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Mass transfer from nanofluid drops in a pulsed liquid–liquid extraction column

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A B S T R A C T

Mass transfer in gas–liquid systems has been significantly enhanced by recent developments in nanotechnology. However, the influence of nanoparticles in liquid–liquid systems has received much less attention. In the present study, both experimental and theoretical works were performed to investigate the influence of nanoparticles on the mass transfer behaviour of drops inside a pulsed liquid–liquid extraction column (PLLEC). The chemical system of kerosene–acetic acid–water was used, and the drops were organic nanofluids containing hydrophobic SiO_2 nanoparticles at concentrations of 0.01, 0.05, and 0.1 vol%. The experimental results indicate that the addition of 0.1 vol% nanoparticles to the base fluid improves the mass transfer performance by up to 60%. The increase in mass transfer with increased nanoparticle content was more apparent for lower pulsation intensities (0.3–1.3 cm/s). At high pulsation intensities, the Sauter mean diameter (d_{32}) decreased to smaller sizes (1.1–2.2 mm), leading to decreased Brownian motion in the nanoparticles. Using an analogy for heat and mass transfer, an approach for determining the mass diffusion coefficient was suggested. A new predictive correlation was proposed to calculate the effective diffusivity and mass transfer coefficient in terms of the nanoparticle volume fraction, Reynolds number, and Schmidt number. Finally, model predictions were directly compared with the experimental results for different nanofluids. The absolute average relative error (%AARE) of the proposed correlation for the mass transfer coefficient and effective diffusivity were 5.3% and 5.4%, respectively.

Keywords: Pulsed column; Nanofluid drops; Mass transfer model; Effective mass diffusivity; Extraction efficiency

1. Introduction

Nanofluids are stable suspensions of nanometre-sized particles in conventional liquids. One advantage of nanofluids is their improved heat transfer: it has been experimentally shown in many instances that nanofluids have higher thermal conductivities and improved convective heat transfer in comparison to host liquids (Chen et al., 2008; Ding et al., 2010; Garg et al., 2009; Li and Peterson, 2006; Wen et al., 2006). In addition to enhancing heat transfer, suspended nanoparticles have been found to improve mass transfer processes inside binary nanofluids. Because convection and mass transfer are similar processes, several authors (Feng et al., 2005; Wen et al., 2005; Olle et al., 2006) have proposed models that postulate that nanoscale convection induced by the Brownian motion of the nanoparticles causes enhanced mixing. This increased mixing leads to mass transfer faster than that predicted by simple diffusion-based theories. The enhanced diffusion in nanofluids can therefore be utilised to improve mass transfer in unit operations.

To determine the degree of thermal conductivity enhancement in nanofluids, Krishnamurthy et al. (2006) experimentally observed the diffusion of a dye droplet in a water-based nanofluid and calculated the effective mass diffusivity of the dye in both the water and nanofluid. The investigation showed that the suspended nanoparticles remarkably increase the mass transfer of the dye. Olle et al. (2006) measured the oxygen absorption rate in the presence of colloidal dispersions of magnetite (Fe_3O_4) nanoparticles coated with oleic acid. Olle et al. determined that this nanofluid improves the gas–liquid oxygen mass transfer coefficient by more than 1.6-fold and the k_La value by up to 6-fold at nanoparticle concentrations

