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The influence of silica nanoparticles on hydrodynamics and mass transfer in spray liquid–liquid extraction column

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ABSTRACT

In this research, the influence of silica nanoparticles on hydrodynamics and mass transfer of a spray liquid–liquid extraction column was studied experimentally. The chemical system of toluene–acetic acid–water was used, and the drops were toluene-based nanofluids containing 0.0005–0.01 vol% silica nanoparticles. In addition to nanoparticles fraction in nanofluids, the effects of dispersed phase drop sizes were evaluated making use of three different distributors with different hole diameters. The experiments were performed at fixed volumetric flow rates of dispersed and continuous phases and mass transfer direction was from dispersed to continuous phase. The results showed that silica nanoparticles have no significant influence on the hydrodynamic parameters, while maximum enhancement of 47% in overall mass transfer coefficient was achieved using 0.001 vol% silica nanoparticles for drops generated by the distributor with the largest hole diameter. At higher and lower nanoparticle concentrations, smaller overall mass transfer coefficient was observed. Brownian motion of nanoparticles and induced microconvection are dominant in low concentrations of nanoparticles resulting in enhanced mass transfer. Nanoparticle aggregation and reduction in free volume because of solid nanoparticles presence can be responsible for deteriorated mass transfer in higher nanoparticle concentrations.

1. Introduction

Recently, nanofluids have received growing attention because of their potential to enhance heat transfer [1–7]. Their desirable characteristics open numerous applications of them as super-coolant in nuclear reactors, car engines, radiators, computers, X-rays and many other industrial products. Nanofluids are also called super-coolant because they can absorb heat more than any traditional fluids, so they can reduce the size of the equipments and increase their performance [1,8].

Since some researchers considered Brownian movement of nanoparticles as one of the major responsible factors in the enhancement of heat transfer, investigation of mass transfer enhancement in nanofluids with similar mechanism has been initiated [9–11]. Investigations on mass transfer in nanofluids can be divided into two main groups. The first group of studies deals with studying diffusion coefficients in nanofluids and the second group of studies focuses on convective mass transfer coefficients in nanofluids [12]. Mass transfer in nanofluids was extensively reviewed in a recent published article [13]. In that work, researches on diffusion coefficient and convective mass transfer coefficient in nanofluids were reported in separate sections. In each section, performed studies, type of nanofluids, size and concentration range of nanoparticles, mass transfer measurement method, maximum observed enhancement and suggested mass transport mechanisms were pointed out [13]. In the field of mass transfer in nanofluids, there are a few researches dealt with mass diffusion in nanofluids [1,9,14–20] and more researches investigated the influence of nanoparticles on convective mass transfer [10,21–40]. Nevertheless, most researches on convective mass transfer in nanofluids are related to the gas absorption processes [21–30] and there have been limited attempts to use nanofluids in other popular separation processes such as liquid–liquid extraction [10,34–40]. Due to the extensive use of liquid–liquid extraction process in chemical industries, producing reliable experimental data and suggesting reliable mechanisms are needed to describe the effects of nanoparticles on this process.

Bahmanyar et al. [10] investigated mass transfer performance and hydrodynamic characteristics of kerosene-based nanofluids in a pulsed liquid–liquid extraction column (PLLEC). They prepared nanofluids by dispersing SiO_2 nanoparticles of 0.01, 0.05 and 0.1 vol% with two different hydrophobicities in kerosene. In their work, the chemical system of kerosene–acetic acid–water was used and different pulsation intensities were maintained for the

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Nomenclature

a	interfacial area (m^2/m^3)
A	surface area of the column (m^2)
b	major (horizontal) radius of an oblate spheroid (m)
c	minor (vertical) radius of an oblate spheroid (m)
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_e	equivalent diameter of drop
d_{ei}	equivalent diameter of ith droplet (m)
d_h	hole diameter of distributor (mm)
d_p	drop diameter, Sauter mean diameter of droplets (m)
d_{32}	Sauter mean diameter of droplets (m)
E	extraction fraction
E_1	ratio of the major (horizontal) to the minor (vertical) axis of the oblate spheroid
g	standard gravity (m/s^2)
H	height of column (m)
K_d	overall mass transfer coefficient (m/s)
M	Morton dimensionless number
n_i	number of droplets with equivalent diameter of d_{ei}
N	total number of analyzed droplets
N_{PG}	inverse of Morton dimensionless number
Q_c	volumetric flow rate of continuous phase (m^3/s)
Q_d	volumetric flow rate of dispersed phase (m^3/s)
r	radius of drop (m)
Re	drop Reynolds dimensionless number
S_{os}	area of an oblate spheroid (m^2)
S_s	area of a sphere which has equal volume of an oblate spheroid
t	contact time (s)
V_s	slip velocity of drop (m/s)
We	drop Weber number

