specifically, the objective was to study the effect of phase velocities, type of oil, and voidage of packing on the hydrodynamic characteristics like flow regime, pressure drop, and phase holdup.

EXPERIMENTAL DETAILS

The hydrodynamic characteristics of the CCDLLS were studied in a glass column of diameter 60 mm and height 2 m. Along the length of the glass column, four sampling ports and ports for measuring pressure drop using differential pressure transmitters (Honeywell STD 810, STD 820) were provided. Water and oil were pumped from their respective storage tanks through calibrated rotameters and sent to the distributor at the top of the glass column. Shell and tube heat exchanger type distributor was used to distribute the liquids so that both the liquids enter the glass column without mixing with each other. The liquid mixture enters the separation tanks after leaving the glass column. Series of separation tanks were used to separate the two-phase mixture leaving the column.

In a typical experimental run, the column was filled randomly with the chosen packing, and a chosen flow rate of oil and water was allowed into the column co-currently downwards. After attaining steady-state, the pressure drop was measured online using the pressure transmitters. Samples of the water-oil mixture were collected from all the four sampling ports. The holdup was calculated from the volume of the two liquids measured after phase separation. The flow regimes for various operating conditions were carefully observed visually. The same procedure was repeated for different flow rates of oil and water, different oils, and packings of different voidage. The static holdup for different oil-packing combinations was also measured.

Three different oils--exxsol, kerosene, and white oil--were chosen to cover a wide range of oil properties. Berl saddles and pall rings were chosen as packings to cover a wide range of packing voidage. The properties of liquids and packings used in the experiments are given in Table 1 and Table 2, respectively. The range of water and oil velocities over which experiments were carried out is given in Table 3. The schematic of the experimental setup is given in Fig. 1.

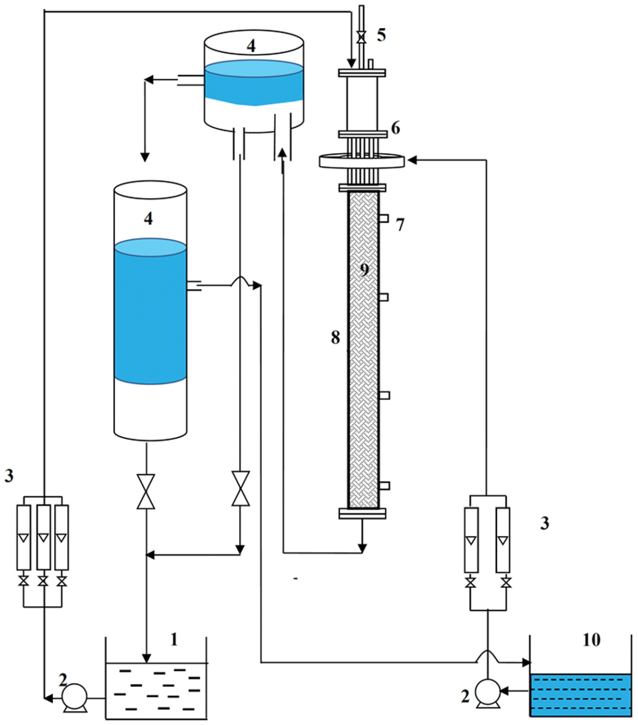

Fig. 1. Schematic of CCDLLS experimental setup.
1. Water tank
2. Pump
3. Rotameter
4. Separation tanks
5. Air vent
6. Distributor
7. Pressure tappings
8. Glass column
9. Packings
10. Oil tank

Table 2. Properties of packing

Packing (Material)	Size	Sphericity	Porosity	Static holdup		
				Exxsol	Kerosene	White oil
Berl saddles (Ceramic)	12 mm	0.40	0.63	0.0354	0.0354	0.0472
Pall rings (Polypropylene)	16 mm	0.14	0.88	0.0177	0.0212	0.0354

RESULTS AND DISCUSSION

1. Flow Regime Map

The flow regimes for the CCDLLS with packing are determined independently based on visual observation and also based on the variation in total pressure drop across the column with water velocity. At a particular oil velocity, as the water velocity is varied, in general two flow regimes are observed with respect to the behavior of the oil phase. At low water velocity, oil flows through the packing as droplets in the voids and spreads as a thin film over the packing surface. Because of the low water velocity and hence lower drag force, some oil drops and adjacent oil film aggregate together at different locations in the test section and form oil lumps. These oil lumps have lower mobility compared to the oil drops. The formation of these oil lumps results in a heterogeneous distribution of oil phase along the bed (heterogeneous dispersed oil regime). On increasing the water velocity, the size of these oil lumps gradually decreases, since the oil is carried away as oil droplets from these oil lumps as a result of increased water drag. At a particular velocity of water, the oil lumps break completely due to the drag exerted by the water phase, and the oil is dispersed as droplets throughout the bed, forming a homogeneous mixture of dispersed oil phase (homogeneous dispersed oil regime). In the presence of packing, for any oil velocity, water exists as the continuous phase even at the lowest water velocity. This is in contrast to the case of CCDLLS without packing [5] where water is the discontinuous phase at lower velocity and changes to continuous phase only at higher velocity. This difference may be due to the high interstitial velocities existing in the column in the presence of packing.

The flow regimes observed visually are also reflected in the total pressure drop. The variation of total pressure drop with water velocity at different oil velocities is shown in Fig. 2 for kerosene with Berl saddles as the packing. For a given oil velocity, the total pressure drop decreases at lower water velocity, goes through a minimum, and then increases for higher water velocity. The total pressure drop has two components: the hydrostatic component and the frictional component. At very low water velocity, the significant component to the total pressure drop comes from the hydrostatic component, and the frictional component is not significant. With an increase in water velocity, the holdup of oil in the column decreases (Section 3.3 Fig. 9), decreasing the hydrostatic component. The frictional component, on the other hand, monotonically increases with water velocity. Hence, the total pressure drop goes through a minimum value. This minimum value corresponds to the transition from oil aggregate (heterogeneous dispersed oil regime) to the oil dispersed regime (homogeneous dispersed oil regime).

