



# Study of holdup and slip velocity in an L-shaped pulsed sieve-plate extraction column

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Received: 28 April 2018 / Accepted: 26 December 2018 / Published online: 23 January 2019  
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## Abstract

High-end applications require a very tall vertical extraction column in some cases which deteriorates protection against radiation and cannot be employed for indoor applications. On the other hand, horizontal extraction columns offer higher efficiency and pretension, but lower maximum throughput. In order to address this issue, the L-shaped pulsed extraction column is a new type of extractors which were recently introduced for such applications with area constraints. The objective of this study is to evaluate the effects of operating parameters and physical properties on the variation of holdup and slip velocity in this type of extractors for three liquid systems including toluene–water, butyl acetate–water and *n* butanol–water without and under mass transfer condition. A comprehensive investigation on the determination of predictive ability of available correlations for the holdup and slip velocity in pulsed plate columns has been conducted. Finally, new correlations are proposed for prediction of these parameters regarding operational conditions and physical properties.

**Keywords** L-shaped pulsed plate column · Slip velocity · Holdup · Pulsation intensity · Mass transfer

## List of symbols

$A$	Amplitude of pulsation, m
$A_f$	Pulsation intensity, m/s
$D$	Column diameter, m
$d$	Hole diameter, m
$f$	Frequency of pulsation, Hz
$g$	Acceleration due to gravity, =9.81 m/s <sup>2</sup>
$h$	Plate spacing, m
$H$	Column length, m
$Q$	Volumetric flow rate, m <sup>3</sup> /s
$V_c$	Superficial velocity of continuous phase, m/s
$V_d$	Superficial velocity of dispersed phase, m/s
$V_s$	Slip velocity, m/s

## Greek symbols

$\alpha$	Fractional free area
$\varphi$	Holdup
$\mu$	Viscosity, N s/m <sup>2</sup>
$\rho$	Density, kg/m <sup>3</sup>

$\Delta\rho$	Density difference between two phases, kg/m <sup>3</sup>
$\sigma$	Interfacial tension between two phases, N/m

## Introduction

Solvent extraction is one of the methods applied in separation industry. There are numerous types of extractors including mixer-settlers, columns, and centrifugal extractors [1]. Pulsed columns are a class of solvent extractors which offer various advantages such as high throughput, simple design, low space requirement, and with no internal moving parts [2].

Various internals have been used so far in pulsed columns such as packing, perforated plates and disc and doughnuts. However, pulsed columns can be classified in two structural groups:

1. Vertical pulsed columns.
2. Horizontal pulsed columns.

Each kind has its own advantages and disadvantages. It is revealed that the mass transfer efficiency is comparable in both types of columns, whereas area limitations are influential variables that affect the industrial use of these columns. Moreover, the need time to start up the vertical columns is less than the horizontal ones, whereas in vertical

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columns, the throughput capacity is higher than the horizontal columns. According to previous investigations on the main features of the horizontal and vertical types of extraction columns, it is observed that the advantages of vertical pulsed columns are more than the horizontal ones [3–6]. It is believed that an L-shaped pulsed plate column has the potential to obviate some of the main disadvantages of the horizontal and vertical types in industrial applications as follows:

1. Throughput of the L-shaped pulsed sieve—plate column is less than the vertical types and more than the horizontal types.
2. Height for installation and requirement surface area of an L-shaped column as indoor is less than that of the vertical or horizontal columns.
3. The energy consumption in the L-shaped column is somewhat between that in the horizontal columns and the vertical columns.

In this regard, various efforts have been made. Amani et al. [7] studied the effects of operating parameters on the two-phase pressure drop in an L-shaped pulsed plate column. They also examined the throughput of the column and proposed new correlations for prediction of pressure drop and flooding points. A particular approach for preventing flooding has been developed as well. Akhgar et al. [8] investigated the flow regime transitions in an L-shaped column and determined the values of characteristic velocities in the column under different steady-state operating conditions. In this study, the transition from dispersion to emulsion regime in the horizontal section and the transitions from mixer-settler to dispersion regime in the vertical section have been correlated, characterizing the minimum and maximum operating capacity of the column. In another study, the measurement of mean drop size and drop diameter distribution has been focused by Amani et al. [9, 10]. The drop behavior in different operating regimes has been evaluated and new correlations have been proposed for prediction of mean drop size in terms of operating parameters and physical properties of the chemical systems. Moreover, the drop size distribution is found to be well correlated using the log-normal probability density function.

Regarding the well description of extraction column operation, it is essential to evaluate the variation of drop population characteristics such as holdup and drop size [11]. In fact, pulsation improves the column performance due to providing higher drop breakage and consequently increasing the interfacial area between two phases. However, because of the entrainment of small drops and thereby increasing axial mixing, the column performance might be affected by pulsation [12]. Thus, investigation of hydrodynamic parameters including holdup and slip velocity is crucial for design

and scaling up of an extraction column to determine the drag coefficients, [13–16] and mass transfer performance [17–20].

The dispersed phase holdup ( $\varphi$ ) can be defined as volume fraction of the column which is occupied by the dispersed phase:

$$\varphi = \frac{v_d}{v_c + v_d}, \quad (1)$$

where  $v_d$  and  $v_c$  represent the volume of the dispersed and continuous phases, respectively. Moreover, the slip velocity is the relative velocity with respect to the continuous phase, which can be characterized by Eq. (2), as the sum of the linear actual velocities of the continuous and dispersed phases under condition of countercurrent flow: [21]

$$V_s = \frac{V_d}{\varphi} + \frac{V_c}{1 - \varphi}, \quad (2)$$

where  $V_d$  and  $V_c$  are the superficial velocities of the dispersed and continuous phases and can be obtained by Eq. (3) as follows:

$$V = \frac{Q}{A}. \quad (3)$$

Various investigations have been implemented on the determination of holdup in extraction columns and numerous correlations have been proposed by researchers [22–26]. There are plenty of papers on the holdup determination in vertical extraction columns [26]. On the other hand, several investigations have also been conducted to determine dispersed phase holdup values in horizontal extraction columns. For instance, Melnyk et al. [3] studied the effect of  $A_f$  and flow rate of phases on the holdup in a horizontal pulsed sieve-plate column and proposed a correlation for prediction of holdup based on operating parameters and physical properties. Khajenoori et al. [27] by studying four different liquid systems, determined the variation of holdup in terms of operating parameters. They also proposed a correlation for prediction of slip and characteristic velocities in a horizontal pulsed plate column. Panahinia et al. [28, 29] studied the effect of mass transfer on the dispersed phase holdup and proposed new correlations for mass transfer and axial dispersion coefficients in a horizontal extraction column. Correlations proposed for prediction of the holdup and slip velocity in pulsed plate columns are summarized in Tables 1 and 2.

However, in accordance with the available literature, there is no investigation concerning the measurement of holdup and slip velocity in an L-shaped extraction column. So, there is a lack of data on the holdup values which are highly required for the design and understanding the performance of an extraction column. Therefore, in this study, the variation of holdup and slip velocity in a novel class of pulsed

