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Dispersed Phase Holdup in a Tall and Low Plate Free Area Liquid Pulsed Sieve-Plate Extraction Column

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Dispersed phase holdup is studied in a tall and low plate free area pulsed sieve-plate extraction column. The 5.0 cm internal diameter column consists of 80 number of plates with percent free area of 13.5. The effects of pulse velocity (product of amplitude and frequency), superficial phase velocities, and solute addition are studied for five liquid-liquid systems with a wide range of interfacial tensions. The experimental holdup data is tested against the most widely recommended correlations and a new correlation has been developed that best fits the data.

Keywords dispersed phase holdup; holdup correlation; hydrodynamics; interfacial tension; pulsed extraction column

INTRODUCTION

The study of hydrodynamics of a liquid pulsed column is important in the design of a new liquid-liquid system with minimal of pilot scale testing (1). The hydrodynamic behavior of the column is largely affected by the dispersed phase holdup. Dispersed phase holdup, defined as the volume fraction of the dispersed phase in a dispersion, is an important property and has fundamental significance in the design and operation of a pulsed column (2). It directly affects interphase mass transfer as well as the capacity of a column. It is also important in providing information regarding solvent inventory (3). Dispersed phase holdup depends on a variety of factors such as pulse velocity (pulsation intensity), superficial phase velocities and physical properties of the liquid phases, and column geometry. A number of researchers such as Cohen and Bayer (4), Logsdail and Thornton (5), Sanvordenker (6), Sehmel and Babb (7), Miyunchi and Oya (8), Bell and Babb (9), Khemangkorn et al. (10), Shenlin et al. (11), Pietzsch and Blass (12), Lorenz et al. (13), Mohanty and Vogelpohl (14), and Venkatnarasaiah and Varma (2) have studied the effect of various influencing parameters on the dispersed phase holdup. However, only a few studies (13), though not detailed, have been carried out describing the effect of interfacial tension on the liquid holdup. In the present study, dispersed phase holdup is studied for five different liquid-liquid systems, namely naphtha-water, kerosene-water, toluene-water, *iso*-amylacetate-water, and *iso*-amylalcohol-water systems comprising a wide range of interfacial tension. Propionic acid is used as a solute in toluene-water system to observe the effect of mass transfer on the dispersed phase holdup. The effect of pulse velocity, superficial phase velocities, interfacial tension, and addition of the solute are studied. To our knowledge, the study of the dispersed phase holdup with systems water-naphta and water-propionic acid-toluene is not reported previously in the published literature. Moreover, most of the literature studies are carried out in columns with plate free area $\geq$19.0%, the column studied in the present study had a plate free area of only 13.5% and was unique in its dimensions. It was a tall column with 424 cm as the effective height and 80 number of plates.

Yadav and Patwardhan (15) have reviewed the holdup correlations and pointed out the correlations after Kumar and Hartland (3) and Venkatnarasaiah and Varma (2) are the most important holdup correlations. In the present study, the experimental holdup data is tested against the above mentioned correlations and the recommendations for the use of the two correlations are outlined. Moreover, a new correlation is developed for the experimental holdup data obtained in the present study.

EXPERIMENTAL

The laboratory pulsed column was 5.0 cm I.D. (internal diameter) glass column and had 80 number of plates. Each plate had 36 number of holes and the plate free area was only 13.5%. The total effective height (extraction section) of the column was 424 cm. Pulsation in the column was produced by a motor-driven pulsator. All the chemicals were of commercial grade and water available in the laboratory was used as received without further purification. Interfacial tensions of the liquid-liquid systems were measured by the drop weight method. The systems studied along with their interfacial tensions are given in Table 1,

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TABLE 1
Systems studied in the present study along with their interfacial tensions

System of study	σ (mN/m)*
Water-naphtha	45.0**
Water-kerosene	42.7
Water-toluene	34.7
Water-*iso*-amylacetate	10.1
Water-*iso*-amylalcohol	4.50
Water-propionic acid-toluene (10.0 wt% aqueous solution)	19.9

*Measured by drop-weight method.
**(20).