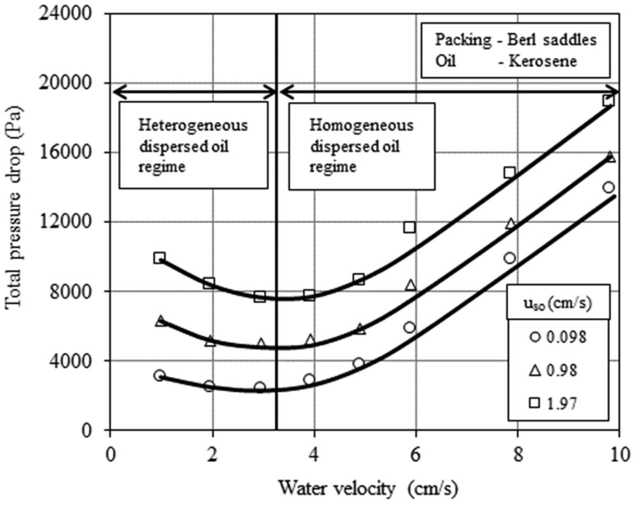

Fig. 2. Flow regime map.

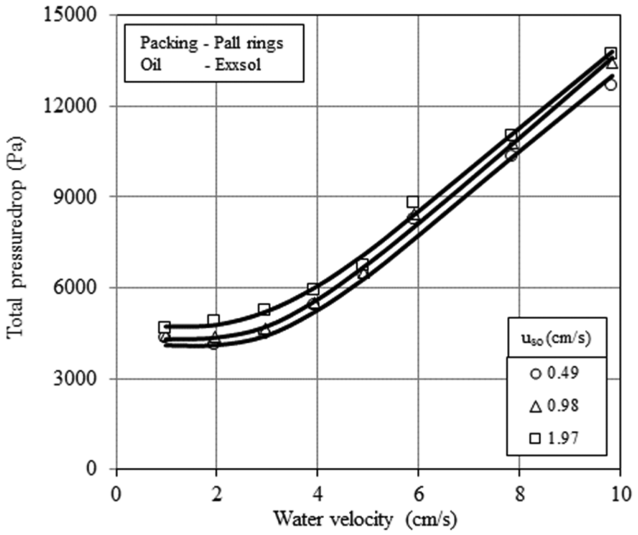

Fig. 3. Variation of total pressure drop with water velocity.

The variation of total pressure drop with water velocity at different oil velocities is shown in Fig. 3 with Pall rings for the exxsol-water system. In general, the variation is similar to that of Berl saddles. However, in the case of Pall rings, the minimum in the total pressure drop is less pronounced and occurs at lower velocity. At very low velocity, oil aggregates are observed similar to the case of Berl saddles. However, when Pall rings are used as packing, the voidage is much higher, and the tendency for the oil to remain as aggregates in the void space between the packing is less. Hence, the oil lumps are broken into the dispersed phase at lower water velocity itself. The minimum in the total pressure drop is less prominent compared to Berl saddles because of higher voidage and lower resistance required for expelling the oil occupying the void space.

2. Frictional Pressure Drop

Frictional pressure drop is obtained by removing the hydrostatic component from the total pressure drop measured across the column, which is given by the equation,

$$\Delta P_{fric}=\Delta P_{Total}-(\rho_w-\rho_m)gL \tag{1}$$

where ρ_m, density of the oil-water mixture flowing through the column is calculated using the expression

$$\rho_m=\rho_w(1-\alpha)+\rho_o\alpha \tag{2}$$

where α is the holdup of oil in the column measured using the sampling method. The effect of different operating parameters on the frictional pressure drop is discussed below.

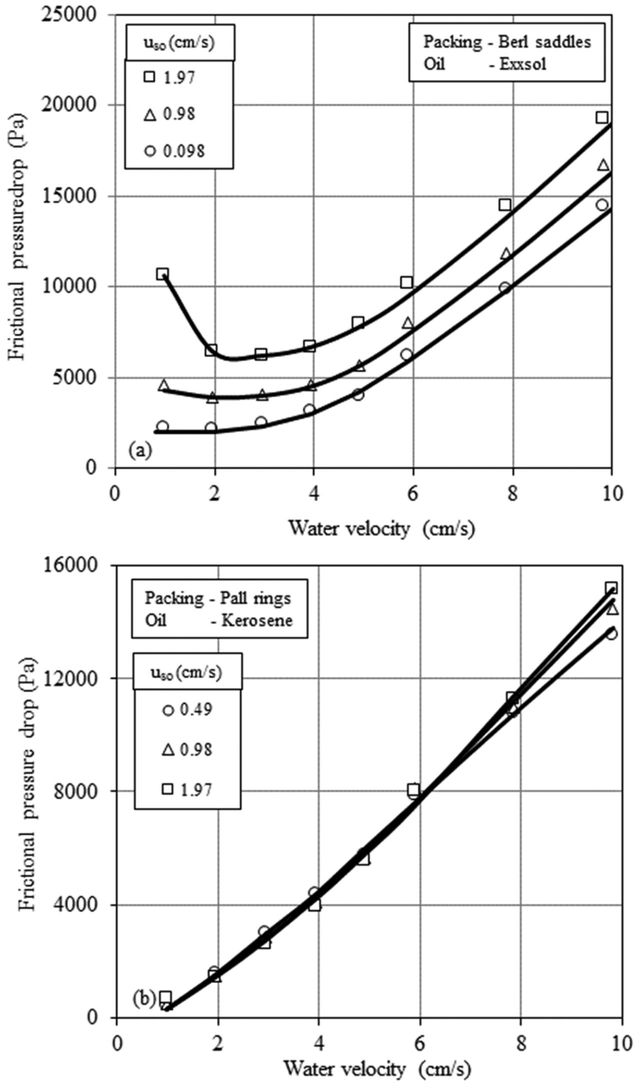

Fig. 4. Variation of frictional pressure drop with water velocity.