**Table 1** Correlation for prediction of holdup in pulsed plate columns

References	Correlations	Comments
[31]	$\varphi = 4.93 \times 10^2 \psi^{0.84} V_d^{2/3}, \psi \leq 0.0031 \text{ m}^{11/12} \text{ s}^{-1}$ $\varphi = 3.42 \times 10^6 \psi^{0.24} V_d^{2/3}, \psi \geq 0.0031 \text{ m}^{11/12} \text{ s}^{-1}$	Vertical pulsed column $\psi = \frac{Af}{(\beta h)^{1/3}} \left( \frac{\mu_d^2}{\sigma \Delta \rho} \right)^{1/4},$ $\beta = \frac{\alpha^2}{(1-\alpha)(1-\alpha^2)}$
[32]	$\varphi = 3.91 \times 10^{-3} \left( \frac{A^2 \rho_c g}{\sigma} \right)^{-0.26} \left( \frac{f^4 \sigma}{\rho_c g^3} \right)^{-0.19} \left( \frac{V_d^4 \rho_c}{g \sigma} \right)^{0.28} \left( 1 + \frac{V_c}{V_d} \right)^{0.19} \left( \frac{\Delta \rho}{\rho_c} \right)^{-0.81} \left( \frac{\mu_d^4 g}{\rho_c \sigma^3} \right)^{-0.13}$ $\varphi = 6.91 \left( \frac{(Af)^3 \rho_c^{1/4}}{\beta h \sigma^{1/4} g^{5/4}} \right)^{0.31} \left( \frac{V_d^4 \rho_c}{g \sigma} \right)^{0.30} \left( 1 + \frac{V_c}{V_d} \right)^{0.14} \left( \frac{\Delta \rho}{\rho_c} \right)^{-0.79} \left( \frac{\mu_d^4 g}{\rho_c \sigma^3} \right)^{-0.01}$ $\varphi = 3.73 \times 10^{-3} \left( \frac{(Af)^4 \rho_c}{\sigma g} \right)^{0.31} \left( \frac{V_d^4 \rho_c}{g \sigma} \right)^{0.31} \left( 1 + \frac{V_c}{V_d} \right)^{0.45} \left( \frac{\Delta \rho}{\rho_c} \right)^{-2.20} \left( \frac{\mu_d^4 g}{\rho_c \sigma^3} \right)^{-0.29}$	Vertical pulsed column First equation is applicable for miser-settler regime Second equation is applicable for dispersion regime: $\left[ \frac{(Af)^3 \rho_c}{\beta h \Delta \rho^{3/4} \sigma^{1/4} g^{5/4}} \right] \leq 0.05$ Third equation is applicable for emulsion regime: $\left[ \frac{(Af)^3 \rho_c}{\beta h \Delta \rho^{3/4} \sigma^{1/4} g^{5/4}} \right] \geq 0.05$
[33]	$\varphi = C \left( \frac{Af}{(\beta h)^{1/3}} \right)^{1.90} \left( \frac{\mu_d^2}{\sigma \Delta \rho} \right)^{0.36} V_d^{1.1},$ $\text{for } \left( \frac{\rho_c (Af)^3}{2\alpha^2} \right) \geq 0.06 \text{ kg/s}^2$	Vertical pulsed column The parameter $C$ is $3.98 \times 10^5$ for no mass transfer and is $2.52 \times 10^5$ for mass transfer $d \rightarrow c$ and $c \rightarrow d$
[34]	$\varphi = K_1 \exp(K_2  Af - (Af)_m ) V_d^{0.86} (V_c + V_d)^{0.28} \Delta \rho^{-0.30} \rho_d^{-0.93} \mu_d^{0.77} \alpha^{-0.56} h^{-0.56},$ $(Af)_m = 9.69 \times 10^{-3} \left( \frac{\sigma \Delta \rho^{3/4} \alpha}{\mu_d^{3/4}} \right)^{0.33}$	Vertical pulsed column $K_1 = 2.10 \times 10^6$ and $K_2 = 44.53$ for no mass transfer $K_1 = 2.14 \times 10^6$ and $K_2 = 44.53$ for $c \rightarrow d$ mass transfer $K_1 = 1.10 \times 10^6$ and $K_2 = 50.56$ for $d \rightarrow c$ mass transfer
[14]	They proposed a correlation for slip velocity (Table 2), by which holdup can be calculated using Eq. (2)	Refer to Table 2
[35]	$\varphi = K_1 \exp(K_2  Af - (Af)_m ) V_d^{1.02} V_c^{0.02} \Delta \rho^{-0.23} \mu_d^{0.52} d^{-0.3} \alpha^{-0.4} h^{-0.4}$	Vertical pulsed column $K_1 = 116.5$ and $K_2 = 39.35$ for no mass transfer $K_1 = 84.6$ and $K_2 = 42.56$ for $c \rightarrow d$ mass transfer $K_1 = 92.0$ and $K_2 = 42.56$ for $d \rightarrow c$ mass transfer
[35]	They proposed a correlation for slip velocity (Table 2), by which holdup can be calculated using Eq. (2)	Refer to Table 2
[3]	$\varphi = 0.87 \left( \frac{A^2 \rho_c g}{\sigma} \right)^{-0.26} \left( \frac{f^4 \sigma}{\rho_c g^3} \right)^{-0.09} \left( \frac{V_d^4 \rho_c}{g \sigma} \right)^{0.12} \left( 1 + \frac{V_c}{V_d} \right)^{0.27}$	Horizontal pulsed column It is applicable for dispersion regime
[27]	They proposed a correlation for slip velocity (Table 2), by which holdup can be calculated using Eq. (2)	Refer to Table 2
[29]	$\varphi = C \left( 1 + \frac{Q_c}{Q_d} \right)^{0.124} \left( \frac{(Af)^4 \rho_c}{g \sigma} \right)^{-0.286} \left( \frac{\rho_c}{\Delta \rho} \right)^{-0.783} \left( \frac{\mu_d^4 g}{\sigma^3 \rho_c} \right)^{-0.071} \left( \frac{(Af)^3 Q_d \rho_d^2}{\sigma^2} \right)^{0.282}$	Horizontal pulsed column It is applicable for dispersion regime $C = 0.97$ for no mass transfer $C = 0.089$ for mass transfer $c \rightarrow d$ $C = 0.101$ for mass transfer $d \rightarrow c$

columns entitled: “L-shaped pulsed sieve-plate column” as a function of operating parameters including pulsation intensity and flow rate of both phases is investigated for three liquid–liquid systems with and without mass transfer. Moreover, new correlations for prediction of the dispersed phase holdup and slip velocity of phases are presented regarding physical properties and operating parameters.

## Experimental

### Description of equipment

In this study, an L-shaped pulsed sieve-plate column is employed which is depicted in Fig. 1. The setup comprises two active parts (vertical and horizontal sections), upper and



**Table 2** Correlation for prediction of slip velocity in pulsed sieve-plate columns

References	Correlations	Comments
[14]	$V_s = K_1 \exp(K_2  Af - (Af)_m ) \Delta\rho^{0.29} \rho_d^{0.67} \mu_d^{-0.66} \alpha^{0.44} h^{0.43},$ $(Af)_m = 9.69 \times 10^{-3} \left( \frac{\sigma \Delta\rho^{1/4} \alpha}{\mu_d^{3/4}} \right)^{0.33}$	Vertical pulsed column $K_1 = 6.14 \times 10^{-6}$ and $K_2 = -36.91$ for no mass transfer $K_1 = 5.04 \times 10^{-6}$ and $K_2 = -30.79$ for $c \rightarrow d$ mass transfer $K_1 = 6.43 \times 10^{-6}$ and $K_2 = -31.81$ for $d \rightarrow c$ mass transfer
[35]	$V_s = K_1 \exp(K_2  Af - (Af)_m ) \Delta\rho^{0.22} \mu_d^{-0.38} \alpha^{0.32} h^{0.31} d^{0.22},$ $(Af)_m = 9.69 \times 10^{-3} \left( \frac{\sigma \Delta\rho^{1/4} \alpha}{\mu_d^{3/4}} \right)^{0.33}$	Vertical pulsed column $K_1 = 1.35 \times 10^{-2}$ and $K_2 = -33.3$ for no mass transfer $K_1 = 1.65 \times 10^{-2}$ and $K_2 = -29.6$ for $c \rightarrow d$ mass transfer $K_1 = 1.55 \times 10^{-2}$ and $K_2 = -29.6$ for $d \rightarrow c$ mass transfer
[27]	$V_s = 0.088 \left( \frac{Af}{V_d} \right)^{-0.568} \left( 1 + \frac{V_c}{V_d} \right)^{0.374} \left( \frac{\rho_d}{\rho_c} \right)^{0.053} \left( \frac{\mu_d V_d}{\sigma} \right)^{0.06}$	Horizontal pulsed column It is applicable for dispersion regime with no mass transfer

lower settlers, two dosing pumps, four storage tanks, and air pulsating system. Two active parts of the column are a pipe in which 24 pairs of stainless steel sieve plates along with 29 individual sieve plates are located in the horizontal and vertical section of the column, respectively. The main characteristics of the column are presented in Table 3.

### Liquid–liquid system

Three liquid–liquid systems are used in this study, namely toluene–water, butyl acetate–water and *n* butanol–water. 3% volumetric fraction of acetone is added into dispersed phase to study the effect of mass transfer ( $d \rightarrow c$ ). These systems have been recommended by EFCE as official test systems for extraction investigations [30]. Physical properties of chemical systems are listed in Table 4.

