

Research Article Modeling of Hydrodynamics in a 25 mm ϕ Pulsed Disk and Doughnut Column

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The hydrodynamic parameters, namely, dispersed phase holdup and flooding throughput, have been investigated in 25 mm diameter pulsed disk and doughnut column (PDDC), in no mass transfer conditions. In this work, using existing correlations on plate pulsed columns, the dispersed phase holdup and the flooding throughput are empirically modelled well using the slip velocity concept. A good agreement is observed between experimental values and predicted values obtained from empirical correlation. The experimental data for dispersed phase holdup and flooding throughput has been modelled using the Van Delden model to describe the hydrodynamics characteristics of a PDDC and necessary adjustable parameters for drop size distribution and dispersed phase holdup are updated for 30% TBP-nitric acid system. The model parameters were estimated by minimizing the absolute error between experimental and theoretical values of flooding throughput and holdup data. It was found that the measured values and observed trends could be described accurately using this model after fitting holdup and flooding data. The error between the experimental and theoretical values of flooding throughput and holdup was found to be less than 10%.

1. Introduction

Liquid-liquid extraction, a major unit operation in the chemical process industries, is also backbone of the aqueous route of nuclear fuel reprocessing. The irradiated fuel from the nuclear reactor contains a mixture of uranium and plutonium along with large number of fission products. For efficient reuse of uranium and plutonium, these are recovered from spent nuclear fuels by PUREX process. The pulsed column, equipped with perforated plate internals and having 23% free area, has traditionally been used in the PUREX process for almost the last six decades. Due to absence of moving parts, the pulsed columns have clear advantage over other mechanical contactors/extractors while processing corrosive or radioactive solutions. A new type of pulsed column with internals, comprising an assembly of alternate disk and doughnuts, has gained attention in recent times. However, the amount of literature available on these columns is severely limited and briefly reviewed as follows.

Jahaya et al. [1] compared the performance of pulsed disc and doughnut column with pulsed sieve plate column of 75 mm diameter and 23% free area for toluene-acetone-water system. While comparing these two designs of extraction columns, they maintained the entire operating envelope identical, for both of the columns. They observed that although total throughput per unit cross-sectional area through the PDDC was less, the mass transfer performance (and in turn, holdup of the PDDC) was better. Hong et al. [2] reported experimentally measured values of holdup and drop size in a 46.6 mm diameter disc and doughnut column using the MIBK(d)-water(c) system. They also reported a functional relationship of the Sauter mean diameter as a function of pulse intensity. Recently, Van Delden et al. [3, 4] reported models to predict holdup, the Sauter mean drop diameter, flooding throughput, and mass transfer performance with respect to operational conditions of PDDC. The models have been tested for extraction of caprolactam with toluene in 40 mm diameter, 26.7% free area, and 4.24 meter active height

column. The interfacial area, available for mass transfer in a countercurrent differential extractor, depends upon the mean droplet size and dispersed phase holdup. It is, therefore, important at the design stage to predict both these parameters for any given system, column geometry, and set of operating conditions.

The present study reports results of the dispersed phase holdup measurement and correlation for organic phase dispersion in PDDC, using the slip velocity and characteristic velocity concept. Hydrodynamic model for pulse column was extended by Van Delden et al. [3, 4] for PDDC. The applicability of the Van Delden model is discussed to describe the flooding characteristics, drop size, and dispersed phase holdup, and this model was tested with 30% TBP-nitric acid system at no mass transfer conditions in 25 mm diameter, 23% free area, and 2 m active height. The corresponding fitted parameters, different from conventional pulsed column, are investigated and compared with values reported by Van Delden for a similar PDDC.