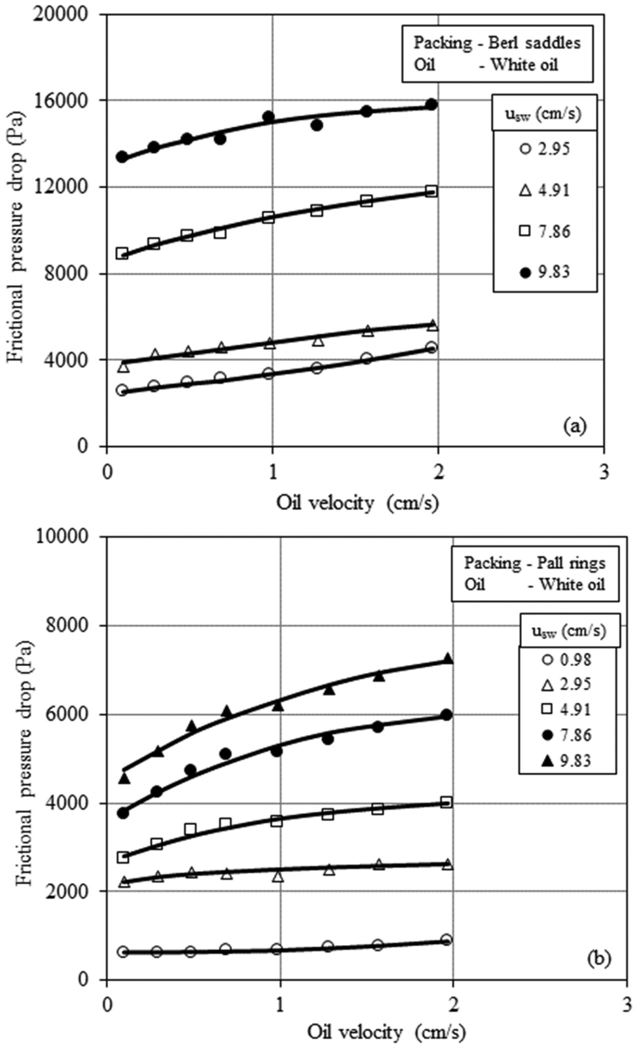

Fig. 5. Variation of frictional pressure drop with oil velocity.

2-1. Effect of Water Velocity

Figs. 4(a) and (b) show the effect of water velocity on frictional pressure drop at different oil velocity for exxsol - with berl saddles and for kerosene - with pall rings respectively. The effect of water velocity on frictional pressure drop is discussed first for Berl saddles, and the differences for pall rings are then highlighted. For a given oil velocity (Fig. 4(a)), with an increase in water velocity, at low water velocity, the frictional pressure drop decreases, and for higher velocity, the frictional pressure drop increases. This results in a minimum in the frictional pressure drop curve. The frictional pressure drop experienced by the water phase has two components: the interfacial friction between water and the oil phase, and the other due to friction between the two-phase mixture and the packing. For a given oil velocity, at low water velocity, oil is in the form of aggregates, as discussed in Section 3.1. These oil lumps are distributed at several places in the column, and with an increase in water velocity, the oil aggregates disintegrate gradually into dispersed drops. This results in the reduction in the size of the oil aggregates, and hence the resistance offered by them decreases. The contribution from friction between water-oil mixture and the solid keeps increasing with water velocity. Since this contribution is not significant at lower water velocity, the overall frictional pressure drop decreases. Beyond the minimum, the oil is in the form of well-dispersed drops, and hence, the resistance offered by them is not significant. However, the friction experienced by oil-water mixture with the packing increases, resulting in an increase in frictional pressure drop with an increase in water velocity.

In the case of Pall rings (Fig. 4(b)), the oil is in the form of drops even at low water velocity, as discussed in Section 3.1, and these drops do not offer significant resistance. Hence, unlike the case of Berl saddles, the frictional pressure drop is close to zero for very low water velocity. The frictional resistance due to the flow of two-phase mixture through the packing increases resulting in a corresponding increase in the frictional pressure drop. So the frictional pressure drop curve for Pall rings does not show a minimum like that of Berl saddles (Fig. 4(b)).

2-2. Effect of Oil Velocity

The effect of oil velocity on the frictional pressure drop is shown in Fig. 5(a) at different water velocity for white oil with Berl saddles. As can be seen from Fig. 5(a), in the case of Berl saddles, the frictional pressure drop increases almost linearly with an increase in oil velocity. The oil being the dispersed phase, the effect of oil on the continuous phase pressure drop, is indirectly realized. The increase in oil velocity results in higher interfacial viscous frictional losses at the oil-liquid interface. An increase of oil velocity leads to the flow of the two-phase mixture at higher velocity through the packing. This also results in higher inertial losses due to the repeated acceleration and deceleration across the packing. Hence, for a given water velocity, the frictional pressure drop increases with an increase in oil velocity.

In the case of Pall rings, in general, it can be seen (Fig. 5(b)) that the frictional pressure drop increases with oil velocity only at high water velocity. This effect is also more pronounced in the case of white oil with very high viscosity compared to exxsol and kerosene. The relatively lower influence of oil velocity on frictional pressure drop in the case of Pall rings than Berl saddles may be due to the higher voidage in the case of Pall rings, resulting in a relatively lower velocity of the two-phase mixture.

2-3 Effect of Oil Type

The effect of oil type on the frictional pressure drop in CCDLLS with packing is shown in Fig. 6 on a plot of frictional pressure drop vs. water velocity for different oil velocities and the two packings. In the case of Berl saddles (Fig. 6(a)), the frictional pressure drop increases in the order white oil, kerosene and exxsol. The holdup of the oil phase in the presence of packing increases in the order white oil, kerosene, and exxsol (Section 3.3, Fig. 12). Higher oil holdup reduces the interstitial area available for liquid flow, and hence the frictional pressure drop increases. In the case of Pall rings (Fig. 6(b)), while the frictional pressure drop is least with white oil, a clear trend is not seen between exxsol and kerosene over the entire range of water velocities. The lower pressure drop for white oil can be explained based on lower holdup, as in the case of Berl saddles.

2-4. Effect of Packing Type

Two different packings, Berl saddles and Pall rings, with a different equivalent diameter and packing voidage have been used. While Berl saddles have higher equivalent diameter (0.0048 m) than that of Pall rings (0.0022 m), a packed bed with Berl saddles has lower voidage (0.63) than that with Pall rings (0.88). The influence of packing on the frictional pressure drop is shown in Fig. 7(a) and (b) at a constant oil velocity for exxsol and white oil. As