while the physical properties of the liquids are given in Table 2. Propionic acid was used as a solute in toluene-water system to observe the effect of addition of solute on the dispersed phase holdup. Propionic acid was of analytical grade from Fischer Scientific® with ≥98% purity. In a typical procedure, primarily the entire column was filled with aqueous phase which behaved as continuous phase in each of the systems studied. Being heavier, aqueous phase was allowed to flow from the top to the bottom. The dispersed phase as lighter than water was allowed to flow from the bottom to the top of the column in counter-current to the aqueous phase flow. For measurement of dispersed phase holdup, sampling method (16) was adopted. There were eight sampling points in the column. 100 mL volume from each tap was taken and collected to settle for the two phases to be separated. Nearly 5 min were given between any two samplings so that each sample was taken under steady-state. This procedure was followed for all eight samples under a constant set of pulsation intensity and phase flow rates. The volume fraction of the dispersed phase in each sample provided the value of the dispersed phase holdup, here called the plate dispersed phase holdup. The average of all these plate holdups was used to report the dispersed phase holdup by sampling method. Figure 1 shows one typical profile showing variation of dispersed phase holdup with height of the column and average value of all these plate holdups. During the course of an experimental run an interface at the top was maintained as the dispersed phase was flowing from the bottom. This step was a precautionary step to avoid flooding in the column. Flooding tremendously decreases the efficiency of a column. Dispersed phase needs coalescence in the top reservoir before leaving the column. The interface was controlled manually by throttling the discharge valve of the continuous phase flow. A wide range of experimental conditions were studied. Table 3 provides the ranges of the experimental conditions.

TABLE 2
Physical properties of liquids

Liquids	$\rho \times 10^{-3}$ (kg · m^{-3})	$\mu \times 10^{3}$ (Pa · s)
Naphtha	0.684	0.52
Kerosene	0.783	1.67
Toluene	0.860	0.56
Iso-amylacetate	0.865	0.87
Iso-amylalcohol	0.810	3.86
Water	0.998	1.0

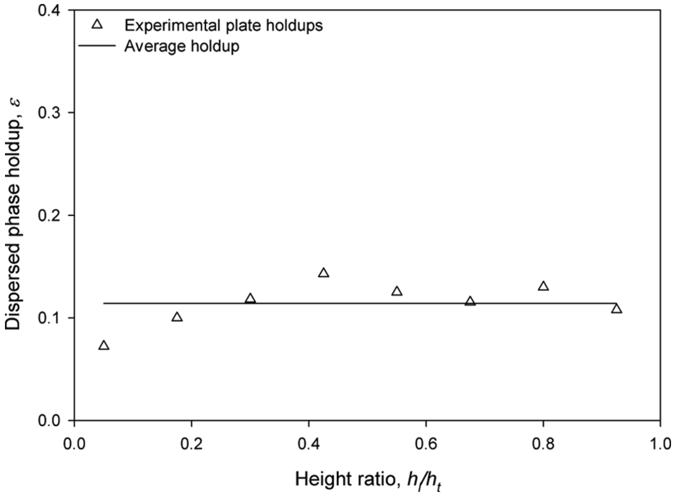

FIG. 1. Variation of dispersed phase holdup with height ratio (defined as height of the *ith* sampling point from the bottom of the column to the total effective column height) and average of these holdups for the *iso*-amylalcohol-water system. $A \cdot f = 6.3 \times 10^{-3}$ m/s, $u_d = 2.73 \times 10^{-3}$ m/s, $u_c = 2.86 \times 10^{-3}$ m/s.

TABLE 3
Ranges of operating conditions for the present study

Ranges of operating conditions	Values
$A \cdot f$ (mm/s)	3.01–32.4
u_d (mm/s)	1.0–5.67
u_c (mm/s)	1.25–6.30
σ (mN/m)	4.50–45.0

RESULTS AND DISCUSSION

Effect of Pulse Velocity

No Mass Transfer

Figure 2 shows the effect of pulse velocity ($A \cdot f$) on the dispersed phase holdup for no mass transfer conditions. Five binary systems with varying interfacial tensions are studied. A wide range of interfacial tension (4.50–45.0 mN/m) is applied to observe the effect of pulse velocity

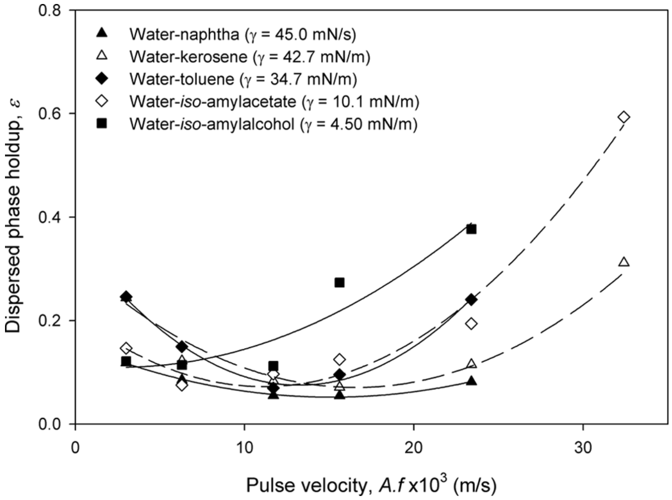

FIG. 2. Effect of pulse velocity on the dispersed phase holdup without mass transfer. $u_d = 2.73 \times 10^{-3}\,\mathrm{m/s}$, $u_c = 2.86 \times 10^{-3}\,\mathrm{m/s}$. For naphtha: $u_d = 2.47 \times 10^{-3}\,\mathrm{m/s}$. The data for water-kerosene and water-*iso*-amylacetate is taken from Khawaja et al. (21).