2. Experimental Details

The PDDC pilot setup is schematically shown in Figure 1. The active column section is comprised of four glass sections each 50 cm in length and 25 mm in internal diameter. The active section was closed on either ends by settlers (height of 42 cm and an inner diameter of 50 mm). The glass sections were connected using PTFE flanges having sample ports in the form of needle valves. The column internals consisted of an alternating sequence of disc and doughnut plates that were held in place with three tie rods. The tie rods were housed inside spacer sleeves and arranged in a triangular pitch as shown in Figure 2. The internals and spacer sleeves were made of stainless steel (SS-304) material to prevent wetting by the organic dispersed phase. The dimensions of the column and the plates are shown in Table 1. The experimental conditions are shown in Table 2. The aqueous phase was introduced at the top and the organic phase at the bottom. In the hydrodynamics experiments, both phases leaving the column returned to their respective storage tanks for recycling. The organic stream was allowed to leave the column via organic exit port. The interface level was controlled by an interface controller working on a jack-leg principle. Pulsing limb was attached to the bottom side of the column. Pressure and vacuum were created in the pulse limb through an arrangement of digital timer, solenoid valves, and an ejector. This periodic reversal of pressurization and depressurization in the pulse leg created periodic upwards and downwards movement of liquid column in the pulse leg which also created similar movement in the liquid column inside the PDDC. This periodic movement is known as pulsing, and this continuous reciprocating movement of the liquid column past the disc and doughnut internals causes turbulence with drop formation. The aqueous and organic phases were pumped by using two valveless digital metering pumps (ISMATEC MFP Process drives with Q3 Pump heads) with maximum capacity of 2300 mL/min each.

TABLE 1: Geometrical characteristics of the PDDC used in this study.

Parameter	Dimensions of disc and doughnut
Diameter of column	2.5 cm
Active column height	200 cm
Height between disc and doughnut	1.0 cm
Free area	23%
Pulse leg diameter	1.0 cm
Diameter of disc	2.195 cm
Internal diameter of doughnut	1.2 cm
Settlers diameter	5.0 cm
Spacer tubes	SS304L tube 0.25 OD \times 0.18 ID \times 1.0 cm length
Tie rod position from centre	1.8 cm (triangular pitch, equispaced)

TABLE 2: Range of variables studied.

Variables	Range
Flow rate $(U_c \text{ and } U_d)$	0.17–1.36 cm/s
Plate spacing, H	1.0 cm
Frequency (f)	1-2 Hz
Amplitude (A)	1.04-4.6 cm

3. Experimental Procedure

3.1. Property Measurements. In all these experiments, the continuous phase was dilute aqueous nitric acid solution (0.5 N HNO_3) . 30%TBP (v/v) solution in normal paraffinic hydrocarbon, an industrial substitute of *n*-dodecane, was used as dispersed phase. Technical grade TBP (99%), AR grade HNO₃ (69–72% M/S RANKEM), commercial normal paraffinic hydrocarbon (density ~0.75 g/mL), and distilled water were used to make the respective solutions. Density of solutions was measured by an automatic vibratingtube densitometer (Anton-Paar DMA-5000) with a builtin thermoelectric Peltier element module for maintaining temperature of sample in a thermostated U-tube. The measurement accuracy was 10^{-6} g/cm³. Kinematic viscosities were determined for the equilibrated phases at 298 K, using Cannon Fenske glass viscometers. The measurement accuracy was 0.01 cP. Interfacial tensions were determined for the ternary TBP-HNO₃-water system at 298 K with a Du Noüy tensiometer using a standard Pt ring of 5.992 cm as circumference, and results were corrected by the procedure of Harkinson and Brown [5]. The standard deviation of the interfacial tension measurements was less than $0.3 \,\mathrm{mN \cdot m^{-1}}$. The physical properties of the aqueous-organic pair used in this study are listed in Table 3.

3.2. Experimental Runs with PDDC. As per the standard practice, the column was first filled with the continuous phase (dilute aqueous nitric acid of 0.5 N concentration). The pulsation was started after setting the frequency to the desired



FIGURE 1: Schematic diagram of the experimental setup.

value with the help of a digital timer. The pulsation amplitude was set to the desired values in the pulse leg by adjusting the compressed air pressure with help of pressure regulator. Then, the organic phase (30% TBP/NPH) was pumped into the column. A fixed ratio between the organic and aqueous flow rates was maintained. The interface was maintained at a given height at the top of the column with help of an interface controller.

3.3. Holdup. Dispersed phase holdup is defined as the fraction of the active column section volume occupied by the dispersed phase. Before carrying out the experiments, both phases were mutually saturated, and the pulse amplitude and frequency were adjusted to the desired values. The continuous-phase and the dispersed-phase flow rates were then set to the required flow rate, and the system was stabilized to allow steady state to be reached. Then, the inlet

TABLE 3: Physical properties of the equilibrated aqueous organic pair.