### Experimental procedure

Before conducting the experiments, both phases were saturated to avoid any solubility during the experiments. Next, storage tanks were filled with saturated phases. Initially, the column was filled with the continuous phase, followed by adjusting  $Q_d$ ,  $Q_c$ , and  $Af$  to the intended values. The experiments cover a range of  $Q_d$  and  $Q_c$  from 1.5 to 7 l/h and 1.75 to 9 l/h, respectively, and a range of pulsation intensity (amplitude  $\times$  frequency) from 0.4 to 1.3 cm/s.

The dispersed-phase holdup was determined by using shutdown method. Accordingly, when the column reached the steady-state condition, pulsation along with the inlet and outlet of both phases was closed at the same time and then the holdup of the horizontal and vertical sections of the column was individually determined. In the horizontal section, holdup was evaluated by measurement of arc length of the part of environment wetted by light phase. The cord length at the interface,  $L_i$  was determined by Eq. (4):

$$L_i = 2r_i \cos \left( \frac{1}{2} \left( \pi - \frac{S}{r_i} \right) \right), \quad (4)$$

where  $r_i$  is the internal radius and  $S$  is the circumference. The dispersed phase holdup can then be calculated using Eq. (4) as follows:

$$\varphi = \frac{A}{\pi r_i^2}, \quad (5)$$

where  $A = \frac{1}{2} \pi r_i^2 - r_i^2 \cos^{-1} \left( \frac{L_i}{2r_i} \right) - \frac{L_i}{2} (r_i^2 - x^2)^{\frac{1}{2}}$ .

In vertical section, variation of interface height was calculated and then holdup was measured by Eq. (1).

## Results and discussion

To study the influence of operating parameters on the dispersed phase holdup and slip velocity, pulsation intensity as well as flow rate of the dispersed and continuous phases are varied in the range of 0.4–1.3 cm/s, 1.5–7 l/h and 1.7–9 l/h, respectively. Moreover, by introducing 3% volumetric fraction of acetone in the dispersed phases, the effect of mass transfer from the dispersed phase to the continuous phase on holdup along with slip velocity of phases is investigated as well.

### Effect of operating parameters on holdup

Variation of holdup versus different pulsation intensities ( $Af$ ) is illustrated in Fig. 2 for toluene–water (T–W), butyl acetate–water (BA–W) and *n* butanol–water (B–W) with acetone (A) in the dispersed phase as a mass transfer agent. Figure 2a shows that the holdup decreases with increasing  $Af$  in the horizontal section of the column. Increasing  $Af$  results in a higher shear stress and drops breakage, leading to the reduction of drop diameter. Therefore, the intense frequency of drops collisions with internal plates in higher turbulent environment leads to the lower residence time of drops which decreases holdup values in the horizontal section of the column. It is also observed that holdup for a system with higher interfacial tension is greater than that of



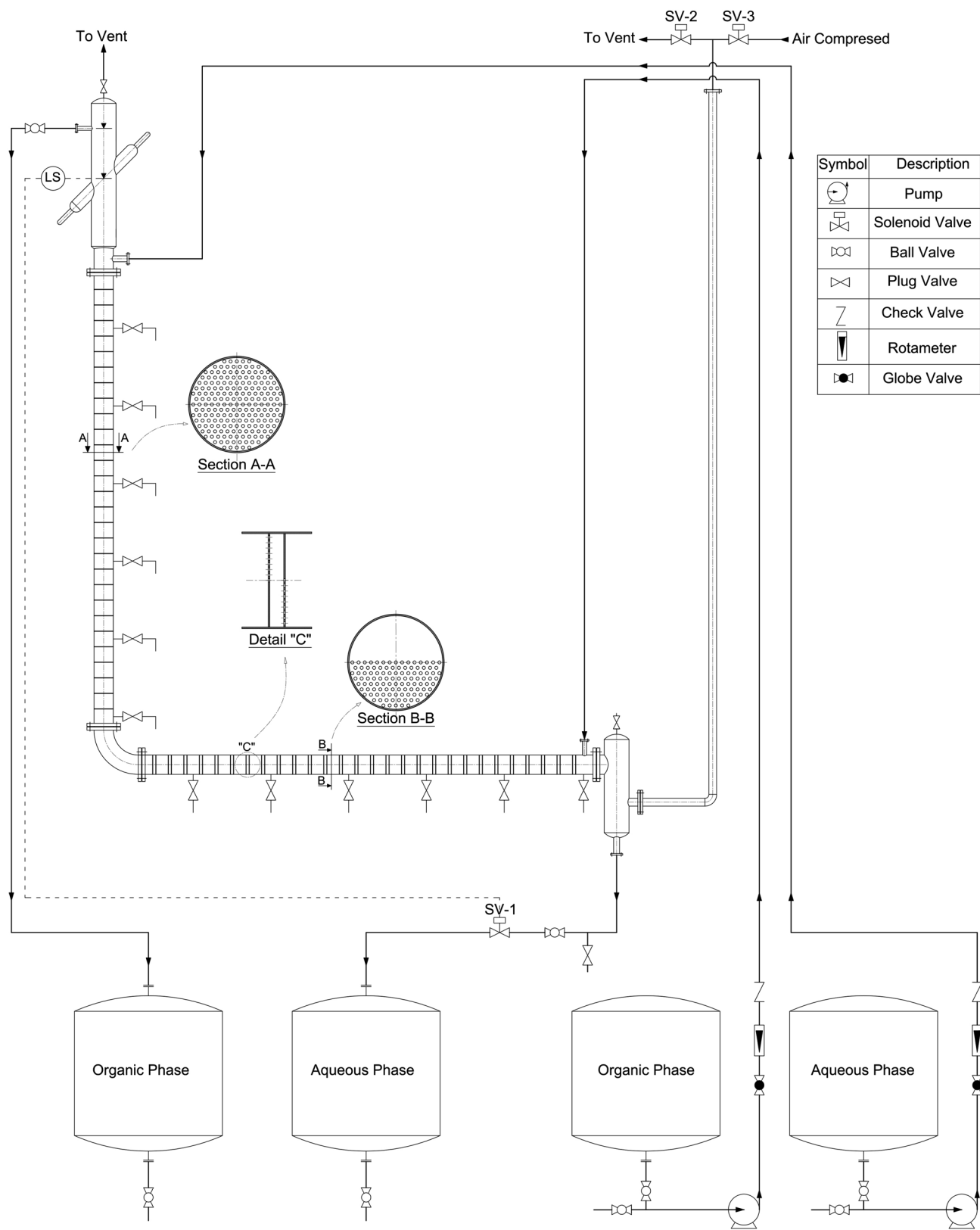


Fig. 1 The L-shaped pulsed sieve-plate column used in this work

**Table 3** Geometrical characteristics of the column and plates

Geometrical characteristics	Active section	
	Horizontal	Vertical
Active parts length of the column (cm)	146	146
Active parts internal diameter of the column (cm)	6	6
Hole pitch (mm)	4	4
Hole diameter (mm)	2	2
Plate thickness (mm)	1	1
Spacing between two plates (cm)	1 <sup>a</sup> , 5 <sup>b</sup>	5
Free area fraction (–)	0.11	0.22

<sup>a</sup>Spacing between two individual plates in a pair<sup>b</sup>Spacing between two pairs in a cell

systems with the lower interfacial tension. Moreover, the impact of Af on holdup for system with higher interfacial tension, toluene–water, is stronger in comparison with that for butyl acetate–water and *n* butanol–water.

The behavior of the dispersed phase holdup versus Af in vertical section of the column is shown in Fig. 2b. According to Fig. 2b, it is observed that the dispersed phase holdup incipiently decreases until it reaches a minimum value and then increases with further increase of Af. The minimum values of holdup are found to be a function of operating parameters and they vary for different systems with different

physical properties. It is also obtained that systems with lower interfacial tension have higher values of holdup and flow regime transition occurs at lower Af region corresponding the position of minimum holdup and vice versa.

