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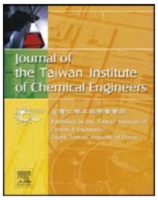

Salting-out effect of NaCl on the rate of mass transfer of liquid–liquid extraction in a two impinging-jets contacting device

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ABSTRACT

The effect of very low NaCl addition in the recommended liquid–liquid extraction chemical system of toluene–acetone–water was investigated using a two impinging-jets contacting device with a high velocity of jet flows. By Adding salt within the concentration range of 10^{-6}–10^{-4} mol/L, while the pH was constant and with the jets colliding force within 70.34–214.6 mN, the extraction efficiency and overall volumetric mass transfer coefficient found enhancements to about 22.7% and 35.6% respectively. A high trend of variation is observed for the salt concentrations till only about 10^{-5} mol/L. This phenomenon can be attributed to the hydration of ions which favours acetone to be transferred easier. Increasing jets force in the impingement of the streams provides a higher efficiency in the extraction process within the range used. In this regard, the variation of interfacial tension with salt concentration was investigated and using the dimensionless Weber and Eotvos numbers in accord with the conditions, an empirical correlation was developed for the prediction of extraction efficiency in the impinging-jets contacting device.

1. Introduction

Liquid–liquid extraction has become one of the most important processes in chemical engineering and has found a vast application in various chemical and hydrometallurgical plants. A variety of different contactors has been developed for this process. This matter is often connected with expensive experimental investigations and therefore, studies on the pilot plants and laboratory scale apparatuses are inevitable. To date it is still difficult to describe the rate of mass transfer as a function of process and physical parameters.

In a number of so far recommended chemical systems for liquid–liquid extraction investigations (Bailes *et al.*, 1983; Misek *et al.*, 1985), water has been selected as the continuous phase. Also, in many industrial processes, at least one of the phases in the liquid–liquid extraction systems is aqueous. The aqueous salt solutions are present in large amounts in environment and using them can greatly influence the mass transfer between phases and change the equilibrium distribution of organic solutes. Water is a dipolar protic solvent containing hydrogen bond donor (O–H bond) and therefore, intermolecular hydrogen bonds can change water solubility of a molecule, considering its hydrophobic or hydrophilic tendency. This phenomenon is often referred to as the salting-in or salting-out effect. During recent years, the salting-out effect (decrease in aqueous solubility due to the presence of inorganic salts) has been investigated on the liquid–liquid equilibrium systems in the separation of organic solutes, using the preferential organic solvents (Görgényi *et al.*, 2006; Govindarjan and Sabarathinam, 1995; Solimo *et al.*, 1997; Vakili-Nezhad *et al.*, 2004; Zurita *et al.*, 1998). This matter has also been intensively investigated in the recovery of inorganic species, mainly for hydrometallurgy purposes. The separation in this case is usually accompanied with an interfacial reaction between extractant and the metal complex being extracted (Cox, 1992).

The influence of some electrolytes and surface potential on ions and charged species has also been demonstrated in a number of publications (Czapla and Bart, 2001; Pfennig and Schwerin, 1998; Pfennig *et al.*, 1998) and the strong influence of electrolytes on the partition behavior is reported. It has been shown that, for instance, the induced charge at the interface, which is caused by a hydrophilic–hydrophobic-oriented covering of surfactants at the interface has a strong influence on the extraction of ionic aqueous species, held with the interfacial reactions (Czapla and Bart, 2001).

Despite its high attraction, no investigation has been done in the case of variation in the rate of mass transfer of organic solutes, in the presence of electrolyte salts for the recommended liquid–liquid extraction chemical systems. The disadvantage of adding extra agents to the continuous operating systems, with respect to

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Nomenclature

C	solute concentration (g/L or mol/L)
d_N	nozzle diameter (mm)
E	extraction efficiency defined by Eq. (5)
Eö	Eotvos number defined by Eq. (11)
F	Jets colliding force (mN)
K_La	overall volumetric mass transfer coefficient (min^{-1})
N	number of data
P	number of parameters
Q	volumetric flow rate (L/min)
R	mass transfer rate (g/min), coefficient of determination
SD	standard deviation
u	jet flow velocity at the nozzle tip (m/s)
V_C	contacting device volume (L)
We	Weber number defined by Eq. (10)

Greek symbols

γ	interfacial tension (mN/m)
ρ	density (g/L)
φ	acetone distribution coefficient
Δ	difference in concentration driving force

Subscripts

a	aqueous phase
or	organic phase
i	inlet flow
m	logarithmic mean value
o	outlet flow

Superscript

*	equilibrium

the problems of contamination and the economic factors in separating the salts from the products could be the reason for this case.