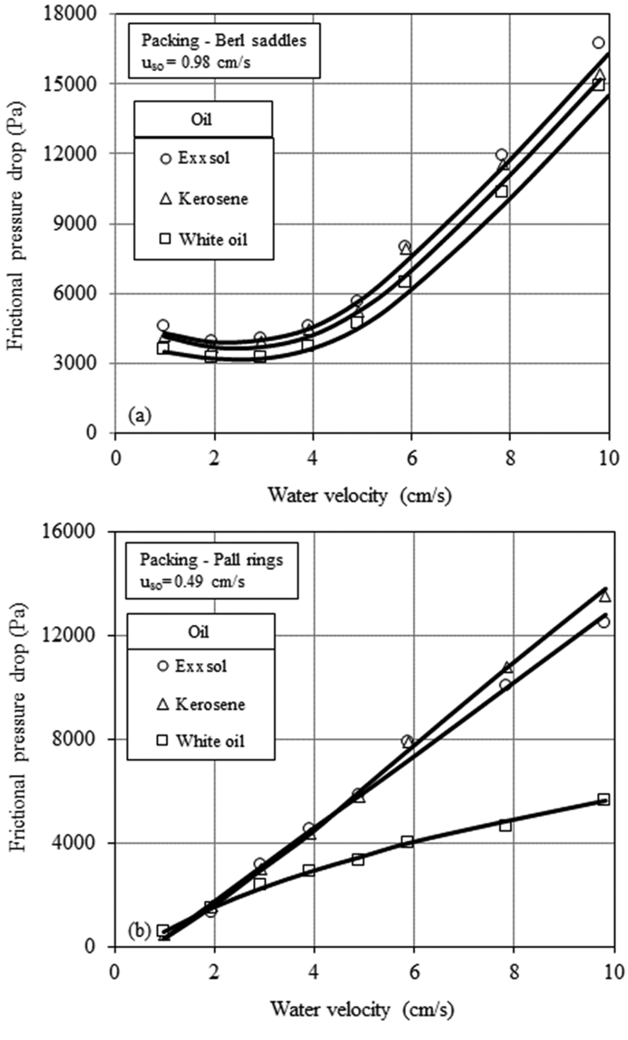

Fig. 6. Effect of oil type on frictional pressure drop.

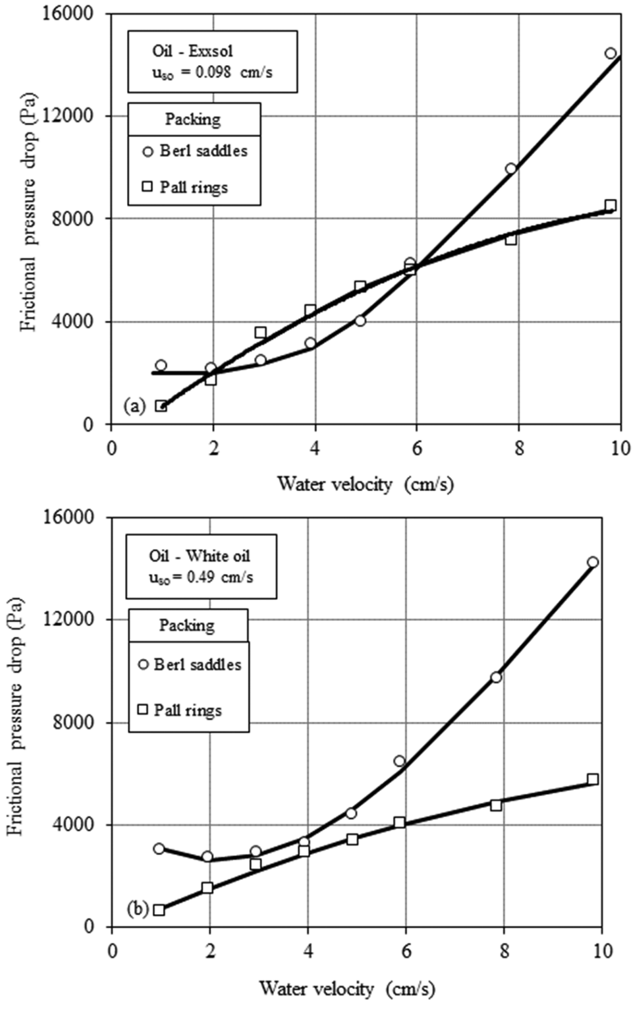

Fig. 7. Effect of packing on frictional pressure drop.

explained in Section 3.2.1, while the frictional pressure drop with Berl saddles goes through a minimum with an increase in water velocity, the frictional pressure drop with pall rings increases monotonically. Hence, for a given oil and water velocity, the frictional pressure drop obtained with either of the packings could be lower or higher.

It can be seen that with exxsol (Fig. 7(a)), at very low and very high water velocity, the frictional pressure drop with Berl saddles is higher than that with Pall rings. At low water velocities, this may be due to the form in which the oil is dispersed inside the voids of the packing. As explained in Section 3.1, at lower water velocities, oil exists as lumps in the case of Berl saddles and as drops in the case of Pall rings. This leads to a higher pressure drop in the case of Berl saddles due to lower free flow area available for the flow of water resulting in higher resistance. At high water velocity, while for both the packings, oil is existing in the form of drops, the lower voidage of Berl saddles may be the reason for higher pressure drop with Berl saddles. At intermediate velocities, the pressure drop with Berl saddles is lower than that with Pall rings. A similar trend is observed in the case of kerosene also (not shown here). In the case of white oil (Fig. 7(b)), the pressure drop obtained using Berl saddles is higher than that using Pall rings over the entire range of water velocity due to the very high viscosity of white oil.

2-5. Prediction of Pressure Drop

Co-current flow of the two immiscible liquids through the packed bed involves complex hydrodynamic interaction between the two liquids and also the liquids and the packing. Contributions to the two-phase pressure drop include the interphase frictional loss between the two liquids and the pressure loss at the liquid-solid interface between the liquid mixture and the surface of the packing. Therefore, it is very difficult to predict the frictional pressure drop for the two-phase flow through packing using a phenomenological approach. Hence in the present work, the pressure drop in CCDLLS with packing is predicted following a semi-empirical approach for the Berl saddles and an empirical approach for Pall rings.

The flow of the two immiscible liquids co-currently downward through the packing is similar to the co-current flow of gas and liquid in a trickle bed in the high interaction bubble regime. Hence, models proposed to predict pressure drop in trickle beds in the high interaction regime were surveyed. Most of the models proposed for trickle beds are in the commercially important low interaction regime of trickle flow or high interaction regime of pulsed flow regime. Very few models have been proposed to predict the pressure drop in trickle beds in the high interaction bubbly regime. One of the semi-empirical equations proposed to the predict pressure drop in the high interaction regimes of pulsed and bubbly flow regimes is by Motil et al. [8].

Motil et al. [8] proposed a semi-empirical equation for predicting frictional pressure drop in a trickle bed operating in the pulsed and bubbly regime. Based on a dimensionless analysis, the authors empirically modified the Ergun equation for single-phase flow through a packed bed, satisfying three limiting conditions. In the present work, a similar approach is used to predict the two-phase pressure drop for co-current downward flow through the packed bed.