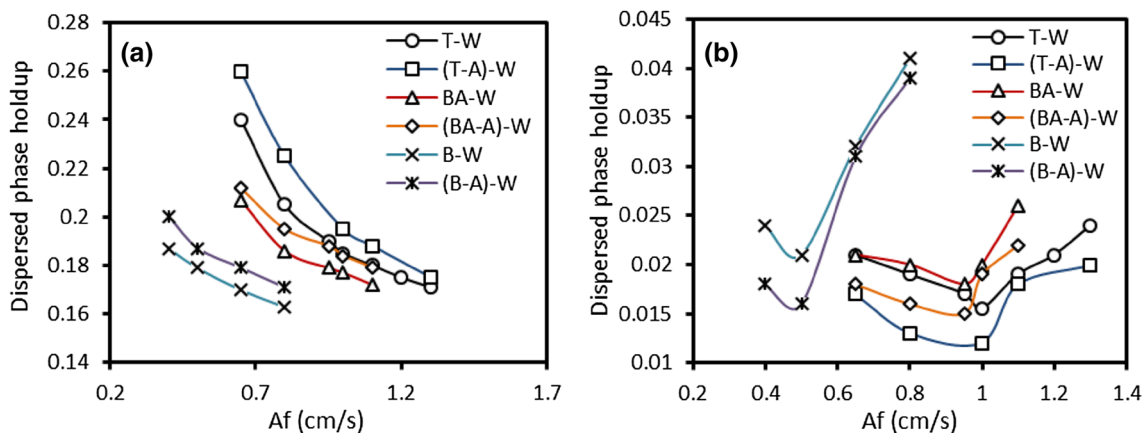
Holdup minima can be justified by evaluation of operating regimes in the column, which here corresponds the transition from mixer-settler regime to dispersion regime. Mixer-settler regime is characterized by the separation of dispersed and continuous phases into individual distinct layers in the inter-plate spaces during the quiescent portion of the pulse cycle. This condition enhances the formation of larger drops which stay on the internals and leads to the increase of holdup. When pulsation introduces into the column, residence time declines due to higher shear forces and drop breakage and as a consequence, the holdup decreases initially. However, with further increase of Af above the critical value, the holdup begins to increase considerably. It is mainly because of frequent drop breakage which leads to the formation of smaller drops and consequently longer residence time for the dispersed phase drops.

Figure 2b also shows that the holdup varies with interfacial tension. It is observed that for system with higher interfacial tension, the formation of larger drops and lower residence time due to higher buoyancy forces leads to higher slip velocities corresponding lower values of holdup in vertical section of the column.

The effect of  $Q_d$  and  $Q_c$  on holdup is shown in Figs. 3 and 4. It is obtained that by increasing the flow rate of phases,

**Table 4** Physical properties of chemical systems at  $T=20^\circ\text{C}$ 

System	$\rho_c$ (kg/m <sup>3</sup> )	$\rho_d$ (kg/m <sup>3</sup> )	$\mu_c$ (mPa s)	$\mu_d$ (mPa s)	$\sigma$ (mN/m)
Toluene–water (T–W)	998	864	0.963	0.586	35.4
Butyl acetate–water (BA–W)	997.6	880	1.0274	0.734	13.5
<i>n</i> Butanol–water (B–W)	985.6	846	1.429	3.36	1.9
(Toluene–acetone)–water [(T–A)–W]	998	865.2	0.963	0.571	30.1
(Butyl acetate–acetone)–water [(BA–A)–W]	997.6	881.4	1.0274	0.729	13.2
( <i>n</i> Butanol–acetone)–water [(B–A)–W]	985.6	847.8	1.429	3.34	1.5

**Fig. 2** The effect of pulsation intensity on holdup: **a** horizontal section, **b** vertical section

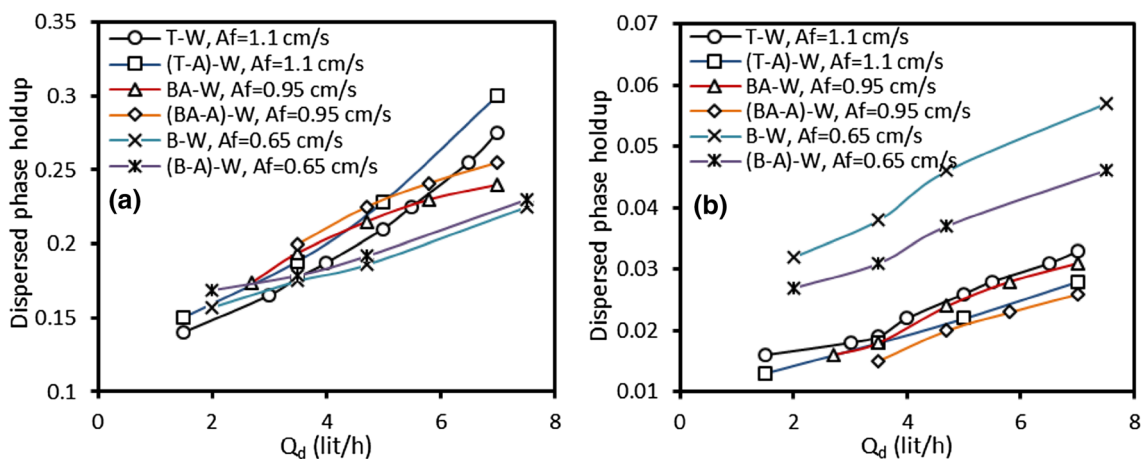


Fig. 3 The effect of dispersed phase flow rate on holdup: a horizontal section, b vertical section

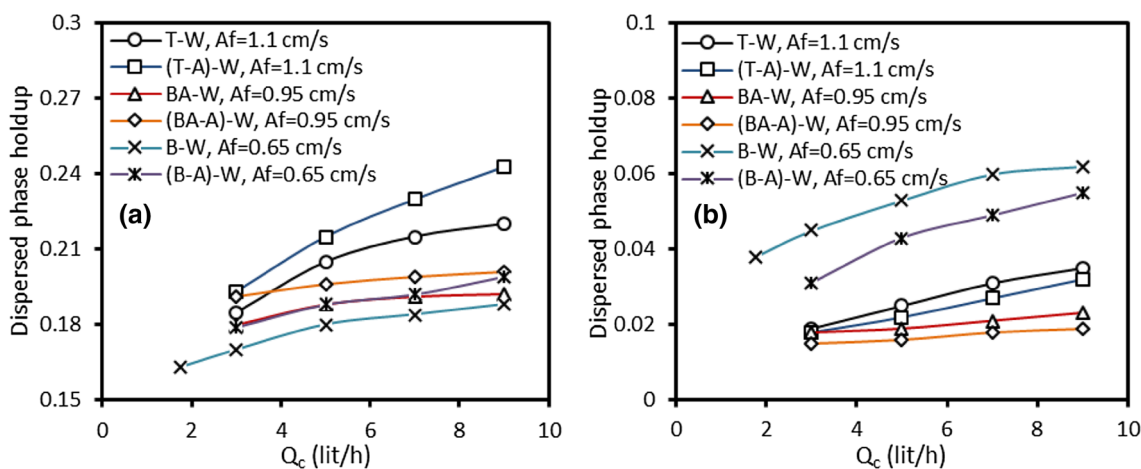


Fig. 4 The effect of continuous phase flow rate on holdup: a horizontal section, b vertical section

holdup will increase. According to the definition of holdup, it is clear that the higher  $Q_d$  increases the number of the dispersed phase drops to a greater extent, simultaneously with the formation of larger drops, which leads to higher values of holdup as shown in Fig. 3. Furthermore, according to Fig. 4, it is obtained that the higher  $Q_c$  results in the slight enhancement of holdup. It is because of the fact that increasing  $Q_c$  increases the drag forces between the dispersed phase drops and the bulk of the continuous phase, thereby limiting the movement of drops and longer residence time, which leads to higher values of holdup. The comparison of Fig. 3 with Fig. 4 also reveals that the influence of  $Q_d$  on holdup is greater than that of the continuous phase in both sections of the column.