on the dispersed phase holdup. Generally, the holdup decreases initially with an increase in the pulse velocity, reaches a minimum value and then starts increasing with an increase in the pulse velocity. Before the point of minimum holdup, holdup decreases with pulse velocity while after this point, holdup continues to increase till flooding occurs. The point of minimum holdup is characterized as transition pulse velocity (7) and it is so called because at the point of minimum holdup transition of mixer-settler region occurs to dispersion region. Before the transition point the mixer-settler region prevails while after the point of minimum holdup the mixer-settler region is transformed into a dispersion region. Sehmel and Babb (7), Bell and Babb (9), Lorenz et al. (13), and Venkatnarasaiah and Varma (2) observed the condition of minimum holdup in their study.

It is observed that for each system with its own interfacial tension, there is a different value of transition velocity. Close observation of Fig. 2 reveals that, generally, the transition velocity is moving to the left with an increase in the interfacial tension. For the lowest interfacial tension system of water-*iso*-amylalcohol ($\gamma = 4.50\,\mathrm{mN/m}$), the minimum holdup condition on the far left of Fig. 2 is yet to arrive. The figure shows that not only the pulsation intensity but interfacial tension has a profound effect on the performance of the pulsed sieve-plate extraction column. It is observed that, generally, in both the dispersion and mixer-settler regions, holdup increases with a decrease in interfacial tension. However, comparing two systems of different interfacial tensions under identical conditions of operation, holdup of the system with lower interfacial tension may be less if the system with lower interfacial tension is in dispersion regime while the system with higher interfacial tension is in mixer-settler regime. This may be explained by an example. In Fig. 2, for the system water-*iso*-amylalcohol (lowest interfacial tension), at $A \cdot f = 6.30 \times 10^{-3}\,\mathrm{m/s}$ holdup is 0.114 which is less than for water-toluene system (greater interfacial tension) which has a holdup value of 0.149.

The following discussion may be helpful in explaining the above observations. The dispersed phase holdup is a complex function of various factors such as drop size, drop velocity, rates of drop coalescence and breakup, shear stress and drag on drops, shape of drop, and circulatory motion of drop swarm. The above factors are written explicitly for the discussion purpose, the factors may themselves depend on each other. The following may be said about the above mentioned factors:

- Increase in drop size increases the drop rise velocity which may lead to a lower holdup.
- If the rate of coalescence of small drops is high, drop size increases and holdup decreases, the opposite may be said for the rate of drop breakup.
- Increase in drop velocity may increase frictional drag and can contribute in lowering the holdup value.
- If the drop size is large enough and the plate hole size hinders the motion of the drop from one cell to the other, at low pulsation intensities, drop may accumulate under the plate (for a light phase dispersed system) and can increase the holdup.
- A non-circular drop (oblong) should have lower drop velocity and should provide a greater holdup.

In the mixer-settler region (characterized as the formation of a distinguished layer of dispersed phase beneath a sieve-plate when light phase dispersed as in the present study) for constant values of phase flows, due to low agitation, larger drops are formed and accumulate below the sieve-plate and cause holdup to increase (12). The phenomenon of drop accumulation was visually observed in the column. Even the bouncing back of drops without breakage after striking with the plate is clearly observed using the high speed digital camera (Casio EX-FH100) in slow motion mode. Figure 3 shows the formation of an accumulated drops layer beneath the 57th number of plate (when counting from the bottom) in the column. In the presence of not enough energy, the rate of drop coalescence may be greater than the rate of drop breakup and larger drops are formed which increase the holdup (accumulation of drops takes place under a plate). As the pulsation intensity is increased, more energy is added and drop size is reduced, and the discrete layer formed beneath the plate starts disappearing and holdup is reduced. The holdup is continuously decreased till the minimum holdup condition is arrived. Further increase in the pulsation intensity causes further agitation and the continuous phase may go into the