The frictional pressure drop for two-phase flow of the immiscible liquids through the packed bed depends on the phase velocities, liquid properties, packing diameter and packing void fraction:

$$\frac{-\Delta P_{TP}}{L}=f(u_{sw},\ u_{so},\ \mu_w,\ \mu_o,\ \rho_w,\ \rho_o,\ \Delta\sigma,\ \phi_s d_p,\ \varepsilon) \tag{3}$$

Based on dimensional analysis, the relation between the dimensionless numbers can be expressed as

$$-\frac{\Delta P}{L}\frac{\phi_s d_p}{\rho_w u_{sw}^2}=f\left[\frac{\rho_o}{\rho_w},\ \frac{\mu_o}{\mu_w},\ \frac{\Delta\sigma}{\rho_w u_{sw}^2\phi_s d_p},\ \frac{\mu_w}{\rho_w u_{sw}\phi_s d_p},\ \frac{u_{so}\rho_o\phi_s d_p}{\mu_o},\ \varepsilon\right] \tag{4}$$

In the work of Motil et al. [8], the effect of density and viscosity ratios was neglected due to weak dependence. However, in the present work, since the flowing fluids are both liquids and their viscosity varies over a very wide range, the dependence on the viscosity ratio is retained. Expressing Eq. (4) in terms of dimensionless numbers, we get

$$f_{TP}=f\left[\frac{1}{We_w},\ \frac{1}{Re_w},\ Re_o,\ \varepsilon,\ \frac{\mu_o}{\mu_w}\right] \tag{5}$$

where $f_{TP}=-\frac{\Delta P_{TP}}{L}\frac{\phi_s d_p}{\rho_w u_{sw}^2}$ $We_w=\frac{\rho_w u_{sw}^2\phi_s d_p}{\Delta\sigma}$;

$Re_w=-\frac{\rho_w u_{sw}\phi_s d_p}{\mu_w}$; $Re_o=\frac{\rho_o u_{so}\phi_s d_p}{\mu_o}$

Expressing Weber number in terms of Reynolds and Suratman number,

$$\frac{1}{We_w}=\frac{Su_w}{(Re_w)^2} \tag{6}$$

where $Su_w=\frac{\rho_w\Delta\sigma\phi_s d_p}{\mu_w^2}$,

Eq. (5) can be written in the form

$$f_{TP}=f\left[\frac{Su_w}{Re_w^2},\ \frac{1}{Re_w},\ Re_o,\ \varepsilon,\ \frac{\mu_o}{\mu_w}\right] \tag{7}$$

The two-phase friction factor (f_{TP}) given by the above equation should satisfy the following limiting conditions: approach single-phase packed bed friction factor for water flow in the limit of zero oil velocity and zero interfacial tension and become a constant at high Reynolds number. The form of an empirical equation which satisfies these limiting conditions is

$$f_{TP}-f_{SP}=a\left(\frac{Re_o}{1-\varepsilon}\right)^b\left(\frac{1-\varepsilon}{Re_w}\right)^{b'}\left(\frac{(1-\varepsilon)^2 Su_w}{Re_w^2}\right)^c\left(\frac{\mu_o}{\mu_w}\right)^d \tag{8}$$

where f_{sp} represents the single-phase friction factor as represented by the equation,

$$f_{sp}=\frac{\Delta P_{sp}\phi_s d_p\varepsilon^3}{L\rho_w(1-\varepsilon)u_{sw}^2}=K_1\frac{(1-\varepsilon)}{Re_w}+K_2 \tag{9}$$

The value of parameters a, b′ and c fitted by Motil et al. [8] for their experimental data on frictional pressure drop for co-current gas-liquid flow through packed bed under microgravity conditions are 1/2, 1/3 and 2/3. This shows that the parameters b′ and c sum up to 1. Similarly, in the present work also, the parameters were assumed to be related by b′+c=1.

Hence, the final form of the two-phase friction factor for the two-phase co-current down-flow of two immiscible liquids through the packed bed is

$$f_{TP}=\frac{1-\varepsilon}{\mathrm{Re}_w}\left[\mathrm{K}_1+\mathrm{a}\left(\frac{\mathrm{Re}_o}{1-\varepsilon}\right)^b\left(\frac{\mathrm{Su}_w(1-\varepsilon)}{\mathrm{Re}_w}\right)^c\left(\frac{\mu_o}{\mu_w}\right)^d\right]+\mathrm{K}_2 \tag{10}$$

The ε in the above equation is the effective void fraction of packing, i.e., the void fraction obtained after subtracting the static liquid holdup from the total void fraction of the packing. Based on the experimental data, the best values for the parameters K_1, K_2, a, b, c, and d are obtained by minimizing the AARE between experimental and predicted two-phase frictional pressure drop. These values are 140, 1.45, 13, 0.65, 0.25 and 0.35, respectively. The predicted data are compared with the experimental data in Fig. 8(a). It can be seen that the semi-empirical equation predicts the data satisfactorily with an AARE of 5%. The range of validity of the above correlation is $230<\mathrm{Re}_w<590$, $0.5<\mathrm{Re}_o<62$, $1.4<\mu^*<30$ and $3.1\times10^5<\mathrm{Su}_w<4.1\times10^5$.

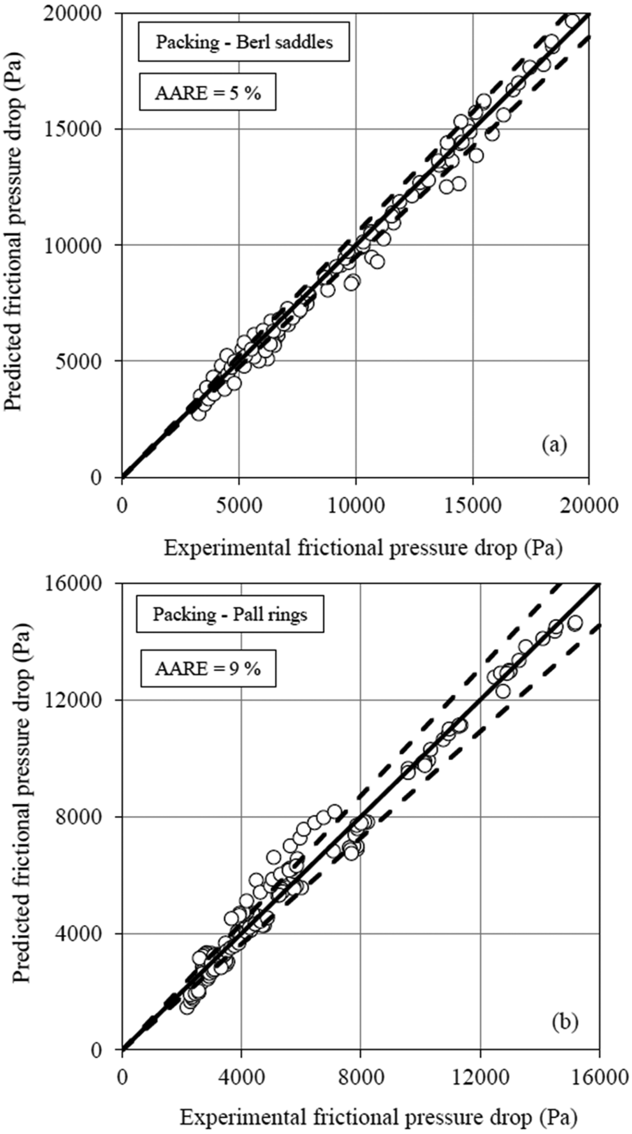

Fig. 8. Comparison of experimental and predicted frictional pressure drop.