In the present work, an attempt has been made to investigate the influence of adding very low amounts of sodium chloride in the aqueous phase with constant pH, on the extraction efficiency and the rate of mass transfer, using an efficient impinging-jets contactor rather than using conventional devices. In a number of previously published articles (Berman and Tamir, 2000; Dehkordi, 2001, 2002a,b,c); in addition to our recent publication (Saien *et al.*, 2006), the great potential of impinging-jets technique for the liquid–liquid extraction process has been demonstrated. The aim in this work is to find conditions for the higher efficiencies in this contactor device.

2. Experimental

2.1. Materials

The chemical system of toluene–acetone–water, a recommended system for liquid–liquid extraction studies (Misek *et al.*, 1985), was chosen. Distilled water with a constant pH value of 6.1 was produced and used as aqueous phase, when saturated with toluene. The acetone solute with concentration of 2 wt% was added always to aqueous phase. Acetone was analytical grade with purity of more than 99.5% but toluene was of technical grade with purity of more than 99% and saturated with water to be used as organic phase. The sodium chloride with purity of 99.8% was the product of Merck Company.

Table 1
Physical properties of chemical system at 20 °C.

Property	Value
Density of aqueous phase, saturated with toluene (g/L)	994.2
Density of aqueous phase saturated with toluene containing 2 wt% acetone (g/L)	990.1
Density of organic phase, saturated with distilled water (g/L)	862.1
Interfacial tension range within the salt concentration range of 0–10^{-4} mol/L (mN/m)	39.29–38.66

Experiments were carried out at the ambient temperature of 20 ± 2 °C; in this regard, the densities of the used chemical system at the average temperature of 20 °C are given in Table 1. The range of interfacial tension with respect to the salt concentration is also given in this table. Densities were measured using a picnometer and a calibrated digital scale with an accuracy 10^{-4} g. Due to very low used level of salt concentrations (maximum of 10^{-4} mol/L or 5.9×10^{-4} wt%), no significant change was appropriate for density of the phases.

Considering the important role of interfacial tension in hydrodynamics and contact of phases, this property was measured in the presence of different salt concentrations, using the drop-weight method which is a reproducible method and has been used by other investigators (Chen and Lee, 2000; Fu *et al.*, 1986). The drop-forming device and the procedure were similar to that described by our previous works (Saien and Akbari, 2006, 2008). A glass capillary with finely ground tip to give an angle of 90° between the ground face and the internal bore at the end with the edges sharp was used. The nozzle tip was very thin and the formation of a neck between the drop and the capillary tip was not observed. The toluene phase was held in a narrow glass syringe conducted by an adjustable syringe pump (Phoenix M-CP, French) and flowed through a rigid tube to the capillary in the stagnant aqueous phase. A very low flow rate (1 mL in 37.6 min, determined from the flow rate indication when calibrated by measuring the time of syringe piston movement) of organic phase was conducted to the capillary and drops were formed very slowly at the tip of capillary in the aqueous phase with the appropriate salt concentration.

Each drop volume was obtained from at least three measurements of time where the maximum deviations from the average value were less than ±0.3%. The whole aqueous media and conducting tube was thermostated with an uncertainty of ±0.1 °C, using an adjustable safely thermostat (OPTIMA 740, Japan).

The relationship between interfacial tension (γ) and the appropriate parameters is given by Harkins and Brown (1919):

$$\gamma = \frac{v \Delta \rho g}{r} \phi \tag{1}$$

where $\Delta\rho$ is the density difference between the aqueous and organic liquids (ρ_a and ρ_o), r is the capillary radius, and ϕ is a constant which should be obtained from the tables of Harkins and Brown (1919) and are correlated in an empirical equation by Drelich *et al.* (2003):

$$\phi = 0.167 + 0.193\left(\frac{r}{\sqrt[3]{v}}\right) - 0.0489\left(\frac{r}{\sqrt[3]{v}}\right)^2 - 0.0496\left(\frac{r}{\sqrt[3]{v}}\right)^3 \tag{2}$$

The values of equilibrium distribution of acetone between the phases at 20 °C, and under different salt concentrations were examined with rigorous stirring of samples by magnetic stirrer for