Property	Value
Density of continuous phase, that is, aqueous phase 0.5 N HNO ₃ (ρ_c)	$1.0155 \mathrm{g/cm^3}$
Density of dispersed phase, that is, organic phase (30% TBP/NPH) (ρ_d)	0.8085 g/cm ³
Interfacial tension (γ)	9.95 dynes/cm
Dynamic viscosity of continuous phase (η_c)	1.05 cP
Dynamic viscosity of dispersed phase (η_d)	2.09 cP

and outlet flows were stopped simultaneously. The dispersion was then allowed to coalesce at the interface. The holdup was then measured either by determining the change of interfacial height or by displacing the solvent layer into a measuring cylinder.

3.4. Flooding. Flooding throughput was measured keeping the pulse velocity and the continuous phase flow rate constant and increasing the dispersed phase flow rate until the onset of flooding. The measurement of pressure drop across the column was a useful indicator for predicting the onset of flooding. At the onset of flooding, the pressure drop across the column became unsteady. When the column approached flooding, the interface position was unstable and kept on varying in spite of adjusting the withdrawal rate of aqueous phase. The incoming and the exiting flow rates did not match at flooding which indicated buildup of dispersed phase within the column. When flooding occurred, all flows were immediately stopped and then the holdup was measured.

4. Results and Discussion

4.1. Equations for Estimating Hydrodynamic Model Parameters. According to the theory for pulsed sieve-plate columns, the column operation may be characterized by the Sauter mean drop diameter (d_{32}) and the dispersed phase holdup, ε of which the latter is dependent on the operational regime in the column. The operational window of the column is limited by flooding that may arise due to either insufficient pulsation or phase inversion or excessive entrainment at high pulsation.

The parameters of the equations describing the column hydrodynamics may be divided into (i) physical properties, (ii) operational variables, and (iii) geometric dimensions of the column and its internals. The physical properties include the continuous and dispersed phase densities (ρ_c and ρ_d), the corresponding density difference ($\Delta \rho = \rho_c - \rho_d$), the dynamic viscosities of the phases (η_c and η_d), and the interfacial tension, γ . The operational parameters include the phase superficial velocities, U_c and U_d , and hence the corresponding volumetric flux and flow ratio and the pulsation intensity Af. The model is developed for the purely hydrodynamic situation and therefore assumes equilibrium conditions in order to avoid the influence of mass transfer.



FIGURE 2: Schematic representation of the internals of the pulsed disk and doughnut column.

4.2. Dispersed Phase Holdup Using Slip Velocity Concept. The slip velocity is a useful concept that is widely used in extraction literature for obtaining the relative velocities between phases that are either in cocurrent or countercurrent flow. Once an expression for slip velocity is available in terms of the geometric, operational parameters as well as the system properties, it could be used to predict holdup. Dispersed phase holdup was one of the important first parameters of column to be addressed by Gayler and Pratt in the early fifties [6, 7] relating to packed columns, followed by Thornton [8] in 1956. Hartland and Kumar did extensive work in this field and they reported correlations for pulsed perforated [9, 10], reciprocating [11], and general [12] columns.

4.3. Correlations Incorporating Slip Velocity for Organic Phase Dispersion. The basic idea of Gayler and Pratt [6, 7] was to calculate the holdup in terms of slip velocity and characteristic velocity as follows:

$$U_{\rm slip} = \frac{U_d}{\varepsilon} + \frac{U_c}{(1-\varepsilon)} = V_o \left(1-\varepsilon\right),\tag{1}$$

where V_o is the characteristic velocity, which is the mean droplet velocity relative to the continuous phase, when $U_c = 0$ and $U_d \rightarrow 0$.

Later, Godfrey and Slater [13] in 1991 proposed the following

$$U_{\text{slip}} = V_o (1 - \varepsilon)^m,$$

$$U_{\text{slip}} = V_o (1 - \varepsilon) \exp(b\varepsilon).$$
(2)

The holdup data is further correlated employing the following slip velocity forms. Kumar and Hartland [14] correlated the holdup in terms of slip velocity as a power function



FIGURE 3: Comparisons of slip velocity measurement with the correlation using equation (3).