The following empirical equation is proposed to predict the two-phase liquid-liquid pressure drop through Pall rings:

$$f_{TP}=\frac{3600(1-\varepsilon)}{\mathrm{Re}_w+\mathrm{Re}_o}\left(\frac{\mathrm{Re}_w}{1-\varepsilon}\right)^{0.15}\left(\frac{\mathrm{Re}_o}{1-\varepsilon}\right)^b\left(\frac{\mu_o}{\mu_w}\right)^{-0.3}\left(\frac{\Delta\sigma}{\sigma_w}\right)^{-0.5} \tag{11}$$

$$\text{with}\quad b=1-1.15\left(\frac{\Delta\rho}{\rho_w}\right)^{0.14}$$

where the values of the parameters are obtained by minimizing the AARE between the predicted and experimental frictional pressure drop. The predicted data is compared with the experimental data in Fig. 8(b). It can be seen that the empirical equation predicts the data satisfactorily with an AARE of 9%. The range of validity of the above correlation is $83<\mathrm{Re}_w<275$, $0.08<\mathrm{Re}_o<29$ and $1.4<\mu^*<30$.

3. Phase Holdup

The phase holdup for the CCDLLS with packing refers to the fractional volume of the dispersed oil phase in the fluid in the voids of the packing. As explained in Section 2, phase holdup has been measured using the sampling method. The effect of different operating parameters--water velocity, oil velocity, type of oil,

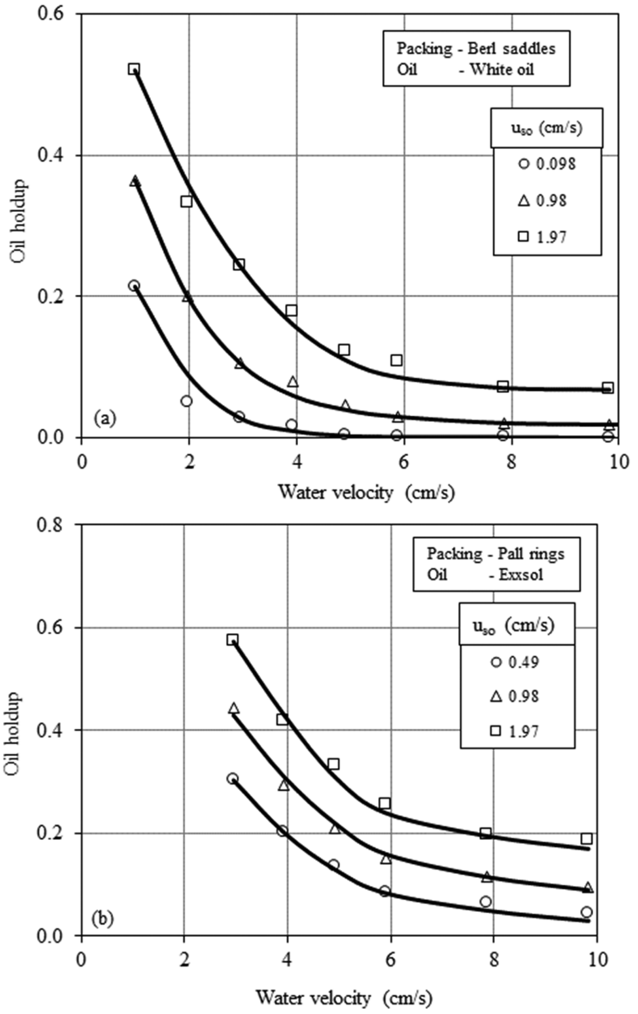

Fig. 9. Variation of oil holdup with water velocity.

and packing--has been studied. These effects are discussed below.

3-1. Effect of Water Velocity

As explained in Section 3.1, at lower water velocity in the heterogeneously dispersed oil regime, for a given oil velocity, the oil phase forms lumps at different locations along the bed. Because of the formation of these oil pockets, the oil holdup is high. The oil holdup is much higher than a holdup of 0.6, which is the maximum holdup that would be expected if the oil phase is present as well dispersed drops. As explained in Section 3.1, the oil aggregates break into drops with an increase in water velocity, and the regime changes to dispersed oil drops in the homogeneous dispersed oil regime. The effect of water velocity on phase holdup is discussed only in this homogeneous dispersed oil regime for both the packings. Similarly, the other effects are also discussed in this regime only.

Effect of water velocity on phase holdup is shown in Fig. 9(a) and (b) at different oil velocities for white oil with berl saddles and exxsol with pall rings, respectively. It can be seen that, for a given oil velocity, the dispersed phase oil holdup decreases with an increase in water velocity. As the water velocity increases, the oil drops are carried out of the test section by the drag exerted by water. Hence, the dispersed phase oil holdup decreases with an increase in water velocity. It can be seen that the holdup decreases steeply at low water velocity because the interstitial velocity of water is higher in the presence of more holdup occupying, more cross-sectional area of the column. Higher the interstitial velocity of water, more oil is flushed out of the voids, thus decreasing the oil holdup at a faster rate.

3-2. Effect of Oil Velocity

Fig. 10 shows the effect of oil velocity on dispersed phase holdup at different water velocity for kerosene with berl saddles. For a given water velocity, as expected, an increase in oil velocity increases the dispersed oil phase holdup. As the throughput of oil increases, the amount of oil in the system increases, hence the oil phase holdup increases.

3-3. Effect of Oil Type

The effect of oil type on the dispersed oil phase holdup is shown in Fig. 11 for different water velocities at an oil velocity for pall rings. In general, the phase holdup at any oil and water velocity increases in the order: white oil, kerosene and exxsol. This variation of phase holdup with the oils can be explained based on the density of the oils used. The density of the three oils used is 846 kg/m^3 (white oil), 800 kg/m^3 (kerosene) and 765 kg/m^3 (exxsol). Hence it can be seen that with a decrease in oil density the phase holdup increases. Because of the increase in buoyancy force with a decrease in oil density, the resistance experienced by the oil drops to the water drag increases. Due to this increased resistance, the amount of oil staying in the column increases, which results in higher oil holdup. Hence, oil with lower density shows relatively higher oil phase holdup.