Greek symbols

γ	interfacial tension (mN/m)
Δ	difference
μ_c	viscosity of continuous phase (mPa/s)
μ_d	viscosity of dispersed phase (mPa/s)
ρ_c	density of continuous phase (kg/m^3)
ρ_d	density of dispersed phase (kg/m^3)
ϕ	hold-up

Subscripts

c	continuous phase
d	dispersed phase

fixed mass flow rates of dispersed (Q_d) and continuous (Q_c) phases (with ratio) $Q_c/Q_d = 1.2$ with mass transfer direction from the dispersed to the continuous phase. They found that the mass-transfer coefficient increased by 4–60% and argued that Brownian motion of nanoparticles is liable of enhancement in mass transfer. It was also reported that in the presence of nanoparticles, static and dynamic hold-ups increased by 23–398%, and 23–257%, respectively. Khoobi et al. [34] investigated the shape of drops, drop size and its distribution under conditions matching previously reported by Bahmanyar et al. [10]. Khoobi et al. [34] observed that different contents of nanoparticles had a marked influence on the geometrical shapes of drops and changed the drop shape from ellipsoidal to spherical. They found that low volume fraction of nanoparticles led to more breakage of the drops and concluded that the turbulence caused by the Brownian motion of nanoparticles inside droplets made breakage easier. Also, Khoobi et al. [34] concluded that high volume fraction of nanoparticles, not only has apparently superseded the effect of the mentioned turbulence inside drops but also has increased drops coalescence. Moreover, they observed that increase in hydrophobicity made little decrease in Sauter mean diameter of droplets.

Moreover, under chemical system and extraction column matching Bahmanyar et al.'s work [10], Ghafoori Roozbahani et al. [35] investigated the influence of hydrophobic SiO_2 nanoparticles on the static and dynamic hold-up in acetic acid transfer from the continuous to the dispersed phase. They performed the experiments with kerosene-based dispersions of 0.05 vol% SiO_2 and compared the results obtained in the absence of nanoparticles and in the absence of both nanoparticles and mass transfer, in various pulses and flow rates. Their results indicated that the presence of nanoparticles increased the dynamic hold-up up to 70% while at the same time decreased the static hold-up in flow rates higher than 70 cc/min and pulse strengths higher than 2.2 cm/s.

Using an analogy for heat and mass transfer, Bahmanyar et al. [36] recently suggested a model to calculate effective diffusivity and mass transfer coefficient in terms of the nanoparticle volume fraction, Reynolds number, and Schmidt number. They compared the model predictions with their previous experimental data [10] for a pulsed liquid–liquid extraction column. The absolute average relative error of the proposed model for the mass transfer coefficient and effective diffusivity were 5.3% and 5.4%, respectively.

Mirzazadeh Ghanadi et al. [37] investigated the effect of nanoparticles on mass transfer in the liquid–liquid extraction process for the chemical system n-butanol–succinic acid–water. They prepared nanofluids with 0.025, 0.05 and 0.1 wt% of ZnO, carbon nanotubes (CNT), and TiO_2 nanoparticles in water. To examine the effect of flow mode on mass transfer, they employed different fluid modes including dropping and jetting in the process. Their results showed that mass transfer enhancement depends on the kind and concentration of nanoparticles and the flow regime. They observed that mass transfer increased with nanoparticles concentration and the positive effect of nanoparticles was more distinctive in laminar flow. Mirzazadeh Ghanadi et al. [37] found that when the flow mode changes to turbulent flow, as a result of eddies movement and reducing the surface effect contribution in mass transport phenomenon, the presence of nanoparticles scarcely influence the mass transfer flow rate. Furthermore, their results indicated that the effect of ZnO nanoparticles on mass transfer enhancement (up to twofold) was more than that of CNT and TiO_2 nanoparticles.

Nematbakhsh and Rahbar-Kelishami [38] investigated the influence of hydrophobic SiO_2 nanoparticles on mass transfer using an irregularly-packed liquid–liquid extraction column and the chemical system toluene–acetic acid–water. They dispersed nanoparticles with sizes of 10, 30 or 80 nm in toluene–acetic acid to produce nanofluids with different volume fractions of 0, 0.01, 0.05 and 0.1 vol%. They observed that the mass transfer enhancement was more significant in nanofluids with smaller particles. They also found that mass transfer coefficient was larger in nanofluids compared to that in dispersed phase without nanoparticles, with a peak enhancement at the nanoparticle concentration of 0.05 vol% for 10 nm particles and 0.01 vol% for 30 and 80 nm particles. In their work, the maximum mass transfer coefficient enhancement was approximately 42% at 0.05 vol% of nanoparticles