 $(1 - \varepsilon)$. Since V_o depends on specific power dissipation, it is a function of (Af). The final form for organic phase dispersion and the correlations of slip velocity in terms of Af and ε are as follows:

$$U_{\rm slip} = 3.4855 (Af)^{-0.4669} (1-\varepsilon)^{-0.7619},$$
 (3)

$$U_{\rm slip} = 3.3241 (Af)^{-0.4713} (1-\varepsilon) e^{2.2780\varepsilon}.$$
 (4)

The calculated U_{slip} values are plotted against experimental U_{slip} data in Figures 3 and 4 respectively. The data are also correlated using holdup ratio as the correction factor for Pratt's equation and the resulting equation is as follows:

$$U_{\rm slip} = 7.6812 (fA)^{-0.4482} (1-\varepsilon) \left(\frac{\varepsilon}{1-\varepsilon}\right)^{0.281}$$
. (5)

The slip velocities calculated with equation (5) are plotted against the experimental slip velocities in Figure 5. Though equation (5) predicts the slip velocities well, this equation should be strictly treated as empirical within the range of variables covered in the present study; as $\varepsilon \rightarrow 0$, U_{slip} becomes zero instead of reducing to V_o , which is not expected.

The response of the dispersed phase holdup to the operational variables in the present PDDC is thus qualitatively similar to the response of the liquid pulse and reciprocating pulse columns to the flow rates of dispersed, continuous phases, and the pulsation intensity.

4.4. Correlation for Flooding Using Slip Velocity Concept. In PDDC, the flow regime might correspond to mixer settler, dispersion, and emulsion regimes although clear demarcation was not possible based on the visual observations. In the mixer settler regime, pulsation amplitude less than 1 cm/s typically leads to large globules of dispersed phase



FIGURE 4: Comparisons of slip velocity measurement with the correlation using equation (4).



FIGURE 5: Comparisons of slip velocity measurement with the correlation using equation (5).

flowing through the test section. In the dispersion regime, with pulsation amplitude of 1-4 cm/s, occasional big drops were seen, while in the emulsion regime corresponding to pulsation amplitude of 4 cm/s and above, the drops were uniform. In this study, throughout the experiment, pulsation amplitude was maintained larger than 1 cm/s.

The flooding throughput is modelled in the present study as a slip velocity concept:

$$\frac{U_{df}}{\varepsilon_f} + \frac{U_{cf}}{\left(1 - \varepsilon_f\right)} = 6.22 \exp\left(-0.10 fA\right) \left(1 - \varepsilon_f\right).$$
(6)

The constants in equation (6) are dependent upon the physical properties of the system, the column geometry, and the material of construction of the internals. Experimental data is compared with predicted values from equation (6) in Figure 6.

4.5. The Applicability of Unified Equation. Hartland and Kumar correlated the holdup directly from the physical property data, energy input, and flow rates, avoiding the problematic concept of characteristic velocity. In a series of articles they reported correlations for sieve-plate pulsed columns [10], Karr column [11], and a unified correlation for pulsed, packed, and reciprocating columns [12]. Unified correlation of Kumar and Hartland [12] has been used by Van Delden et al. [3, 4] for PPDC as follows:

$$\varepsilon = \Pi \Phi \Psi \Gamma,$$
 (7a)

where

$$\Pi = C_{\Pi} + \left[\frac{E}{g} \cdot \left(\frac{\rho_c}{g \cdot \gamma}\right)^{0.25}\right]^{n_1}, \tag{7b}$$

$$\Phi = \left[U_d \cdot \left(\frac{\rho_c}{g.\gamma}\right)^{0.25} \right]^{n_2} \exp\left[n_3 \cdot U_c \cdot \left(\frac{\rho_c}{g\cdot\gamma}\right)^{0.25} \right], \quad (7c)$$

$$\Psi = C_{\Psi} \cdot \left(\frac{\Delta \rho}{\rho_c}\right)^{n_4} \cdot \left(\frac{\eta_d}{\eta_c}\right)^{n_5},\tag{7d}$$

$$\Gamma = C_{\Gamma} \cdot e^{n_6} \cdot \left[H \cdot \left(\frac{\rho_c \cdot g}{\gamma} \right)^{0.5} \right]^{n_7}, \tag{7e}$$

$$E = \left(\frac{\Pi^2}{2}\right) \left(\frac{1-e^2}{e^2 C_o^2 H}\right) \left(A \cdot f\right)^3.$$
(7f)

Equation (7a) is a semiempirical relation valid in the dispersion and emulsion operational regime. The group Π allows for the influence of the energy input per unit mass, Φ for the effect of phase velocities, Ψ for the influence of the physical properties, and Γ for the dimensions of the internals. The value for C_{Ψ} was taken unity since the system operated without mass transfer and n_6 was set to 0 as all the pulsed columns studied had the same value of the fractional plate free area (0.23). Van Delden suggested that the energy input would be different for a PDDC compared to a pulsed sieve-plate or the Karr column. Therefore, the parameters C_{Π} , C_{Γ} , and n_1 might differ for a PDDC compared to the literature values. Same reasoning applies for n_5 when the viscosity influence in equation (7a) gets changed compared to the literature. The deviation in n_5 is probably not large as long as the continuous phase viscosity is close to the value of water. The parameter values are presented in Table 4 together with original values derived for pulsed sieve-plate column by Kumar and Hartland and Van Delden fitted limited number of parameter for PDDC.