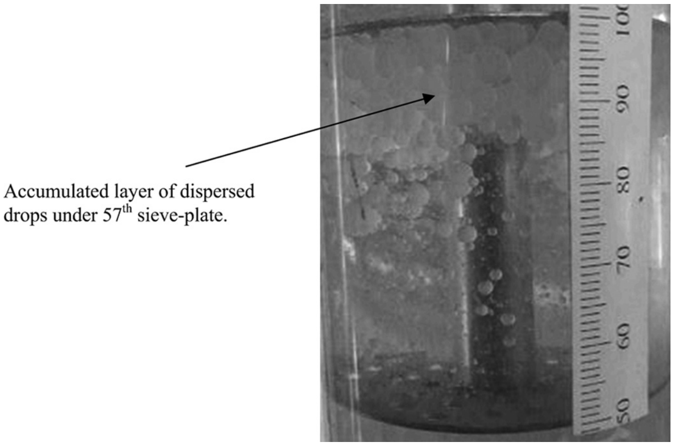

FIG. 3. Mixer-settler region showing accumulation of dispersed phase (toluene) drops under 57th sieve-plate for the water-toluene system. $A \cdot f = 6.3 \times 10^{-3}$ m/s, $u_d = 2.73 \times 10^{-3}$ m/s, $u_c = 2.86 \times 10^{-3}$ m/s.

dispersed phase drop body more readily thus increasing the density of the drop and lowering the drop velocity. A large number of drops of various diameters are formed and the column is packed with drops. The drops collide more frequently and frictional drag reduces the upward motion. Drops may start circulatory motion and accumulate in the cell. Although there is a greater chance of drop coalescence but high energy input destabilizes the drops and the rate of drop breakup is also high. All this increases the dispersed phase holdup in the dispersion and emulsion regions.

The reason for moving the transition velocity to a lower value with a decrease in interfacial tension may be explained on the basis that for a system with lower interfacial tension, drops are destabilized even at low energy input and the mixer-settler region disappears earlier.

With Mass Transfer

Carboxylic acids such as formic, acetic, and propionic acids are extensively employed in the chemical and pharmaceutical industry. The acids are frequently found in the effluent aqueous streams and are mostly not recovered because of high cost associated with the extraction (17). Removing and recovering a carboxylic acid from an aqueous stream is not only environmentally beneficial but it is also favorable in the economic point of view. Moreover, the recent hype in the petroleum prices has paved the way for the fermentation industry to grow rapidly. The energy efficient and economics of large scale production of fermentation chemicals is haltered by the difficulty of recovering the fermentation product. Propionic acid also called propanoic acid in aqueous stream is used in the present study to see the effect of mass transfer on the dispersed phase holdup. Toluene was used to observe the effect of propionic acid extraction on the dispersed phase holdup. 10% by weight solution of propionic acid in water was prepared which acted as continuous phase in the column. Dispersed phase holdup was measured mainly as a function of pulsation intensity and compared with no mass transfer condition discussed above.

Figure 4 compares the effect of pulse velocity on the dispersed phase holdups between mass transfer and no mass transfer conditions for water-propionic acid-toluene and water-toluene system respectively. For the direction of mass transfer from the continuous phase to the dispersed phase as the case in the present study, rate of drop breakage may increase which may result in decreasing the size of the drops (18). Also, the interfacial tension of the system may be decreased due to solute presence. Table 1 shows the decrease in interfacial tension measured by drop-weight method for the water-propionic acid-toluene system when 10.0 wt% water-propionic acid solution was used with toluene. The decrease in interfacial tension may decrease the drop size. Both of these reasons may result in an increase in the value of the dispersed phase holdup. This is true for the high pulse velocity region in Fig. 4 which shows that in the high pulse velocity regime holdup is greater in the case of with mass transfer conditions. A lower holdup with mass transfer conditions in the low pulse velocity regime may be explained on the same basis as described in Section titled "No Mass Transfer". Again the transition velocity moves to the left for the lower interfacial tension system. Higher extraction of propionic acid at higher pulse velocity may be an additional parameter here.

Effect of Phase Velocities on the Dispersed Phase Holdup

Figures 5 and 6 show the effect of phase velocities under no mass transfer conditions for different water-organic systems with varying interfacial tensions on the dispersed phase holdup. It is observed that the effect of continuous

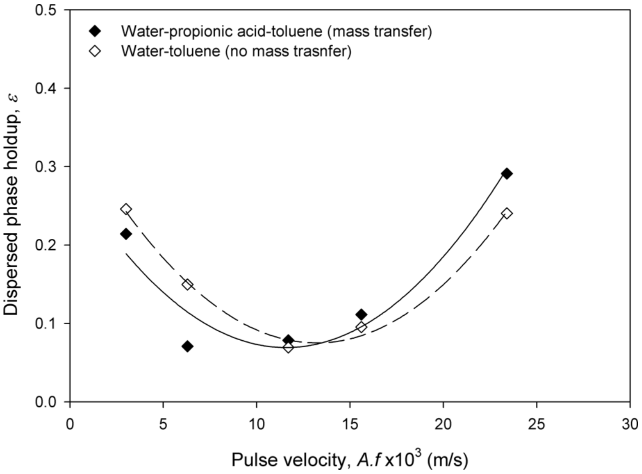

FIG. 4. Comparison of the effect of pulse velocity on the dispersed phase holdup with and without mass transfer for water-propionic acid-toluene. $u_d = 2.73 \times 10^{-3}$ m/s, $u_c = 2.86 \times 10^{-3}$ m/s.