In this study, an attempt has also been conducted to evaluate the impact of mass transfer direction, in particular from the dispersed phase to the continuous phase, on the dispersed phase holdup in an L-shaped pulsed sieve-plate column. The effect of mass transfer  $d \rightarrow c$  on holdup can be obtained from

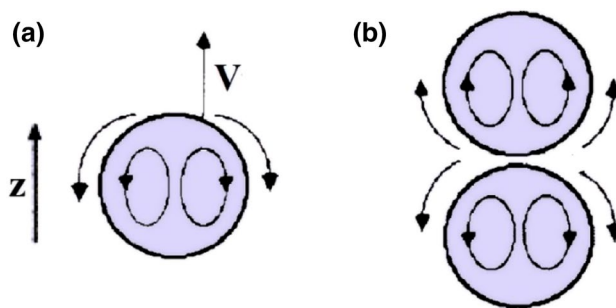


Fig. 5 The effect of  $d \rightarrow c$  mass transfer direction on inner circulation and interface motion: a stability of a single drop, b coalescence of two adjacent drops

Figs. 2, 3, 4. The presence of mass transfer  $d \rightarrow c$  has two distinctive impacts on holdup with respect to the structure of the column. In fact, acetone transfer  $d \rightarrow c$  increases holdup

in horizontal section while it decreases the holdup in vertical section. Generally, the presence of mass transfer causes the interface deformations. However, when mass transfer  $d \rightarrow c$  occurs, the concentration of acetone in the top of the drops is higher than that in the bottom of the drops. Therefore, the interface motions have the same direction with the inner circulation of drops as illustrated in Fig. 5a. As a consequence of the resulting interfacial tension gradient, the dispersed phase drops become more stable in mass transfer  $d \rightarrow c$  in comparison with in the case of no mass transfer. Moreover, when mass transfer  $d \rightarrow c$  carries out, the coalescence of two adjacent drops will be greater and the drop breakage will be reduced due to the interfacial tension gradient between the dispersed phase drops which leads to higher draining film between the two adjacent drops in comparison with the surrounding bulk liquid (Fig. 5b).

Based on what has been discussed above, mass transfer  $d \rightarrow c$  direction leads to formation of larger drops which can be referred to the Marangoni convection induction of local

differences in the acetone concentration. Thus, when mass transfer  $d \rightarrow c$  occurs, the residence time of the dispersed phase drops will be longer and consequently the holdup increases in horizontal section of the column. However, because of higher buoyancy forces on larger drops, the residence time of the dispersed phase drops will decrease with mass transfer  $d \rightarrow c$  in vertical section of the column, which leads to lower holdup in this section.

### Effect of operating parameters on slip velocity

The slip velocity is calculated using Eq. (2). The influence of Af on slip velocity is shown in Fig. 6. The shear forces increase with increasing Af and lead to intense drops breakage and thereby the slip velocity increases. However, according to Fig. 6, different behavior is observed for each section. When Af increases, the slip velocity in horizontal section increases, while it decreases in vertical section. It is because of variation of holdup in each section of the column. In particular, higher

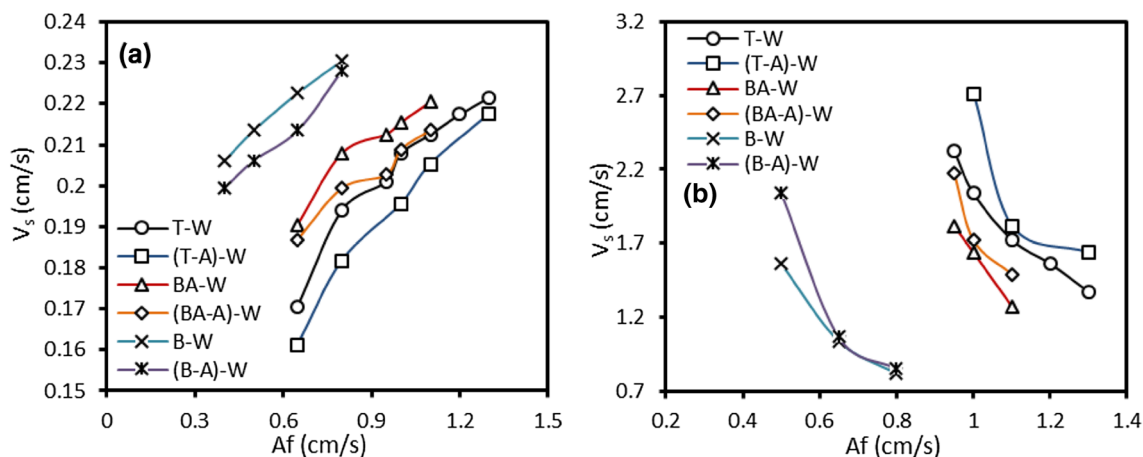


Fig. 6 The effect of pulsation intensity on slip velocity: **a** horizontal section, **b** vertical section

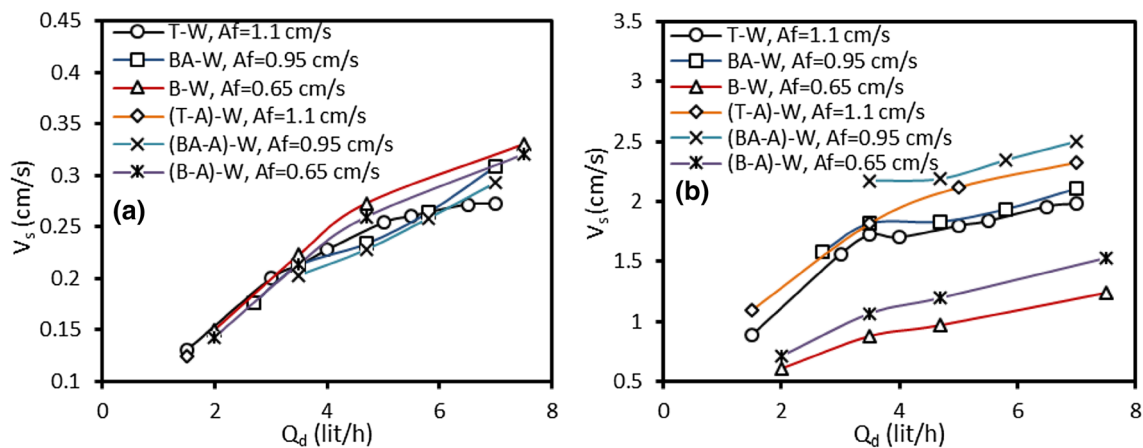


Fig. 7 The effect of dispersed phase flow rate on slip velocity: **a** horizontal section, **b** vertical section





superficial velocity as well as lower holdup, as illustrated in Fig. 2a, results in higher slip velocity in horizontal section. However, in vertical section, due to the reduction of buoyancy forces on smaller drops, which are made at higher Af, the Holdup increases. According to Eq. (2), the enhancement of holdup leads to the reduction of slip velocity in vertical section when Af increases as shown in Fig. 6b. However, with further increase of Af, the reduction is gradual and it can be inferred that further drop breakage into smaller ones is limited.

The effect of variation of interfacial tension of the liquid systems can be also obtained from Fig. 6. According to Fig. 6, it is observed that the enhancement of the interfacial tension leads to the reduction of slip velocity in horizontal section, while it results in higher slip velocities in vertical section of the column. It is because of the formation of smaller drops in systems with lower interfacial tension and the variation of holdup which is discussed in Sect. “Effect of operating parameters on holdup”.

The influence of  $Q_d$  on slip velocity of phases is illustrated in Fig. 7. It is observed that when  $Q_d$  increases, the slip velocity increases in both sections of the column. According to the definition of slip velocity, when  $Q_d$  and consequently the superficial velocity of dispersed phase increases, the slip velocity will increase. The enhancement of  $Q_d$  tends to the monotonous increase of dispersed phase holdup along with higher superficial velocity of dispersed phase drops. However, it is obtained that the impact of superficial velocity growth is dominant, leading to higher slip velocities in each section of the column. Furthermore, Fig. 8 shows the impact of  $Q_c$  on slip velocity. It is observed that the increase of  $Q_c$  leads to the slight enhancement of slip velocity in horizontal section of the column, while it decreases the slip velocity in vertical section. Increasing  $Q_c$  causes a rise in superficial velocity of the continuous phase which leads to higher slip velocity in horizontal section. However, the enhancement of drag

forces arising from the relative velocity between the dispersed phase drops and the bulk continuous phase results in longer residence time as well as the increase of holdup in vertical section, thereby declining the slip velocity. It should be noted that there is a moderate variation of slip velocity by increasing  $Q_c$  and the influence of  $Q_d$  on slip velocity is much stronger than the effect of  $Q_c$ .