4.6. Dispersed Phase Holdup Comparison between Experimental Data of This Work with Van Delden Correlation. The fitted parameters, suggested by Van Delden, were based on limited



FIGURE 6: Comparisons of slip velocity measurement with the correlation using equation (6).



FIGURE 7: Comparison of holdup measurements with the Van Delden model.

number of experimental data for caprolactam extraction in PDDC having column diameter 40 mm and plate spacing of about 9 mm with 26.3% free area. Figure 7 shows comparison of experimental data with the original Van Delden model. As column diameter is different in this study and aqueous-organic pair is also different, the parameters reported in this work (C_{Π} and n_1) differ from the values reported by Van Delden. New fitted parameters are $C_{\Pi} = 3.1054$ and $n_1 = 0.6768$ for 95% confidence interval. The calculated holdup

TABLE 4: Adjustable parameters of correlations for estimating holdup.

ε	C_{Π}	C_{Γ}	n_1	n_2	n_3	n_4	n_5	n_7
Kumar and Hartland	0.27	6.87	0.78	0.87	3.34	-0.58	0.18	-0.39
Van Delden	2.39	0.45	0.34	_	_		-0.08	-0.12
Present work	3.1054	—	0.6768	—	—	_	_	_

TABLE 5: Adjustable parameters of correlations for estimating drop size.

		(a)					
d_{32} equation (8)	C_1	C_2	C_3	n_1	n_2	n_3	n_4
Kumar and Hartland	1.38	0.16	1.25	0.3	0.18	0.14	0.06
Delden	2.84	_	-2.59	_	—	_	_
Present work	3.7557	_	-0.7517	_	—	_	_
		(b)					
d_{32} equation (8)	C_{Ψ}	C_{Ω}	C_{Π}	п		n_1	n_2
Kumar and Hartland	1^*	1.55	0.42	0.32	-	0.35	1.15
*							

* No mass transfer.

profile using the new fitted parameters is shown in Figure 8 together with experimental data. From Figure 8, it may be observed that the experimental data are described well within $\pm 10\%$.

4.7. Mathematical Model for Estimation of the Sauter Mean Drop Diameter. Knowledge of the drop size is of fundamental importance in the design of liquid-liquid extraction columns. It affects the dispersed-phase holdup, the residence time of the dispersed phase, and the allowable throughputs. Kumar and Hartland [14, 15] made major study of the drop size, and based on wide range of experimental conditions, they developed unified correlations for drop size, as a function of system parameters for a wide variety of columns. The correct description of influence of energy input on drop size has not yet been found.

In 1986, Kumar and Hartland developed the following model for the pulsed sieve-plate column [14]:

$$\frac{d_{32}}{\sqrt{\gamma/\Delta\rho g}} = C_1 e^{n_1} \left(H \cdot \sqrt{\frac{\rho_* g}{\sigma_*}} \right)^{n_2} \left(\frac{\eta_d g^{0.25}}{\sigma_*^{0.75} \rho_*^{0.25}} \right)^{n_3}$$

$$\left(\frac{\gamma}{\sigma_*} \right)^{n_4} \left[C_2 + \exp\left(\frac{C_3 \left(Af\right)}{e} \left(\frac{\rho_*}{\sigma_* g} \right)^{(1/4)} \right) \right].$$
(8)

Later in 1996, Kumar and Hartland [15] presented a unified correlation for many types of columns. Its form for pulsed columns is as follows:

$$=\frac{\frac{u_{32}}{H}}{\left(C_{\Omega}(\gamma/\Delta\rho g H^{2})^{0.5}\right)^{-1} + \left(C_{\Pi}\left[(E/g)\left(\Delta\rho/g\gamma\right)^{0.25}\right]^{n_{1}}\left[H(\Delta\rho g/\gamma)^{0.5}\right]^{n_{2}}\right)^{-1}}.$$
(9)

These equations are valid in all operating regimes, take energy input into account via pulsation intensity (Af), and are based



FIGURE 8: Parity plot of holdup experimental values with predicted values based on new fitted parameters.

on the physical properties and geometrical properties of the system. Both equations are similar. However, Equation (8) takes into account the influence of dispersed phase viscosity. The parameters η^* and σ^* represent reference density and surface tension values of water at 298 K.