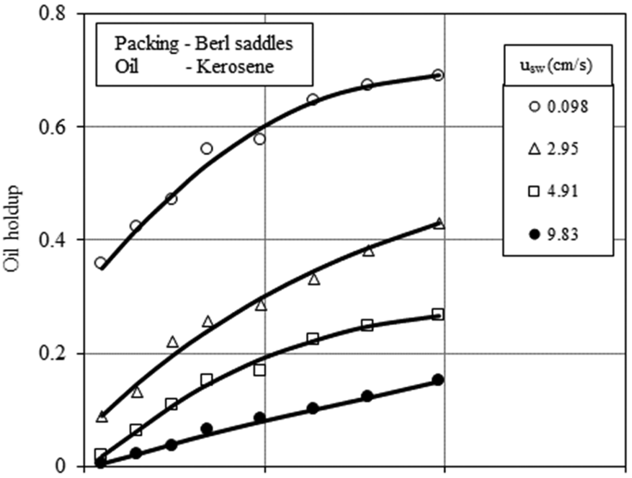

Fig. 10. Variation of oil holdup with oil velocity.

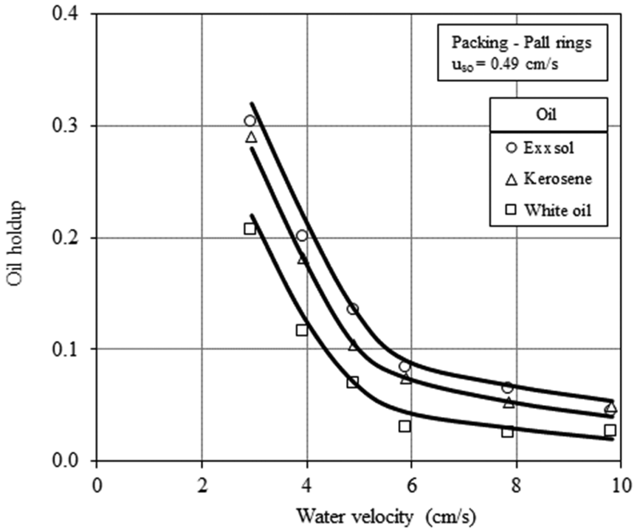

Fig. 11. Effect of oil type on oil holdup.

3-4. Effect of Packing Type

Samdavid et al. [5] studied the effect of phase velocities on the dispersed phase holdup in the oil dispersed regime in the CCDLLS without packing. In this section, the effect of contacting the two liquids in the presence of packing, on the phase holdup is discussed. The influence of the type of packing (differing in void fraction) is also discussed. Fig. 12 shows the effect of type of the packing used, Pall rings and Berl saddles, on the dispersed phase holdup for kerosene and white oil. To compare the effect of using a packed bed for contacting the two liquids, the data on phase holdup in the system without packing is also included in these figures. For the system without packing, the holdup in the dispersed oil regime only is shown. Similarly, for the system with packing, holdup in the homogeneous oil dispersed regime only is shown.

In general, the use of packing results in lower phase holdup. The lower holdup in the system with packing is due to the higher interstitial water velocity in the presence of packing. Comparing the two packings, higher phase holdup is obtained when Pall rings are used. Pall ring has a higher void fraction (packing voidage of 0.88) compared to Berl saddles (packing voidage of 0.63). Hence, the interstitial velocity is lower in the case of Pall rings, which results in higher holdup compared to Berl saddles. It can also be seen (Fig. 12) that the difference in phase holdup for the two packings de-

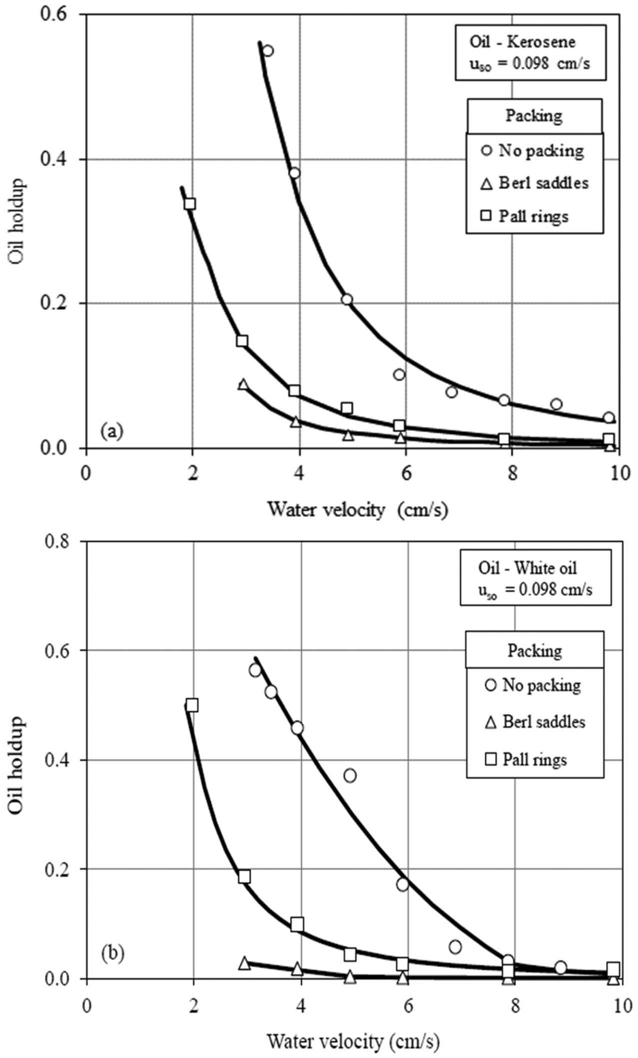

Fig. 12. Effect of packing on oil holdup.

creases with an increase in water velocity. At higher water velocity, the interstitial velocity is more through both the packings flushing out almost all the oil from the voids of the packing, resulting in almost same holdup.

3-5. Correlation for Prediction of Phase Holdup

All the experimental data on holdup of oil in the presence of packing is empirically correlated using the equations

$$\alpha = \frac{1.4\mu^{*0.55}}{\left(1+\frac{\mathrm{Re}_w}{\mathrm{Re}_o}\right)} \qquad (12)$$

$$\alpha = \frac{1.4\mu^{*0.75}}{\left(1+\frac{\mathrm{Re}_w}{\mathrm{Re}_o}\right)} \qquad (13)$$

for Berl saddles and Pall rings, respectively. Figs. 13(a) and (b) show the comparison between experimental and predicted holdup for Berl saddles and Pall rings, respectively. The experimental holdup for Berl saddles and Pall rings is predicted satisfactorily with an AARE of 15% and 14%, respectively. The range of validity of the above correlations is the same as that of the correlations for friction factor for Berl saddles and Pall rings, respectively.