The results of presence of mass transfer from the dispersed phase to the continuous phase are also depicted in Figs. 6, 7, 8. The slip velocity for mass transfer  $d \rightarrow c$  direction is lower than that for cases with no mass transfer in horizontal section of the column, while an inverse trend exists in the vertical section of the column. This behavior can be referred to the interfacial tension gradient, interface motions, and consequently lower drop breakage and higher coalescence along with the variation of dispersed phase holdup with the presence of mass transfer ( $d \rightarrow c$ ) which is previously shown in Figs. 2, 3, 4, 5 and well discussed in previous section. According to Eq. (2), a decrease of holdup leads to the enhancement of slip velocity in the horizontal section of the column, while an inverse trend is observed in the vertical section.

### Predictive correlation for holdup

Many correlations are proposed for holdup in the literature. However, in this study, the experimental data are compared with most recommended correlations which are presented for pulsed sieve-plate column with wide applicability. Correlations from the work of Miyauchi and Oya [31], Kumar and Hartland [32], Tung and Luecke [33], Kumar and Hartland [34], Venkatanarasaiah and Varma [35], Melnyk et al. [3] and Khajenoori et al. [27]. are considered. Figure 9 shows the predictive ability of correlations proposed for holdup in vertical pulsed columns. It is observed that these correlations are not satisfactorily accurate for prediction of holdup

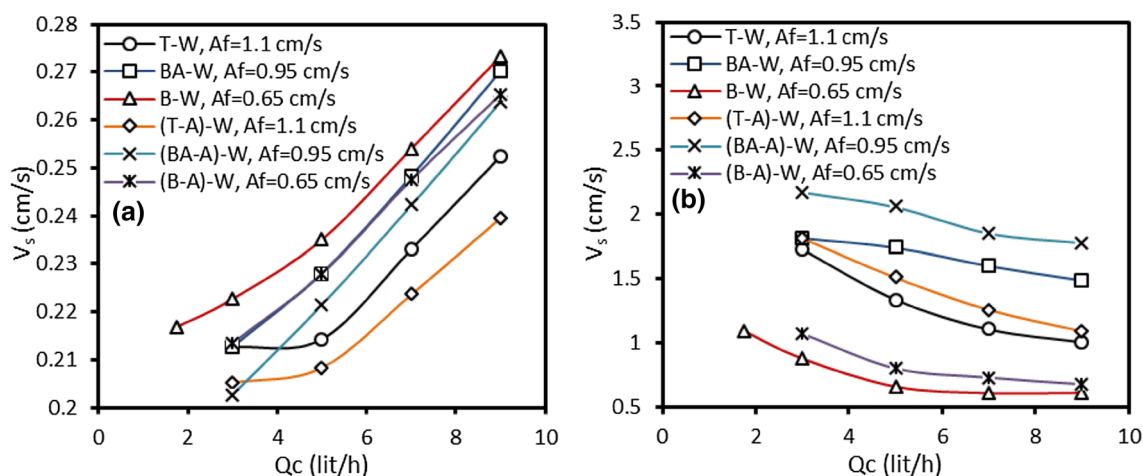
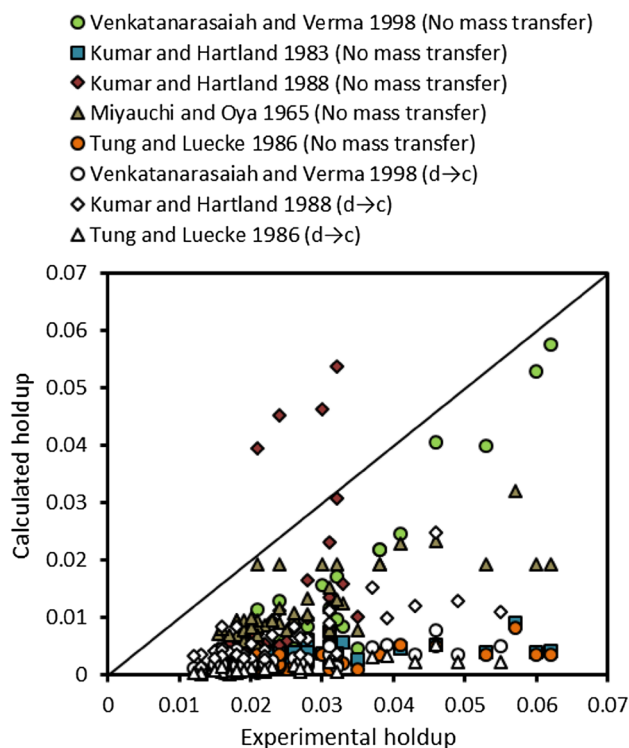


Fig. 8 The effect of continuous phase flow rate on slip velocity: **a** horizontal section, **b** vertical section





**Fig. 9** Comparison of the experimental data of holdup in the vertical section with those calculated by previous correlations

in vertical section of the column. The Average Absolute Relative Error (AARE) is used to determine the predictive ability of the proposed correlations. The AARE can be calculated by Eq. (6):

$$\text{AARE} = \frac{1}{n} \sum_{i=1}^n \frac{|\text{Experimental } X_i - \text{Calculated } X_i|}{\text{Experimental } X_i} \quad (6)$$

**Table 5** The AARE of calculated holdup from previous correlations with the experimental data

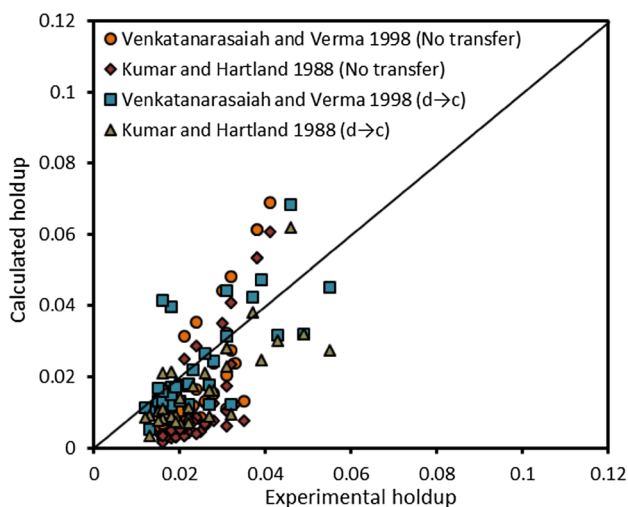
References	Column section	Condition	AARE (%)
Miyauchi and Oya [31]	Vertical	No transfer	55.6
Kumar and Hartland [32]	Vertical	No transfer	86.2
Kumar and Hartland [34]	Vertical	No transfer	91.9
		$d \rightarrow c$	74.7
Tung and Luecke [33]	Vertical	No transfer	93.1
		$d \rightarrow c$	78.5
Venkatanarasaiah and Varma [35]	Vertical	No transfer	70.5
		$d \rightarrow c$	89.4
Kumar and Hartland [14] <sup>a</sup>	Vertical	No transfer	66.3
		$d \rightarrow c$	41.4
Venkatanarasaiah and Varma [35] <sup>b</sup>	Vertical	No transfer	51.8
		$d \rightarrow c$	29.4
Melnyk et al. [3]	Horizontal	No transfer	196.6
Khajenoori et al. [27]	Horizontal	No transfer	79.8

<sup>a,b</sup>Using their correlations of slip velocity along with Eq. (2)

The AARE values of calculated holdup obtained from previous correlations are listed in Table 5, which shows high deviation from the experimental data. Furthermore, Kumar and Hartland [14] and Venkatanarasaiah and Varma [35] proposed new correlations for directly prediction of slip velocity. These correlations have been also used for prediction of holdup in vertical section of the column using Eq. (2). The results of comparison between the experimental data with those calculated by these two equations are plotted in Fig. 10, indicating that slip velocity correlation of Kumar and Hartland [14] and Venkatanarasaiah and Varma [35] offer better prediction of holdup in the column in comparison with other correlation (Table 5). The better prediction of slip velocity correlation of Venkatanarasaiah and Varma [35] can be referred to the fact that their correlation considers the effect of perforation diameter of plates, while the  $V_s$  correlation of Kumar and Hartland [14] does not. Moreover, it is achieved that the results are in accordance with the conclusion from the work of Yadav and Patwardhan [26], in which they recommended the  $V_s$  correlation of Venkatanarasaiah and Varma [35] for prediction of the dispersed phase holdup in pulsed sieve-plate columns.