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Nomenclature

a	interfacial area, m^2/m^3
A	pulsation amplitude, cm
C	solute concentration in the dispersed phase, kg/m^3
C_0	initial concentration of solute in the dispersed phase, kg/m^3
C^*	equilibrium concentration of solute in the dispersed phase, kg/m^3
d	droplet diameter, m
d_{32}	Sauter mean diameter of droplets, m
d_i	the ith group droplet diameter, m
D_d	molecular diffusivity of transferred component in the dispersed phase, m^2/s
D_E	effective diffusivity in Handlos–Baron equation, Eddy diffusivity in the Temos equation, m^2/s
D_{OE}	overall effective diffusivity, m^2/s
E	mass transfer enhancement
E_0	Eotvus number, $1\,s^{-1}$
E_{0c}	Eotvus number when the droplet has critical diameter pulsation frequency, $1\,s^{-1}$
f	pulsation frequency, s^{-1}
f_V	fractional segmental volume of drop which is stagnant
g	gravity acceleration, m^2/s
H	effective height of the column, cm
k	the dimensionless number in Eq. (14), $=E_{0c}/6$
k_d	dispersed phase mass transfer coefficient, m/s
k_H	empirical constant of Eq. (12), which varies between 0 and 1
K_B	Boltzmann constant, $=1.3807 \times 10^{-23}$ J/K
L	column height, m
n_i	the number of the ith group droplets
Nu	Nusselt number, dimensionless
PI	pulsation intensity, cm/s
Pr	Prandtl number, dimensionless
Q_c	continuous phase flow rate, m^3/s
Q_d	dispersed phase flow rate, m^3/s
$\Re$	the modifying coefficient of the transferred component molecular diffusivity due to the internal circulations
Re	Reynolds number, dimensionless
Sc	Schmidt number, dimensionless
Sh	Sherwood number, dimensionless
t	resident time of the dispersed phase in column, contact time, s
T	temperature, K
V_t	terminal velocity of a droplet, m/s

Greek symbol

γ	interfacial tension, N/m
ϕ	nanoparticle volume fraction
ρ	density, kg/m^3
α	thermal diffusivity, m^2/s
μ	dynamic viscosity, Ns/m^2
υ	kinematic viscosity, m^2/s
κ	ratio of the dispersed phase viscosity to continuous phase viscosity
φ	dispersed phase hold-up

Subscripts

c	continuous phase
d	dispersed phase
p	particle
s	solid
ad	auxiliary diffusivity
bf	base fluid
nf	nanofluid

below 1 vol% in an agitated, sparged reactor. Interestingly, the enhancement in $k_L a$ levelled off at a nanoparticle volume fraction of approximately 1% (v/v).

Although the mechanism of the enhanced mass transport from the suspended nanoparticles is still not well understood, some existing work assumed that the irregular Brownian motion of the nanoparticles is one of the main factors contributing to the enhancement of mass transport (Xuan et al., 2003; Prasher et al., 2005).

In another study, Lee et al. (2010) found that the absorption rate of ammonia by nanofluids is higher than that of conventional fluids. Lee et al. also showed that despite the higher thermal conductivity of a CNT-nanofluid compared to a Al_2O_3-nanofluid, the absorption performance of the CNT-nanofluid is not better than that of the Al_2O_3-nanofluid. Lee et al. speculated that this behaviour was due to the higher aspect ratio of CNTs, which leads to less Brownian motion in comparison to spherical Al_2O_3 nanoparticles.

To date, the use of nanofluids to enhance mass transfer has dealt only with gas–liquid systems. However, little is known regarding the effects of nanoparticles on the mass transfer behaviour of droplets in liquid–liquid systems. Such phenomena are examined both experimentally and theoretically in this study using hydrophobic SiO_2 nanoparticles with droplet flows in a pulsed liquid–liquid extraction column (PLLEC). The decision to use a pulsed column in this study was based on the column's ability to offer a more robust medium for the investigation of nanoparticle influence on droplet behaviour. Experimental and computational investigations were conducted to study the effect of nanoparticles on the mass transfer characteristics of nanofluid drops. Employing the analogy between heat and mass transfer, an approach for determining the effective mass diffusivity and mass transfer coefficient was suggested and discussed. The final aim of this study was to clarify how nanoparticles can be utilised to improve mass transfer in liquid–liquid unit operations. Numerical analysis supports the concept that the Brownian motion of the nanoparticles increases the internal circulation of droplets. In this study, the enhanced diffusion coefficient has been predicted, and its effect on mass transfer has been calculated. These findings have direct implications for separation technology and are promising for the application of nanofluids in other liquid–liquid contact devices, such as rotary disc contractors and packed columns.

2. Experiments

A schematic diagram of the experimental setup used in this study is presented in Fig. 1. The column consisted of a 70 cm long vertical Pyrex tube with an inner diameter of 90 mm. The column contained 10 perforated stainless steel plates regularly spaced 5 cm apart and was supported on an 8 mm