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Chemical Engineering Research and Design

journal homepage: www.elsevier.com/locate/cherd


Packing effect on mass transfer and hydrodynamics of rising toluene drops in stagnant liquid

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ARTICLE INFO

Article history:

Received 7 June 2016

Received in revised form 8 August 2016

Accepted 3 September 2016

Available online 12 September 2016

Keywords:

Sherwood number

Mass transfer coefficient

Structured packed column

Liquid–liquid extraction

Terminal velocity

ABSTRACT

Terminal velocity and mass transfer of rising drops in a stagnant liquid were experimentally measured. The chemical system included the toluene drops whose acetic acid content was transferred to the surrounding water. Three sets of structured packing were used in the column to investigate the impact of packing at different heights of 10, 25 and 40 cm. The effects of flow rate (Q), drop size (d), inverse viscosity (N_f), Eötvös number (E_o), and Reynolds number (Re) on terminal velocity, u_t , and Froude number, Fr , were investigated. The critical points of $d = 3.4$ mm, $E_o = 0.5$ and $N_f = 200$ were found at which two regions of circulating and oscillating drops were separated, and the Fr was constant within each region. The effect of packing height on Fr and Sherwood number against Reynolds number was also investigated. Compared to the non-packed column it was revealed that a 30% increase in Sherwood number could be achieved using a packing with 40 cm in height. Moreover, it was found that simultaneous increase of packing height and the flow rate consistently enhanced the mass transfer coefficient. Finally, a correlation was proposed which permitted the prediction of Sherwood number versus the dimensionless numbers of Reynolds, Weber and the packing height ratio.

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1. Introduction

The separation process such as distillation, adsorption, liquid–liquid extraction and desorption are based on mass transfer between two phases of liquid, gas and solid. In most cases, one of the phases, namely dispersed or drop phase, is dispersed in the other phase, namely continuous phase. Liquid–liquid contacting is an important operation that occurs in a wide range of chemical, pharmaceutical, petroleum and food processing operations (e.g., nitrification, sulphonation, emulsion polymerization, polymer washing, and other liquid–liquid extraction applications). It is also used for removing dangerous soluble components from effluents and waste management sites (Al Taweel et al., 2007).

Much research has been conducted on the extraction of the solute when a drop vertically moves in a column of continuous phase, and mass transfer occurs between the two phases, as listed in Jammoal and Lee (2015), Kadam et al. (2009), Kamp and Kraume (2014) and

Saien and Daliri (2014). The rate of mass transfer is quantified by calculating the overall mass transfer coefficient (MTC), which itself can be obtained from available theoretical models for Sherwood number (Saadat Gharehbagh and Mousavian, 2009). Improvement of MTC in solvent extraction contactors was the focal point of several studies, in which altering the influencing parameters was discussed (Saien and Daliri, 2014; Saadat Gharehbagh and Mousavian, 2009). Various shapes of packing used since early last century are known to increase the extraction tower's efficiency as well as to reduce the operating costs (Pich'e et al., 2001). The presence of packing in liquid–liquid contactors has increasingly attracted the attention of many investigators who reported that the material can be highly effective in mass transfer of both phases (Verma and Sharma, 1975; Slater et al., 1988). Batey and Thornton (1989) studied the effect of single packing on mass transfer coefficient of single drop, and evaluated different hydrodynamic events caused by the presence of packing. Koncsag and Barbulescu (2008) investigated the removal of mercaptans from liquid hydrocarbon

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Nomenclature

c	Solute concentration in dispersed phase (kg/m ³)
c_0	Initial concentration of solute in dispersed phase (kg/m ³)
c^*	Equilibrium concentration of solute in dispersed phase (kg/m ³)
d	Drop diameter (m)
d_N	Needle size of nozzle (m)
D	Molecular diffusivity (m ² /s)
E	Extraction ratio (–)
Eo	Eötvös number ($\frac{(\rho_c - \rho_d)gd^2}{\gamma}$)
Fr	Froude number ($\frac{u_t}{\sqrt{\frac{(\rho_c - \rho_d)gd}{\mu_c}}}$)
h	Rising distance
h_p	Packing height (m)
k	Mass transfer coefficient (m/s)
M	Molecular weight of solvent (kg/kmol)
N_f	Inverse viscosity ($N_f = \frac{\sqrt{\rho_c(\rho_c - \rho_d)gd^3}}{\mu_c}$)
Q	Volumetric flow rate of dispersed phase (m ³ /s)
Re	Reynolds number
Sh	Sherwood number
t	Rising time (s)
T	Temperature (K)
u_t	Terminal velocity of a single drop (m/s)
V	Molar volume at normal boiling temperature (m ³ /kmol)
We	Weber number, ($\frac{\rho_c u_t^2 d}{\gamma}$)
Greek symbols	
γ	Interfacial tension (N/m)
μ	Viscosity (Pa s)
φ	Association factor of the solvent (=2.6 for water)
ρ	Density (kg/m ³)
$\Delta\rho$	Density difference ($\rho_c - \rho_d$), (kg/m ³)
Subscripts	
A	Solute
c	Continuous phase, critical
d	Dispersed phase
i	Counter
m	Mixture
np	Non-packed
p	Packed
o	Overall

