



Holdup, characteristic velocity and slip velocity between two phases in a multi-impeller column for high/medium/low interfacial tension systems



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ABSTRACT

In this research work, liquid–liquid extraction via three different systems has been investigated for determination of holdup, slip velocity and characteristic velocity in a multi-impeller column. The effects of the agitation speed, dispersed as well as continuous phase velocity, direction of mass transfer, and interfacial tension were studied. The findings revealed that an increase in agitation speed and continuous phase velocity led to the reduction of slip velocity while it increased with increasing dispersed phase velocity. More buoyancy and faster upward movement of larger drops accelerate the slip velocity in the dispersed to continuous phase mass transfer condition as compared with the case of no mass transfer. Empirical correlations for prediction of holdup, and slip and characteristic velocities are recommended. The results of the proposed correlations were compared with the experimental data obtained from the literature and the present investigation. Findings of this study demonstrated that the proposed correlations give accurate predictions for slip velocity, characteristic velocity and holdup.

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1. Introduction

Solvent extraction is one of the most important unit operations in the fuel recovery unit of nuclear power plants [1–4]. Among different types of solvent extraction units, the mechanically agitated extraction columns are emerging as the best choices because of the highly agitated flow regime compared with the most commonly used mixer-settler type extraction units [5,6].

Among the counter-current agitated differential extraction columns, the multi-impeller column is used widely in industrial solvent extraction processes. The advantages of these columns are their higher mass transfer rate and higher number of theoretical stages than the other types of extraction columns [7–9].

The agitation is provided via the discs mounted on the rotor shaft improving the multi-impeller column performance by breaking the disperse phase droplets, and thereby enhancing the interfacial area for mass transfer [10–14]. However, the performance of extraction columns can be affected by two unwanted side effects including the entrainment of small droplets

and hence an increase in axial mixing [15,16]. Therefore, investigation of hydrodynamic parameters comprising dispersed phase holdup, slip velocity and characteristic velocity is vital for the scale-up and design of the multi-impeller column.

In recent years, the hydrodynamic parameters of different kinds of extraction columns have been investigated by several researchers [17–19]. Unfortunately, no experimental work for comparing three different systems (low, medium and high interfacial tension systems) in the multi-impeller column has been reported in the literature to date. A great deal of experimental effort has been expended principally for the purpose of evaluating column performance for design and scale-up. The design of these columns requires determination of a suitable cross-sectional area for flow and the height required to achieve a specified degree of mass transfer [20]. Predictions of slip velocity have fundamental importance in calculating the extraction column diameter, and it is required to estimate the mass transfer and drag coefficients. Knowledge of the characteristic velocity is important to predict flooding time and maximum volumetric capacity of an extraction column [21].

Hydrodynamics in the liquid–liquid extraction columns has generally been described by means of the correlations of the slip velocity with fractional holdup of drops moving through the

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Nomenclature

AARE	average absolute relative error (–)
Af	pulsation intensity (m/s)
C_R	construction factor (–)
D_c	column diameter (m)
d_s	stator diameter (m)
d_r	rotor diameter (m)
d_{32}	sauter mean diameter (m)
e	void fraction of packing (–)
Fr	Froude number (–)
g	acceleration due to gravity (m/s ²)
G_f	$\left(\frac{d_s}{d_r}\right)^{8.4166} \left(\frac{d_r}{D_c}\right)^{-1.1385} \left(\frac{h_c}{d_r}\right)^{2.1279}$
H	effective height of the column (m)
h_c	compartment height (m)
N	rotor speed (1/s)
Mo	Morton number (–)
m	exponent (–)
$\frac{P}{V}$	power per units volume (W/m ³)
V	superficial velocity (m/s)
V_d	dispersed phase velocity (m/s)
V_c	continuous phase velocity (m/s)
V_{slip}	slip velocity (m/s)
V_k	characteristic velocity (m/s)