The results from the correlation of Melnyk et al. [3], are compared with the experimental data of holdup in horizontal section of the column. Moreover, holdup is determined from the correlation of Melnyk et al. [3], for slip velocity using Eq. (2) and also compared with the experiments. The predictive ability of these correlations is shown in Fig. 11. It is observed that these correlations are not proper to predict holdup in horizontal section of the column. The AARE of these equations is presented in Table 5.

Since the previous correlations are not able to satisfactory predict the dispersed phase holdup in horizontal and vertical section of the column, new correlations are proposed



**Fig. 10** Comparison of the experimental data of holdup in the vertical section with correlations of Kumar and Hartland [14] and Venkatanarasaiah and Varma [35] for slip velocity using Eq. (2)

for prediction of holdup in each section in terms of physical properties and operating parameters. As the hydrodynamic behavior of each two section is different, for example, an increase in pulsation intensity resulted in increasing holdup in vertical part and a decrease in horizontal part of the column was observed. So because of this dual behavior, in terms of statistically we cannot offer just one correlation for both sections. Equation (7) is proposed for determination of holdup in horizontal section:

$$\varphi = C \left( \frac{Af}{V_d} \right)^{-0.308} \left( \frac{\Delta\rho}{\rho_c} \right)^{1.181} \left( \frac{\mu_c}{\mu_d} \right)^{0.863} \left( \frac{\mu_d V_d}{\sigma} \right)^{0.184} \left( 1 + \frac{V_d}{V_c} \right)^{-0.208}, \tag{7}$$

where  $C = 1.629$  and  $C = 1.64$  for conditions with no mass transfer and for mass transfer  $d \rightarrow c$  respectively. The comparison of the experimental data with those calculated by Eq. (7) is illustrated in Fig. 12a. The AARE values for no mass transfer and mass transfer  $d \rightarrow c$  condition are 3.5 and 3.7%, respectively, which shows good agreement with the experiment.

Moreover, Eq. (8) is proposed for holdup in vertical section of the column:

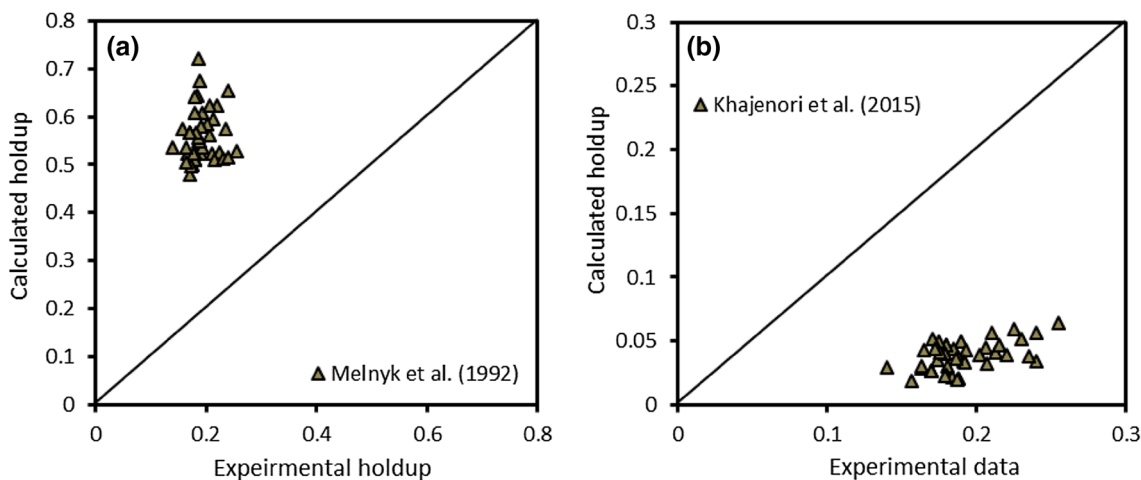
$$\varphi = K_1 \exp(K_2 |(Af) - (Af)_m|) \left( \frac{Af}{V_d} \right)^{0.486} \left( \frac{\Delta\rho}{\rho_c} \right)^{6.475} \times \left( \frac{\mu_c}{\mu_d} \right)^{3.921} \left( \frac{\mu_d V_d}{\sigma} \right)^{1.241} \left( 1 + \frac{V_d}{V_c} \right)^{-0.34}, \tag{8}$$

$$\text{where } (Af)_m = 7.7 \times 10^{-3} \left( \frac{\sigma \Delta\rho^{1/4} \alpha}{\mu_d^{3/4}} \right)^{0.18},$$

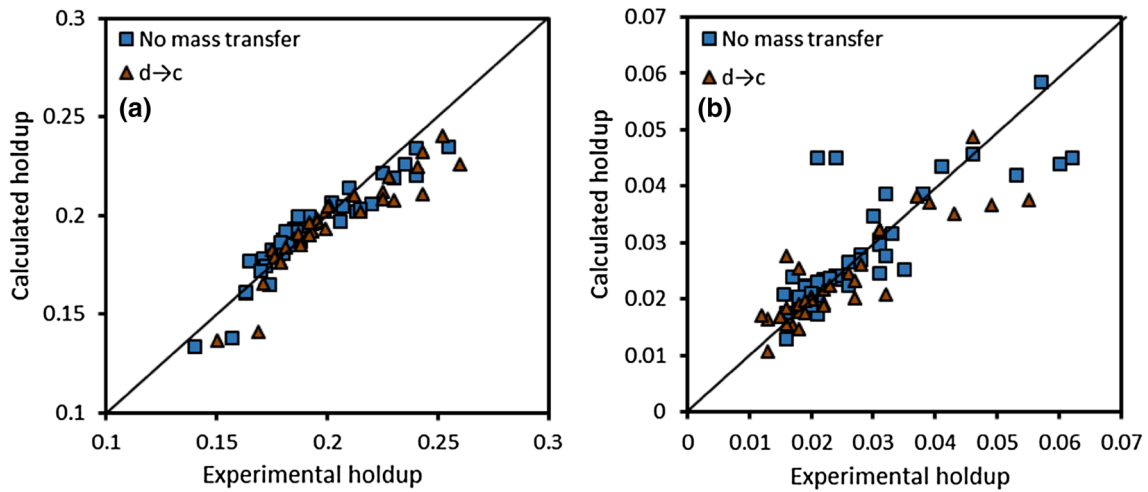
Also,  $K_1$  and  $K_2$  are the parameters which are fitted with the experimental data and presented in Table 6. The predictive ability of Eq. (8) is shown in Fig. 12b. The AARE values in the calculated holdup obtained by Eq. (8) to the experimental data of holdup without mass transfer and with mass transfer  $d \rightarrow c$  are 15.5 and 13.8% respectively, which show satisfactory agreement with the experiments.

### Predictive correlation for slip velocity

A comparison between the correlations of Kumar and Hartland [14], Venkatanarasaiah and Varma [35] and



**Fig. 11** Comparison of the experimental data of holdup in the horizontal section with correlations of **a** Melnyk et al. [3], for holdup and **b** Khajenoori et al. [27], for slip velocity using Eq. (2)



**Fig. 12** Comparison of the experimental data of holdup with those calculated by **a** Eq. (7) for horizontal section and **b** Eq. (8) for vertical section

**Table 6** Values of constants in Eq. (9) for different mass transfer conditions

Mass transfer condition	$K_1$	$K_2$
No solute transfer	$1.12 \times 10^9$	11.53
$d \rightarrow c$ direction	$9.21 \times 10^8$	23.56