However, the characteristic internal sizes, e and H, are different for a PDDC compared to sieve-plate internals, and the resulting energy input is thus different as well. Therefore, the parameters C_1 , C_2 , C_3 , and n_2 in (8) and C_{Ω} , C_{Π} , n_1 , and n_2 in (9) might differ from the original values. In the experiments conducted by Van Delden, however, the characteristics of the internals, H and e, were almost the same for the forward extraction and back extraction. So the parameters n_1 and n_2 could not be fitted, and the original values were thus applied. C_1 and C_3 of Equation (8) were fitted, and the results were listed in Table 5.

4.8. Mathematical Model for Estimation of Flooding Throughput. This section is based on the concept of balances of forces, originally proposed by Baird and Lane [16]. Under steady sate conditions, the net weight of the dispersed phase droplets will be balanced by the drag force acting on them. This may be expressed in a simple quantitative way if it is assumed that the droplets are rigid spheres of a uniform size *d*. Let us consider the superficial velocity V_s of the continuous phase relative to the droplets of dispersed phase as follows:

$$V_{s} = U_{\text{slip}} \left(1 - \varepsilon\right) = \left(\frac{1 - \varepsilon}{\varepsilon}\right) U_{d} + U_{c}.$$
 (10)

The frictional pressure gradient may be estimated from the Ergun packed bed equation

$$\left(-\frac{dp}{dz}\right)\frac{d(1-\varepsilon)^3}{\rho_c V_s^2\varepsilon} = \frac{150\varepsilon}{\text{Re}} + 1.75,\tag{11}$$

where $\text{Re} = V_s d\rho_c / \mu_c$.

The net weight of the dispersed phase balances the frictional force as follows:

$$\left(-\frac{dp}{dz}\right) = \varepsilon g\left(\Delta\rho\right). \tag{12}$$

Substitution of Equation (12) into (11) provides

$$\frac{d(1-\varepsilon)^3 g\left(\Delta\rho\right)}{\rho_c V_s^2} = \frac{150\varepsilon}{\text{Re}} + 1.75.$$
 (13)

The substitution of Equation (10) into Equation (13) will yield

$$\frac{d_{32}\left(1-\varepsilon\right)g\left(\Delta\rho\right)}{\rho_{c}V_{\rm slip}^{2}} = \frac{150\varepsilon}{{\rm Re}_{\rm slip}\left(1-\varepsilon\right)} + 1.75.$$
(14)

The equations proposed by Kumar and Hartland [15], however, are of comparable form as shown in

$$\frac{d_{32} \cdot g \cdot \Delta \rho}{\rho_c V_{\rm slip}^2} \cdot \frac{4/3 \cdot (1-\varepsilon)}{1+4.56 \cdot \varepsilon^{0.73}} = \frac{24}{\rm Re_{\rm slip}} + 0.53.$$
(15)

At flooding, maximum value of holdup is reached. The superficial velocities U_c and U_d do not increase beyond their value at flooding. Therefore,

$$\left(\frac{\partial \left(U_{d}\right)}{\partial \varepsilon}\right)_{f} = \left(\frac{\partial \left(U_{c}\right)}{\partial \varepsilon}\right)_{f} = 0.$$
 (16)

Kumar and Hartland derived the correlation for pulsed column at flooding by applying the above criterion given by Equation (16). This correlation is listed in Equation (17a) as follows:

$$\begin{bmatrix} \varepsilon_f + R \cdot (1 - \varepsilon_f) \end{bmatrix} \times \begin{bmatrix} (\beta_3 - \beta_1) \cdot (1 - 2\varepsilon_f) - \frac{2 \cdot \beta_2 \cdot \varepsilon_f \cdot (1 - \varepsilon_f)}{\beta_3 \cdot (1 + 4.56 \cdot \varepsilon_f^{0.73})^2} \\ (1 + 4.56 \cdot \varepsilon_f^{0.73} + 3.33 \cdot \varepsilon_f^{-1.27} \cdot (1 - \varepsilon_f)) \end{bmatrix} + (\beta_3 - \beta_1) \cdot \varepsilon_f \cdot (1 - \varepsilon_f) (R - 1) = 0,$$
(17a)