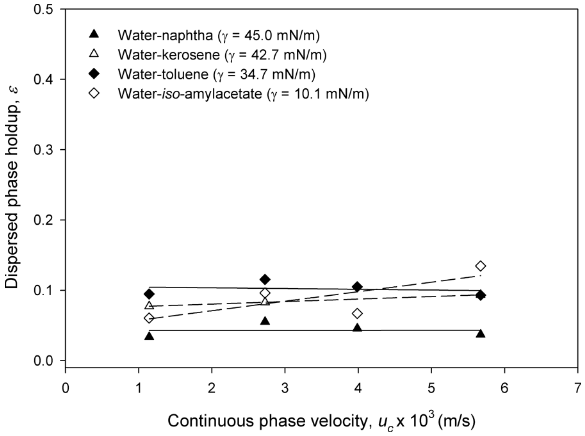

FIG. 5. Effect of continuous phase superficial velocity on the dispersed phase holdup. $A \cdot f = 11.7 \times 10^{-3}\,\mathrm{m/s}$, $u_d = 2.73 \times 10^{-3}\,\mathrm{m/s}$. For naphtha: $u_d = 2.47 \times 10^{-3}\,\mathrm{m/s}$. The data for water-kerosene and water-*iso*-amylacetate is taken from Khawaja et al. (21).

phase velocity is, generally, negligible irrespective of the system of study apart from the low interfacial tension system of *iso*-amylacetate-water system. For the *iso*-amylaceate-water system there is a slight increase in dispersed phase holdup with continuous phase superficial velocity. In contrast to the above effects, holdup is increased with increase in the dispersed phase superficial velocity for all the systems studied. The change in the effect of dispersed phase velocity seems to increase with the change in interfacial tension and the slope of the line is increasing with increase in interfacial tension. Moreover, the change in the slope has more variation in the lower interfacial tension region. This can easily be shown by comparing the slopes of water-kerosene system ($\gamma = 42.7\,\mathrm{mN/m}$) and water-*iso*-amylacetate system ($\gamma = 10.1\,\mathrm{mN/m}$) with slopes of water-*iso*-amylacetate system ($\gamma = 10.1\,\mathrm{mN/m}$) and water-*iso*-amylalcohol system ($\gamma = 4.5\,\mathrm{mN/m}$). For the effect of dispersed phase velocity, other investigators in the literature have observed the same variation. Cohen and Bayer (4), Sehmel and Babb (7), Miyauchi and Oya (8), Mishra and Dutt (19), Bell and Babb (9), Khemangkorn et al. (10), Lorenz et al. (13), and Venkatanarasaiah and Varma (2) observed substantial increase in holdup with increase in dispersed phase velocity for their conditions of experimentation. For the effect of continuous superficial phase velocity, there is a contradiction among the researchers. Cohen and Beyer (4) observed change of holdup with continuous phase velocity, while most of the other researchers found practically no change of hold up with continuous phase velocity. In the present study, a relatively important change in holdup is only observed for a low interfacial tension system, that is, water-*iso*-amylcetate system. It is important to mention here that Cohen and Beyer (4) also observed the change for a low interfacial tension system, water-boric acid-*iso*-amylalcohol system, $\gamma = 4.58\,\mathrm{mN/m}$ (15). Moreover, most of the studies on holdup are performed for a plate free area $\geq 19\%$. However, the study performed by Cohen and Beyer (4) is for a plate free area $\sim 9.0\%$ which is close to the plate free area of the column used in the present study ($\alpha = 13.5\%$).

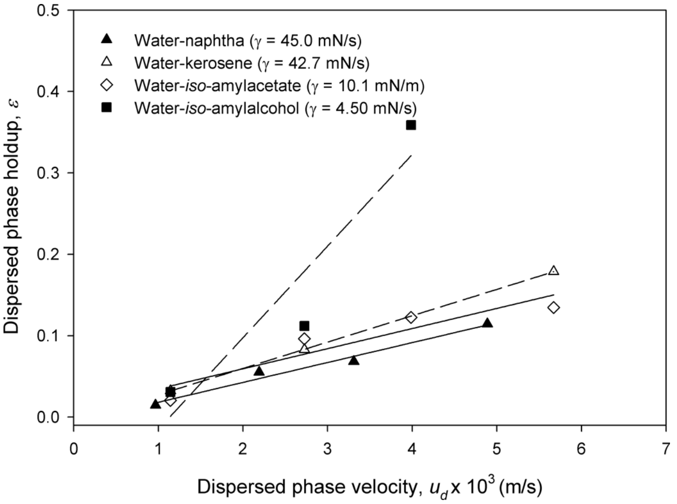

FIG. 6. Effect of dispersed phase superficial velocity on the dispersed phase holdup. $A \cdot f = 11.7 \times 10^{-3}\,\mathrm{m/s}$, $u_c = 2.86 \times 10^{-3}\,\mathrm{m/s}$. The data for water-kerosene and water-*iso*-amylacetate is taken from Khawaja et al. (21).

