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Hydrodynamic performance of a pulsed extraction column containing ZnO nanoparticles: Drop size and size distribution

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ABSTRACT

This article concerns the influence of different ZnO nanoparticle concentrations (0.001, 0.003, 0.005 and 0.01 wt%) along with operating parameters (i.e., pulsation intensity and flow rate of dispersed and continuous phases) and physical properties on mean drop size and drop size distribution in a horizontal pulsed perforated-plate extraction column for the toluene–acetone–water and butyl acetate–acetone–water systems (mass transfer direction from the dispersed phase to the continuous phase). According to the results, it is observed that the addition of nanoparticles has a remarkable influence on breakage and coalescence of drops and consequently their size distribution. Accordingly, adding nanoparticles reduces the interfacial tension due to internal turbulence caused by nanoparticles' Brownian motion inside each drop. It is found that drop size distribution will shift to the left and the density of small droplets will increase in the presence of ZnO nanoparticles in the column. Furthermore, new correlation is proposed to predict mean drop size in terms of operating parameters, physical properties and nanoparticle concentration. It is also found that the maximum entropy principle is suitable to predict drop size distribution in a horizontal extraction column.

1. Introduction

Pulsed columns are among the extractors which provide a large interfacial area using external energy input in the form of pulsing motion usually sinusoidal superimposed on counter-current flow of the liquid phases (Amani et al., 2017a,b,c). One of the key parameters in the design and optimization of pulsed columns is the mean drop diameter and drop size distribution which are important in separation industries. They are directly related to the interfacial area available for mass transfer and directly affects the heat and mass transfer, stability of emulsions, rheological characteristics, reaction rate, extraction performance and final polymer particle size and properties in suspension polymerization (EL-Hamouz et al., 2009; Maaß et al., 2011; Quadros and Baptista, 2003; Yang et al., 2000). Furthermore, other parameters such as solutes, salts, surface active agents (surfactants), and nanoparticles have considerable impact on the hydrodynamic and mass transfer performance in solvent extraction by affecting the coalescence behavior of the chemical system. Nanoparticles provide a steric hindrance around dispersed phase drops when they adsorb at the interface of two immiscible phases and form more stable dispersed phase drops against

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Nomenclature

A	Amplitude of pulsation, m
Af	Pulsation intensity, m/s
d_{32}	Sauter mean diameter, m
f	Frequency of pulsation, Hz
g	Acceleration due to gravity, m/s^2
Q	Volumetric flow rate, m^3/s
U	Velocity, m/s

Greek symbols

λ	Lagrange multipliers of probability maximum entropy function
μ	Viscosity, N s/m^2
ρ	Density, kg/m^3
$\Delta\rho$	Density difference between phases, kg/m^3
$\bar{\rho}$	Density of mixture of phases, kg/m^3
σ	Interfacial tension between two phases, N/m
ω	Weight fraction

Subscripts

c	Continuous phase
d	Dispersed phase

coalescence. There are many investigations on the effect of adding different nanoparticles on the enhancement of conductive and convective heat transfer coefficients (Buongiorno et al., 2009; Heris et al., 2006; Kwek et al., 2010; Lee et al., 1999; Putra et al., 2003; Wen and Ding, 2005) and several reviews are available in this field (Das et al., 2006; Yu et al., 2008). Using nanofluids offers various benefits such as stronger temperature-dependent thermal conductivity (Das et al., 2003), a substantial enhancement in the heat transfer coefficient and thermal conductivity at low nanoparticle concentration (Choi et al., 2001; Heris et al., 2006), an increment in critical heat flux in pool boiling (You et al., 2003). One of the major factors which is responsible for enhancement of heat transfer in the presence of nanoparticles is Brownian movement of nanoparticles (Amani et al., 2017a,b). This mechanism similarly leads to the enhancement of mass transfer performance (Bahmanyar et al., 2011; Beiki et al., 2013a,b; Jang and Choi, 2016; Keshishian et al., 2013; Krishnamurthy et al., 2006). Regarding the impact of nanoparticles on mass transfer, there are a number of studies in the literature, while most of them only investigated the convective mass transfer performance between liquid and gas phases and there have been limited investigations on the study of the presence of nanoparticles in liquid–liquid extraction which is the other popular separation process (Ashrafmansouri and Nasr Esfahany, 2015; Bahmanyar et al., 2014; Khoobi et al., 2013; Mirzazadeh Ghanadi et al., 2014; Roozbahani et al., 2014). Khoobi et al. (2013) investigated the influence of adding SiO_2 nanoparticles on droplet size and its distribution along a pulsed liquid–liquid extraction column. They revealed that addition of nanoparticles change the droplet shape from ellipsoidal to spherical. Fan et al. (2007) investigated the impact of hydrophilic SiO_2 nanofluids on the behavior of droplets in a microchannel and a bubble column. They revealed that nanoparticles reduce the diameter of bubbles and lead to the significant reduction in holdup due to the reduction of interfacial tension. Davoodi-Nasab et al. (2013) revealed that the presence of SiO_2 nanoparticles in a mixer-settler extractor leads to the increase of holdup and the reduction of the drop size about 8.1–19.4%.