Greek letters

α	index (–)
ρ	density (kg/m ³)
$\Delta\rho$	density difference between phases (kg/m ³)
μ	viscosity (Pa s)
σ	interfacial tension (N/m)
φ	dispersed phase holdup (–)
ε	power dissipated per unit mass (m ² s ³)
ψ_1	$\left(\frac{V_d}{(\sigma\Delta\rho g/\rho_c^2)^{0.25}}\right)^{0.81} 1 + \frac{V_c}{V_d}$
ψ_2	$Fr^{-0.42} Mo^{-0.01} \left(\frac{\mu_c}{\mu_d}\right)^{0.09} \left(\frac{\Delta\rho}{\rho_c}\right)^{-0.51}$

Subscripts

c	continuous phase
d	dispersed phase

column [22]. The dispersed phase holdup is necessary to calculate the interfacial area per unit volume and slip velocity. It also indicates the onset of flooding. Table 1 describes the experimental dispersed phase holdup correlations for rotating columns obtained by experimental investigations of various workers. However, the available correlations for the prediction of dispersed phase holdup are either approximate or not always applicable. Therefore, the design of an extraction column for a given separation warrants the availability of reliable correlations for holdup and slip velocities.

The slip velocity is the relative velocity of drops with respect to the continuous phase, which is defined as the sum of the linear actual velocities of the dispersed and continuous phases under conditions of counter-current flow, as follows [23]:

$$V_{slip} = \frac{V_d}{\varphi} + \frac{V_c}{1 - \varphi} \quad (11)$$

and for a packed column [24]:

$$V_{slip} = \frac{V_d}{e\varphi} + \frac{V_c}{e(1 - \varphi)} \quad (12)$$

Some authors considered the effect of column internals on slip velocity and defined a constriction factor, C_R , as follows [25]:

$$V_{slip} = \frac{1}{C_R} \left(\frac{V_d}{\varphi} + \frac{V_c}{1 - \varphi} \right) \quad (13)$$

Such studies on rotating disc columns showed that C_R is a function of the column geometry, velocity of the phases, and agitation conditions.

Several correlations have been reported by researchers for different types of liquid–liquid extraction columns as given in Table 2. In these correlations, slip velocity is directly correlated in terms of the physical properties of liquid systems, column geometry and operational variables. The physical properties, operating conditions and column dimensions for illustrated correlations in Tables 1 and 2 are shown in Table 3.

In addition, there are several equations given in the literature relating slip velocity to the continuous phase holdup by means of a characteristic velocity:

$$V_{slip} = V_k f(\varphi) \quad (20)$$

These equations have been summarized by Godfrey and Slater [26].

As Gayler and Pratt [27] and Gayler et al. [28] pointed out, the simplest equation for calculation of characteristic velocity for $\varphi < 0.2$ is as follows:

$$V_{slip} = V_k(1 - \varphi) \quad (21)$$

Godfrey and Slater suggested that the slip velocity in various types of extraction columns can be described by the empirical equation proposed by Richardson and Zaki [29]:

$$V_{slip} = V_k(1 - \varphi)^m \quad (22)$$

The validity of this equation is $0 < \varphi < 0.3$.

Slater [30] formulated an equation for $\varphi > 0.5$:

$$V_{slip} = V_k(1 - \varphi)^m + a\varphi^n \quad (23)$$

The term $a\varphi^n$ indicates coalescence behavior.

Misek [31] derived a more complicated correlation for RDC and ARDC columns in the form:

$$V_{slip} = V_k(1 - \varphi)\exp(-\alpha\varphi) \quad (24)$$

The validity of this equation is $-10 < \alpha < 10$ where α represents the effects of coalescence of drops.

Letan and Kehat [32] suggested the following empirical equation:

$$V_{slip} = V_k \exp(-b\varphi) \quad (25)$$

Due to the importance of slip velocity and holdup for the design of extraction columns, in the present work, slip velocities and holdup through the column are measured for three different systems in conditions with and without mass transfer. The operational parameters such as agitation speed, and continuous and dispersed phases velocities are studied in order to investigate the dispersed phase holdup and slip velocity using three various liquid–liquid systems. The results are discussed and compared with the predicted values from several available correlations. Finally, new correlations are proposed for determination of holdup, slip and characteristic velocities in the multi-impeller column.

2. Experimental

2.1. Liquid–liquid systems

The liquid–liquid systems investigated were *n*-butanol–water (low interfacial tension), *n*-butyl acetate–water (medium interfacial tension) and toluene–water (high interfacial tension) for

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