where

$$\beta_{1} = \frac{24 \cdot \eta_{c}}{0.53 \cdot d_{32} \cdot \rho_{c}}; \qquad \beta_{2} = \frac{4 \cdot d_{32} \cdot g \cdot \Delta \rho}{1.59 \cdot \rho_{c}}; \qquad (17b)$$
$$\beta_{3} = \left(\beta_{1}^{2} + \frac{4 \cdot \beta_{2} \left(1 - \varepsilon_{f}\right)}{\left(1 + 4.56 \cdot \varepsilon_{f}^{0.73}\right)}\right)^{0.5}.$$



FIGURE 9: Parity plot of total throughput experimental values with predicted values based on the Van Delden parameters.

Using Equation (17a) the holdup at flooding conditions can be calculated from physical properties and the Sauter mean drop diameter, which is described via Equation (8) or Equation (9). Since authors did not perform experiments for measurement of the Sauter mean drop diameter, they did reverse modeling to estimate adjustable parameters of Equation (8) or Equation (9) for drop size to minimize error between the experimental flooding throughputs and theoretically estimated flooding throughput via Equation (17a). The error minimization was performed in MATLAB.

The throughput values predicted by the model were found to be in agreement with those obtained experimentally as shown in Figures 9 and 10. Figure 11 shows variation of the estimated Sauter mean drop diameter with pulsation velocity.

5. Conclusions

The dispersed phase holdup and flooding throughput were modelled in the present study following the slip velocity concept. The characteristic velocity was correlated to the pulsation intensity for organic phase dispersions. Using existing correlations on plate pulsed columns, the new parameters applicable for PDDC were estimated. It was found that the measured values and observed trends could be described accurately using this model after fitting holdup and flooding experimental data. A very good agreement is observed between experimental values and predicted values obtained from empirical correlation. Using existing theory on pulsed columns, unified equations, and equations derived for pulsed sieve-plate, and Karr columns, a theoretical model was developed by Van Delden to describe the operational characteristics of a PDDC. The observed trends and determined data were described according to a previously developed



FIGURE 10: Parity plot of total throughput experimental values with predicted values based on new fitted parameters.



FIGURE 11: Variation of the Sauter mean drop diameter with pulsation velocity of PDDC column for organic dispersion.

model, covering the operational window, drop size, and holdup. It was found that the measured values and observed trends could be described accurately using this model after fitting drop diameter, holdup, and flooding data.

Nomenclature

- d_{32}, d_{max} : The Sauter drop diameter and maximum drop diameter, respectively, cm
- D_c : Internal column diameter, cm

- D_d : Disc diameter, cm
- D_r : Diameter of ring aperture in doughnut, cm
- e: Fractional free cross-sectional area, $e = 1 D_d^2/D_c^2$
- f: Frequency, s⁻¹
- Af: Pulsation velocity, $\text{cm} \cdot \text{s}^{-1}$
- Flux: Total throughput, Flux = $U_d + U_c$, m·h⁻¹
- g: Gravitational constant, 9.81 $\text{g} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$
- *H*: Disc to doughnut spacing, cm
- *R*: Flow ratio, $R = U_d/U_c$
- Re: Reynolds number, $\operatorname{Re}_{\operatorname{slip}} = d_{32} \cdot U_{\operatorname{slip}} \cdot \rho c / \mu c$
- U_{slip}, V_o : Slip velocity and characteristic velocity, respectively, cm·s⁻¹.

Greek Letters

- γ : Interfacial tension, N·m⁻¹
- ε: Dispersed phase holdup defined as volume fraction of the dispersed phase
- η : Dynamic viscosity, kg·m⁻¹·s⁻¹
- η^* : Reference dynamic viscosity of water at 298 K, $\eta^* = 0.001 \text{ kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$
- ρ : Density (kg·m⁻³)
- ρ^* : Reference density of water at 298 K, $\rho^* = 997.0 \text{ kg} \cdot \text{m}^{-3}$
- $\Delta \rho$: Density difference, kg·m⁻³
- σ^* : Reference surface tension of water at 298 K, $\sigma^* = 0.0728 \text{ N} \cdot \text{m}^{-1}$.

Subscript

- aq: Aqueous organic phase
- org: Organic phase, respectively
- c: Continuous phase
- d: Dispersed phase
- *f*: At flooding condition.

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