Standard vertical extraction columns meet the needs for industrial applications, but when height limitation (especially in indoor applications) is concerned it is required to use horizontal columns. It is also revealed that the mass transfer efficiency in both types of the columns is comparable (Hanson, 1971; Panahinia et al., 2017). However, considering the significant role of adding nanoparticles on hydrodynamic and mass transfer performance in a horizontal extraction column, no analytical and experimental investigation has been conducted in this regard. Therefore, this article concerns the influence of adding nanoparticles on mean drop size and drop size distribution in a horizontal pulsed perforated-plate extraction column. Mirzazadeh Ghanadi et al. (2014) studied the impact of different nanoparticles including TiO_2, ZnO and CNT on the mass transfer performance in an extraction column. It was observed that the effect of ZnO nanoparticles on mass transfer is much greater than that of TiO_2 and CNT nanoparticles. Therefore, in this study, the influence of ZnO nanoparticles on hydrodynamic performance of the extraction column is evaluated for different liquid systems. In this work, the stability of nanofluids is firstly examined and then the effect of operating conditions and physical properties on drop size and its distribution with and without ZnO nanoparticles presence are investigated. In addition, new empirical correlations are proposed to predict the mean drop size and drop size distribution under the influence of ZnO nanoparticles.

Table 1 – Geometrical characteristics of the column used.

Material for construction of the column	Glass
Material used for plates, spacers and rod	Stainless steel
Column length (m)	1.65
Column diameter (cm)	7
Upper and lower settler diameter (cm)	9
Upper settler length (cm)	50
Lower settler length (cm)	50
Holes pitch (mm)	4
Holes diameter (mm)	2
Plates thickness (mm)	1
Plate spacing (cm)	1[a], 6[b]
Average free area of the plates (%)	0.11

[a] Spacing between two individual plates in a pair.
[b] Spacing between two pairs in a cell.

2. Experimental

2.1. *Discerption of the equipment*

In this study, the experiments are conducted in a horizontal pulsed sieve-plate column with an internal diameter of 7 cm and length of the active area of 165 cm. The plates are half-perforated and the perforations laid on triangular pitch of 4 mm. The pulsation applies to the liquid by the pressure of air compressor and controlled by two solenoid valves. To control the liquid level in the column and regulate the discharge of heavy phase, an optical sensor in the collecting tank, in the output of the light phase, is embedded. Two rotameters are placed at the inlet of the phases to measure the flow rates. For more information, the column characteristics are listed in Table 1. A schematic of experimental setup is illustrated in Fig. 1. In addition, Fig. 2 exhibits how drops tend to move horizontally whereas the density difference drives them down or top of each compartment during the quiescent portion of the pulsation.

2.2. *Liquid–liquid systems and nanofluid preparation*

The chemical systems investigated in this study are toluene–acetone–water and butyl acetate–acetone–water supplied by Merck Company. The continuous phase is DI-water. Technical grade solvents of toluene and *n*-butyl acetate with at least 99.5 wt% purity in the presence of 3% volume fraction of acetone as a mass transfer agent ($d \rightarrow c$) are used as the dispersed phase. In order to evaluate the impact of ZnO nanoparticles on mean drop size, the experiments are carried out at four different ZnO nanoparticle concentrations