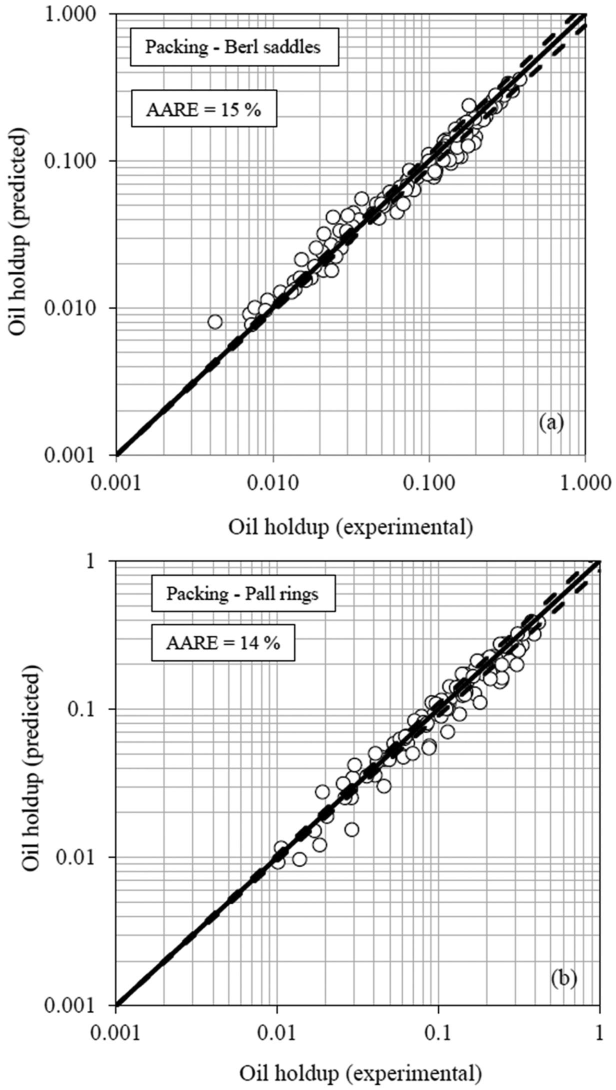

Fig. 13. Comparison of oil holdup experimental and predicted.

CONCLUSIONS

Hydrodynamic characteristics were experimentally studied in a co-current downward liquid-liquid system with packing by varying the phase velocities, oil properties, and voidage of packing. The hydrodynamic characteristics studied included flow regimes, pressure drop, and holdup. In the CCDLLS with packing, two flow regimes were observed, depending on the state of aggregation of the oil phase. At low water velocity, oil is distributed heterogeneously due to the formation of oil lumps, resulting in heterogeneous dispersed oil regime. On increasing the water velocity, the oil lumps break into droplets, forming a homogeneous oil-water mixture resulting in homogeneous dispersed oil regime. The regime transition is marked by a minimum in the total pressure drop with water velocity. This is due to the opposite effect of water velocity on the hydrostatic component (decreases due to a decrease in oil holdup with water velocity) and frictional component (increases with water velocity).

Frictional pressure drop shows a minimum with an increase in water velocity. This is due to the opposite effect of water velocity on the friction between oil and water (decreases due to breakage of oil lumps) and friction between the two-phase mixture and the packing (increases with water velocity). For a given water velocity, the frictional pressure drop increases with an increase in oil velocity because of the two-phase mixture flowing at high velocity through the packing. Frictional pressure drop increases in the order white oil, kerosene, and exxsol. This is due to higher oil holdup, which reduces the interstitial area available for liquid flow. In general, the frictional pressure drop with Pall rings is lower than that with Berl saddles. The difference is large at lower (due to aggregation of oil) and higher water velocities (due to higher voidage for Pall rings), and frictional pressure drop is nearly the same for both the packings in the intermediate range of water velocities. Semi-empirical or empirical correlations have been proposed to predict frictional pressure drop with Berl saddles and Pall rings as packings.

As the water velocity increases, the oil drops are carried out of the test section by the drag exerted by water. Hence, the dispersed phase oil holdup decreases with an increase in water velocity. For a given water velocity, an increase in oil velocity increases the dispersed oil phase holdup. The phase holdup increases in the order, white oil (846 kg/m^3), kerosene (800 kg/m^3), and exxsol (765 kg/m^3) due to higher buoyancy force resulting from a decrease in oil density. In the presence of packing, the holdup of the dispersed phase is reduced due to the higher interstitial water velocity in the presence of packing. Higher phase holdup is obtained when Pall rings are used, due to larger void fraction. At high water velocity, the holdup is almost the same with both the packings due to flushing out of almost all the oil from the voids of the packing.

The results of the present work can help identify suitable operating conditions for the operation of CCDLLS. While CCDLLS without packing provides higher holdup, it can also have the limitation of high back mixing in the continuous liquid phase. With the use of packing, this back mixing can be reduced, though at the expense of reduced phase holdup. The selection of suitable CCDLLS and operating conditions will depend on the preference between high holdup or low back mixing.

NOMENCLATURE

d_p : diameter of packing [m]
D : diameter of the column [m]
g : acceleration due to gravity [m/s^2]
L : length of the test section [m]
Re_o : oil phase Reynolds number [dimensionless]
Re_w : water phase Reynolds number [dimensionless]
Su_w : suratman number of water [dimensionless]
u_o : interstitial velocity of oil [m/s]
u_{so} : superficial velocity of oil [m/s]
u_{sw} : superficial velocity of water [m/s]
u_w : interstitial velocity of water [m/s]
We_w : weber number of water $\left(\frac{\rho_w u_w^2 D}{\mu_w}\right)$ [dimensionless]

Greek Letters

μ^* : viscosity ratio (μ_o/μ_w) [dimensionless]
μ_o : viscosity of oil [Pa·s]
μ_w : viscosity of water [Pa·s]
α : volume fraction of oil [dimensionless]
$\Delta\rho$: density difference between water and oil ($\rho_w-\rho_o$) [kg/m^3]
$\Delta\sigma$: interfacial tension between water and oil [N/m]
ε : voidage of packed bed [dimensionless]
ρ_m : density of liquid-liquid mixture [kg/m^3]
ρ_o : density of oil [kg/m^3]
ρ_w : density of water [kg/m^3]
σ_w : surface tension of water [N/m]
ϕ_s : sphericity of packing [dimensionless]

Abbreviations

CCDLLS : co-current downward liquid-liquid system
AARE : average absolute relative error

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