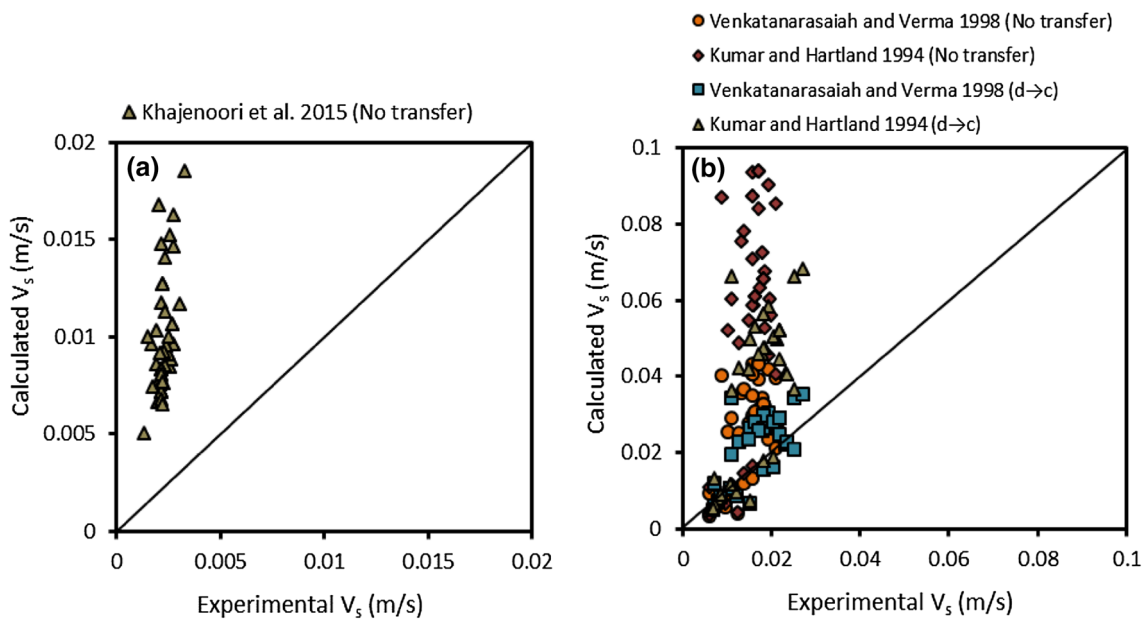
Khajenoori et al. [27] and the experimental data of slip velocity is shown in Fig. 13. The AARE values of these equations are presented in Table 7. It is observed that none

of these correlations gives satisfactory prediction of slip velocity.

Consequently, new correlations are proposed as a function of operating parameters and physical properties of the liquid systems by dimensional analysis method as follows:

For horizontal section:

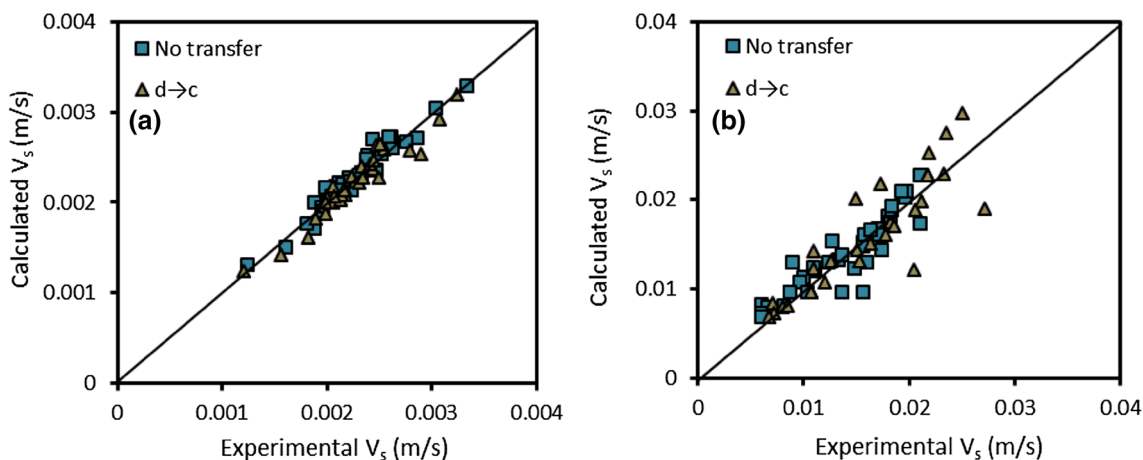
$$\frac{V_s \mu_c}{\sigma} = C \left( \frac{Af}{V_d} \right)^{0.173} \left( \frac{\Delta\rho}{\rho_c} \right)^{-0.573} \left( \frac{\mu_c}{\mu_d} \right)^{0.570} \times \left( \frac{\mu_d V_d}{\sigma} \right)^{0.918} \left( 1 + \frac{V_d}{V_c} \right)^{-0.341}, \tag{9}$$



**Fig. 13** Comparison of the experimental data of slip velocity with those calculated by previous correlations: **a** horizontal section, **b** vertical section

**Table 7** The AARE of calculated slip velocity from previous correlations with the experimental data

References	Column section	Condition	AARE (%)
Kumar and Hartland [14]	Vertical	No transfer	283.4
		$d \rightarrow c$	125.7
Venkatanarasaiah and Varma [35]	Vertical	No transfer	100.0
		$d \rightarrow c$	40.8
Khajenoori et al. [27]	Horizontal	No transfer	76.2

**Fig. 14** Comparison of the experimental data of slip velocity with those calculated by **a** Eq. (9) for horizontal section and **b** Eq. (10) for vertical section

where  $C=0.653$  and  $C=0.698$  for no mass transfer and for  $d \rightarrow c$  mass transfer.

For vertical section:

$$\frac{V_s \mu_c}{\sigma} = C \left( \frac{Af}{V_d} \right)^{-0.864} \left( \frac{\Delta \rho}{\rho_c} \right)^{-9.66} \left( \frac{\mu_c}{\mu_d} \right)^{-5.422} \times \left( \frac{\mu_d V_d}{\sigma} \right)^{-0.962} \left( 1 + \frac{V_d}{V_c} \right)^{0.782}, \quad (10)$$

where  $C=2.37 \times 10^{-15}$  and  $C=1.041 \times 10^{-14}$  for no mass transfer and for  $d \rightarrow c$  mass transfer. The AARE values in the calculated slip velocity using Eqs. (9) and (10) to the experimental data of slip velocity are 3.49% and 11.39%, respectively, which show accurate agreement with the experiments. Figure 14 illustrates the predictive ability of these correlations.

### Application performance of an L-shaped extraction column

In order to evaluate the performance of an L-shaped extraction column over the conventional vertical and horizontal columns, Amani et al. [9] conducted a comparative study on the mean drop size in various columns. The

results of Kagan et al. [36], Miyauchi and Oya [31], Kleczek et al. [37], for vertical extraction columns and the data of Khajenoori et al. [38], and Panahinia et al. [29] for horizontal extraction columns were used for this comparison. The operating conditions and column characteristics were close to each other and to the current L-shaped column used in this study. It was seen that the horizontal section of the L-shaped column provides larger droplets compared to similar horizontal columns. On the other hand, in the vertical section of the column, smaller droplets have been formed compared to the conventional vertical columns with similar structures. Furthermore, from the comparative study conducted in this study (as partly presented in Figs. 9 and 10), one can find that the values of holdup in the horizontal section is higher than that in a separate horizontal extraction equipment. Therefore, it can be concluded that the horizontal section of the column performs better than a separate horizontal column and offers higher interfacial area available for mass transfer, while the vertical section of the column operates in a comparable manner with a separate vertical column. It is worth noting that the findings also recommend the construction of a combined tower instead of employing two separate horizontal and vertical extraction equipment in cases where we suffer from area limitations.



## Conclusion

In this study, the effect of operating parameters including pulsation intensity and flow rate of the continuous and dispersed phases on the dispersed phase holdup and slip velocity of phases is investigated in a new type of extraction column entitled “L-shaped pulsed sieve-plate column”. The results reveal that increasing  $Q_d$  and  $Q_c$  leads to the enhancement of holdup in the column, while holdup decreases in horizontal section and increases in the vertical section when  $A_f$  increases. Moreover, with respect to the variation of holdup and superficial velocities of phases under different operating conditions, it is observed that the slip velocity increases at higher  $Q_d$  in each section, while increasing  $Q_c$  leads to higher slip velocity in horizontal section and lower slip velocity in vertical section. Pulsation intensity is found to pose two different impacts on slip velocity similar with increasing  $Q_c$ .

A comparison between the experimental data with those calculated by previous correlations for holdup and slip velocity is conducted. Furthermore, new correlations are proposed for prediction of these two parameters in each section of the column, with AARE from 3.49 to 15.5%. The presented correlations give a satisfactory agreement with the experiments.

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