From the overall discussion, it may be concluded that under identical conditions of pulse velocity, dispersed phase velocity, and column geometry, the change in holdup with continuous phase velocity may be expected for a system with lower interfacial tension. Moreover, a low percent free area of the column imparts a significant effect on the drop size and shear stress on the drops to vary holdup even with continuous phase velocity.

DEVELOPMENT OF THE HOLDUP CORRELATION

A number of dispersed phase holdup correlations have been developed over the years. Some of the correlations were developed for the specified regimes such as for the mixer-settler or the dispersion regime; however, others are developed for all the three regimes of pulsed column operation. Yadav and Patwardhan (15) have reviewed the published dispersed phase holdup correlations. They have found correlations after Kumar and Hartland (3) and Venkatanarasaiah and Varma (2) as the most important correlations. In this section, the experimental data obtained in the absence of mass transfer is collected and tested against the above two correlations. While modifying the form of the better correlation, new constants and exponents are derived, and a new holdup correlation is developed that best fits the data obtained in the present study.

Testing of Previous Correlations

All the experimental holdup data without mass transfer and the relevant information of the column geometry and physical properties of the liquid-liquid systems were arranged and subjected to regression in SigmaPlot® program (statistical regression software). The following objective function (the sum of squares of the errors) is minimized (ideally approaches to zero):

$$SSE = \sum_{i=1}^{i=N} (\varepsilon_{obs} - \varepsilon_{mod})^2 \tag{1}$$

where, SSE stands for the sum of squares of the errors, ε_{mod} is the model value of the dispersed phase holdup, ε_{obs} is the observed or experimental value of the dispersed phase holdup, i is the ith value, and N is the total number of data points.

Testing of Kumar and Hartland's Correlation

Kumar and Hartland (3) have developed a single expression for the prediction of dispersed phase holdup for all the operating regimes of the column. The correlation is based on 1574 data points without mass transfer and 14 liquid-liquid systems. The correlation of Kumar and Hartland (3) is given below as Eq. (2).

$$\begin{aligned} \varepsilon = K_1 \cdot \exp\left(K_2 \cdot \left|A \cdot f - (A \cdot f)_m\right|\right) \cdot \\ u_d^{0.86} \cdot (u_c + u_d)^{0.28} \cdot \Delta\rho^{-0.3} \\ \times \rho_d^{-0.93} \cdot \mu_d^{0.77} \cdot \alpha^{-0.56} \cdot p^{-0.56} \end{aligned} \tag{2}$$

where, $K_1 = 2.10 \times 10^6$, $K_2 = 44.53$, and

$$(A \cdot f)_m = 9.69 \times 10^{-3} \cdot \left(\frac{\sigma \cdot \Delta\rho^{0.25} \cdot \alpha}{\mu_d^{0.75}} \right)^{0.33} \tag{3}$$

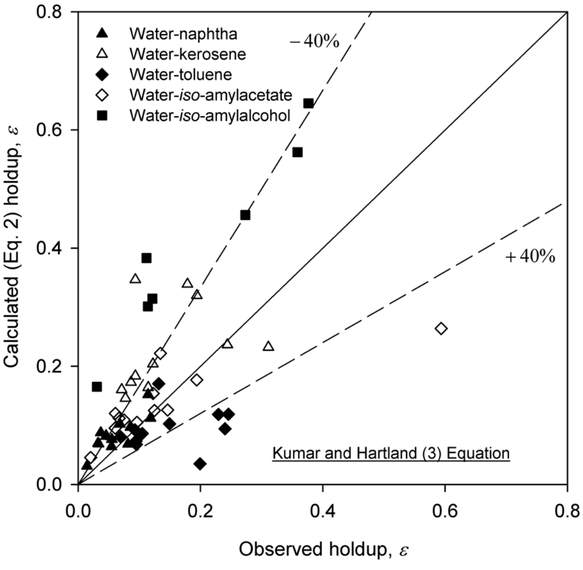

FIG. 7. Scatter diagram between observed dispersed phase holdup and the dispersed phase holdup calculated from Eq. (2).