streams in structured packed column, and showed the mass transfer coefficient depended on geometrical characteristics of the packing. The mass transfer coefficients of drop swarms of high viscosity solvents were investigated in a column packed with super mini ring packing, and it was concluded that the packing increased overall mass transfer coefficient significantly up to 100% due to the increase of drop breakage probability and inner circulation of drops, which is known to have a positive effect on MTC (Jie et al., 2005). Salimi-Khorshidi et al. (2013) in an experimental investigation evaluated the effects of the holdup on the mean drop size, and also on the dispersed phase mass transfer coefficient, in the packed and spray extraction columns. They reported that the presence of the packing improved the performance of the spray column by approximately 25.6%. In an experimental and correlational study on a structured packed column, Azizi et al. (2014) showed that the Sherwood number was affected by the packing height, and should be

accounted for the predictive correlation. Recently, the hydrodynamics and the mass transfer performance of immiscible fluids in the packed microchannels were investigated experimentally. It was reported that the packing intensified the extraction efficiency in the microchannel (Su et al., 2010).

Numerous works were performed in the past on the rise and fall of drops in liquid media (Jammool and Lee, 2015; Wesselingh and Bollen, 1999; Rezamohammadi et al., 2015). Azizi and Al Taweel (2011) calculated the volume-average energy dissipation rate for a co-current flow of the organic and aqueous phase using the pressure drop. They also simulated drop breakage and coalescence processes in turbulently flowing liquid–liquid dispersions taking place in multi-stage screen-type static mixers. In terms of fluid dynamics, prediction of the terminal velocity or the drag coefficient of the drops has always been a challenging issue since it is affected by Marangoni instabilities caused by interfacial tension gradient (Wegener et al., 2014, 2007). This interfacial tension gradient can be the result of a concentration disturbance at the interface of a moving drop. The induced Marangoni phenomenon is a function of drop diameter and initial concentration, and known to promote the MTC (Wegener et al., 2014; You et al., 2014). However, according to the above literature review, investigations on the hydrodynamics and mass transfer of drops in liquid–liquid contactors considering the packing height as a variable are limited (Batey and Thornton, 1989; Koncsag and Barbulescu, 2008; Jie et al., 2005; Salimi-Khorshidi et al., 2013; Azizi et al., 2014; Su et al., 2010); the drops rising in a packed column are subject to breakage and coalescence which in turn are usually discussed within a complex list of physical and geometrical properties (Wegener et al., 2009). In a previous work (Rahbar et al., 2011), the height of packing and the height of collecting samples were identical; therefore, these two important parameters were not evaluated independently of each other. Thus, in the present work, the distance from the initial to the collecting point, i.e., rising distance, was kept fixed in all experiments while the height of packing was increased from 0 to 0.4 m. The objective was to evaluate the effect of packing height on Sherwood number of the drop phase, which can yield an optimum point, and also to study the variation of terminal velocity with packing height over a range of drop size. Since the scale-up of extractors still depends on large quantities of pilot experiments, measuring mass transfer coefficients was carried out by single drop experiments in the present work, which is known as a promising method, more economical and less time-consuming (Zappe et al., 2000; Wei and Fei, 2004; Saïen and Bamdadi, 2012).

2. Methodology

2.1. Chemical system

The chemical system of toluene–acetic acid–water, which has a high interfacial tension (Azizi et al., 2014), was used in this study. This chemical system is recommended by European Federation of Chemical Engineering (EFCE) (Yadav and Patwardhan, 2008), and permits behavior prediction of packed extraction columns for other systems having low and medium interfacial tension. Indeed, water is used widely in experiments as the continuous phase because of its practicality, affordable costs, and also the fact that many industrial operations involve aqueous mixtures with considerable fraction of water. Toluene and acetic acid were Merck products with purities of more than 99.9%. Deionized water of high quality was saturated with toluene, and then used as the continuous phase. The toluene saturated with water was the dispersed phase containing specific amount of acetic acid as the solute. The physical properties of the chemical system such as density, viscosity and the interfacial tension are presented in Table 1. The density was measured using portable DMA 35N density meter (Anton Paar Co.) with an error of 0.0001 g/cm³. The viscosity was evaluated by a laboratory LAUDA viscometer

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