The observed experimental holdup data is used with Eq. (2) and the results of the measured holdup and that predicted by Eq. (2) are plotted as shown in Fig. 7. Figure 7 is the scatter diagram between experimentally observed holdups and the holdups calculated by Eq. (2). It is observed that the fit is not very promising and most of the values are over predicted. Similar findings were reported by Yadav and Patwardhan (15) while fitting Eq. (2) with part of the published data in the literature. The average percentage error as defined in Eq. (4) (3) came out be 55.2%.

$$\%\ error = \frac{100}{N} \cdot \sum_{i=1}^{i=N} \left(\frac{\varepsilon_{mod} - \varepsilon_{obs}}{\varepsilon_{obs}} \right) \tag{4}$$

Testing of Venkatanarasaiah and Varma's Correlation

In Kumar and Hartland (3) correlation, the effect of u_c is not introduced as a separate function, while holdup is considered to be proportional to $(u_c + u_d)$. Venkatanarasaiah and Varma (2) while working on kerosene-water system and including the study of previous six researchers developed their own correlation in which the separate effect of u_c as well as of plate hole diameter was included. Moreover, in contrast to Kumar and Hartland (3), the separate effect of dispersed phase density was avoided. Venkatanarasaiah and Varma (2) developed the following correlation for the dispersed phase holdup:

$$\begin{aligned} \varepsilon = K_1 \cdot \exp(K_2 \cdot |A \cdot f - (A \cdot f)_m|) \cdot u_d^{1.02} \cdot u_c^{1.02} \cdot \\ \Delta\rho^{-0.23} \times \mu_d^{0.52} \cdot d_o^{-0.3} \cdot \alpha^{-0.4} \cdot p^{-0.4} \end{aligned} \tag{5}$$

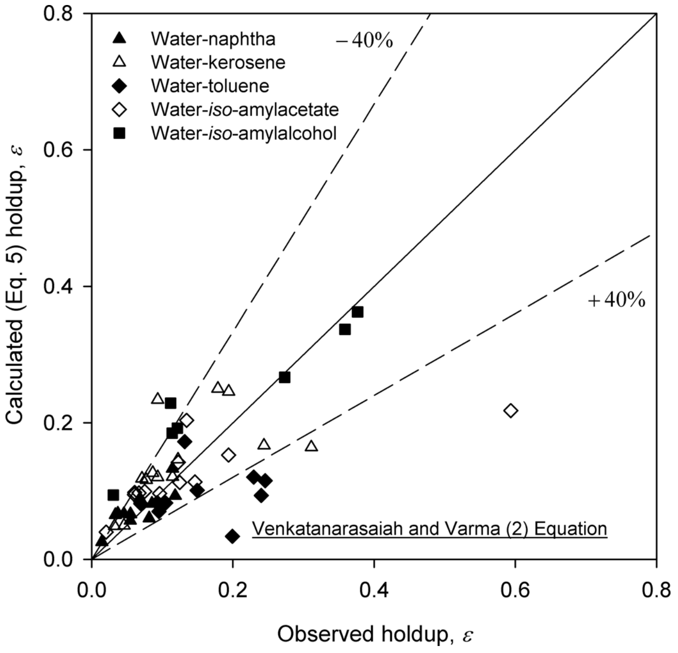

FIG. 8. Scatter diagram between observed holdup and holdup calculated from Eq. (4).

TABLE 4
Comparative fitting behavior of the holdup correlations

Equations	R^2	SSE	% error (Eq. 4)
Kumar and Hartland (3), Eq. (2)	−0.164	0.675	55.2
Venkatanarasaiah and Varma (2), Eq. (5)	0.424	0.334	20.0
Development correlation, Eq. (6)	0.692	0.179	17.1

where $K_1 = 116.5$, $K_2 = 39.35$, and $(A \cdot f)_m$ is the same as given by Kumar and Hartland (3) in Eq. (3).

The experimental data was fitted with Eq. (5) and Fig. 8 shows the scatter diagram between the observed holdup and the model holdup values calculated from Eq. (5). Clearly, the experimental holdup data was much better fitted with the Venkatanarasaiah and Varma (2) correlation than Kumar and Hartland (3) correlation. As shown in Table 4, the value of R^2 is much improved. The sum of squares of the errors (SSE) is halved as compared to the Kumar and Hartland (3) correlation.

Development of the New Correlation for the Dispersed Phase Holdup

The correlation of Venkatanarasaiah and Varma (2), Eq (5), was used as the base case for the development of the new correlation that will best fit the experimental dispersed phase holdup data obtained in the present study. In the first attempt, all of the exponent values are kept intact as that of the original correlation and the equation was fitted for the values of K_1 and K_2. The results of regression showed improvement over the original correlation. Further attempts were continued and the equation with the least value of SSE was adopted as the best fit equation. The final form of the best-fit correlation is given in Eq. (6).

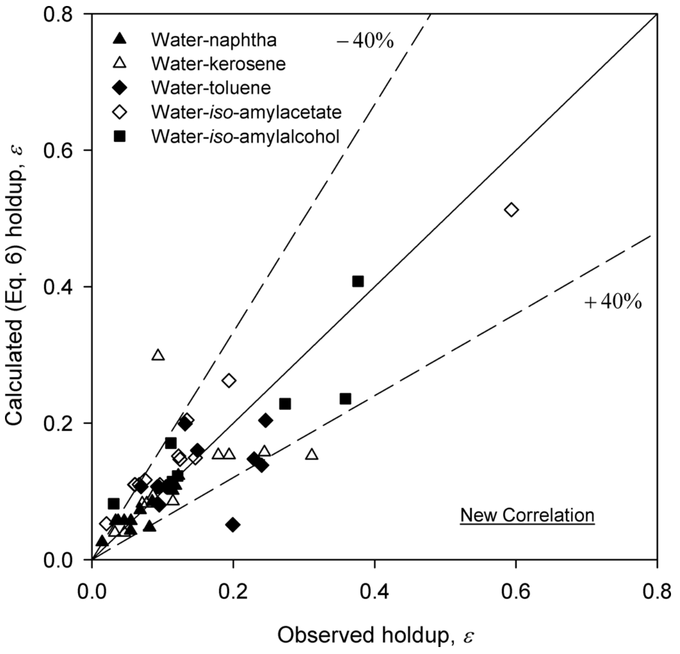

FIG. 9. Scatter diagram between observed holdup and holdup calculated from the new development correlation Eq. 5.

$$\varepsilon = K_1 \cdot \exp(K_2 \cdot |A \cdot f - (A \cdot f)_m|) \cdot u_d^{0.848} \cdot \Delta\rho^{-0.910} \cdot \mu_d^{0.294} \tag{6}$$

Where, $K_1 = 9371.6$ and $K_2 = 74.4$, and $(A \cdot f)_m$ as defined in Eq. (3).

SSE and R^2 values for Eq. (6) are compared in Table 4 and Fig. 9 is the scatter diagram between the measured holdups and the holdup values calculated from Eq. (5).

CONCLUSIONS

The dispersed phase holdup irrespective of the system decreases with the pulse velocity and after reaching a minimum holdup condition (transition velocity condition) it increases with an increase in the pulse velocity. The minimum holdup condition apart from other physical properties depends upon the interfacial tension of the system. Generally, the transition velocity reduces with an increase in interfacial tension. With solute transfer (lower interfacial tension and direction of mass transfer from continuous phase to dispersed phase) the holdup is found higher with mass transfer than with no mass transfer conditions in the region of high pulse velocity and opposite is observed for relatively low values of the pulse velocity.

The effect of continuous phase superficial velocity on dispersed phase holdup is found only minimal, apart from low interfacial tension system where a moderate effect is observed. Dispersed phase velocity has shown a profound effect on the dispersed phase holdup. Holdup is increased with an increase in the dispersed phase velocity irrespective of the liquid-liquid system.

Experimental data of dispersed phase holdup obtained under varying conditions of pulse velocity, dispersed phase velocity, and continuous phase velocity, for a variety of liquid-liquid system when tested against the recommended holdup correlations shows that the correlation of Venkatanarasaiah and Varma (2) for dispersed phase holdup is better fitting the experimental data than Kumar and Hartland (3). The new correlation, although better fitting for the data obtained in the present study, is developed for fewer variables. The holdup correlation after Venkatanarasaiah and Varma (2) is therefore recommended for preliminary design of new systems before the actual pilot scale testing.

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NOMENCLATURE

A	pulse amplitude, m
$(A \cdot f)_m$	pulse velocity at minimum holdup condition, $\mathrm{m \cdot s^{-1}}$
d_o	plate hole diameter, m
f	frequency, $\mathrm{s^{-1}}$
h_i	height in the column at ith point from the bottom, m
h_t	total effective height of the column, m
N	number of data points
p	plate spacing, m
u_c	continuous phase superficial velocity, $\mathrm{m \cdot s^{-1}}$
u_d	dispersed phase superficial velocity, $\mathrm{m \cdot s^{-1}}$
α	plate free area
ε	dispersed phase holdup
ε_{obs}	observed dispersed phase holdup
$\varepsilon_{\mathrm{mod}}$	model or calculated dispersed phase holdup
μ	liquid viscosity, $\mathrm{kg \cdot m^{-1} \cdot s^{-1}}$
μ_d	dispersed phase viscosity, $\mathrm{kg \cdot m^{-1} \cdot s^{-1}}$
ρ	density of a liquid, $\mathrm{kg \cdot m^{-3}}$
$\Delta\rho$	density difference between phases, $\mathrm{kg \cdot m^{-3}}$
σ	interfacial tension, N/m

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