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Determination of mass transfer coefficient for continuous removal of cadmium by emulsion liquid membrane in a modified rotating disc contactor

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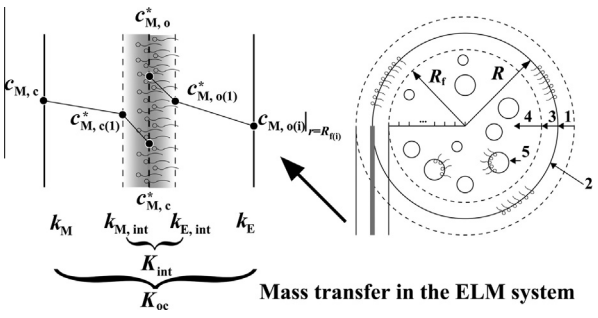
HIGHLIGHTS

- Overall mass transfer coefficient (K_{oc}) in a MRDC for an ELM system was calculated.
- Mass transfer resistance at the external interface of drops ($1/K_{int}$) was estimated.
- Effects of type and concentration of surfactant on the $1/K_{int}$ was investigated.
- Influences of different variables on mass transfer rate of Cd removal were studied.
- Empirical correlations were established for the coefficients of K_{oc} and K_{int}.

GRAPHICAL ABSTRACT



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ABSTRACT

Based on our earlier proposed model, the mass transfer characteristics in a modified rotating disc contactor (MRDC) for continuous removal of cadmium by emulsion liquid membrane (ELM) were investigated. The overall mass transfer coefficient (K_{oc}) in the water and oil layers at the external interface of emulsion drop was calculated using the model. Unlike the classical two-film theory, the mass transfer resistance in the interfacial film ($1/K_{int}$) between the water and oil layers could not be ignored due to the effect of surfactant. As a result, the overall mass transfer resistance ($1/K_{oc}$) was composed of the mass transfer resistances in the water layer ($1/k_M$), the interfacial film ($1/K_{int}$), and the oil layer ($1/k_E$). The $1/K_{int}$ increased significantly with the molecular weight and the concentration of the surfactant. The effects of different experimental conditions on the mass transfer rate of Cd removal were also studied, respectively. The results showed that the increase in rotating speed and paddle width could increase the turbulence which led to the increase in the K_{oc}, the mass transfer coefficient (K_{int}) in the interfacial film, and specific interfacial area (a). Flow ratio mainly affected the a, while total flow markedly influenced the K_{oc} and the K_{int}. The variables of extractant concentration, pH in feed solution, and sulfuric acid concentration in internal phase primarily influenced the partition equilibriums between the phases. Finally, dimensionless correlations were calculated to estimate the K_{oc} and the K_{int} with the AAREs of 14.2% and 13.3%, respectively.

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Nomenclature

a	specific interfacial area at external interface (m^2/m^3)
c	concentration (mol/m^3)
c^*	concentration at the external interface (mol/m^3)
c^0	concentration for $z = 0$ (mol/m^3)
c'	concentration at the continuous phase outflow (mol/m^3)
d	emulsion drops diameter (m)
d_{32}	Sauter mean diameter (m)
d_μ	Sauter mean diameter of internal aqueous droplets in emulsion (m)
D	diffusivity (m^2/s)
$D_{E,\ eff}$	effective diffusivity in emulsion phase (m^2/s)
D_H	column diameter (mm)
D_r	disc diameter (mm)
D_{32}	dimensionless d_{32}
E_M	axial dispersion coefficient (m^2/s)
H_C	compartment height (m)
H_r	propeller width (mm)
H_r^*	dimensionless propeller width
k_M	mass transfer coefficient in the water layer (m/s)
k_E	mass transfer coefficient in the oil layer (m/s)
K_{int}	mass transfer coefficient in the interfacial film (m/s)
K_{oc}	overall mass transfer coefficient (m/s)
L	column height (m)
m	external interface partition coefficient
Mr	relative molecular weight
Mr^*	dimensionless relative molecular weight
n	internal interface partition coefficient
N	rotating speed (rpm)
r	radial co-ordinate (m)
R	radius (m)
Re	Reynolds number
R_f	emulsion droplet inner core radius ($0 \leqslant r \leqslant R_f$) (m)
Sh	Sherwood number
U	superficial velocity (m/s)
v	volume (m^3)
V	flow (L/h)
z	axial co-ordinate (m)

Greek letters

γ	flow ratio ($\gamma = V_E/V_c$)
δ	thickness of oil layer (m)
μ	viscosity (Pa s)
ρ	density (kg/m^3)
ε	volume fraction of surfactant in membrane phase (%)
η	emulsion leakage ratio (%)
σ	interfacial tension (N/m)
τ	dimensionless residence time
φ	volume fraction of internal phase in emulsion phase
φ'	volume fraction of internal phase in emulsion drop inner core ($0 \leqslant r \leqslant R_f$)
Φ	emulsion phase holdup

Subscripts

aqu	aqueous phase
c	continuous phase
calc	calculated value
E	emulsion
exp	experimental value
f	inflow
int	external interface
j	internal phase
M	metal ion
o	organic phase (membrane phase)
org	organic phase
s	surfactant

1. Introduction

Cadmium ion is a well-known toxic heavy metal ion which could be accumulated through food chain and affect the health of human and other organisms seriously [1,2]. Large amounts of wastewater containing cadmium have been produced during the manufacturing of nickel–cadmium batteries, cadmium alloys, cadmium plating, non-ferrous or ferrous metallurgy, etc. The emission of the wastewater containing cadmium not only pollutes environment greatly but also wastes resources. Therefore, it is very necessary to research a feasible and effective method for the removal of cadmium from the industrial wastewater.

Emulsion liquid membrane (ELM) technique was widely investigated in the field of wastewater treatment to remove heavy metal ions [3–6], organic pollutants [7,8], and other contaminants [9,10]. However, most of the ELM studies were carried out in batch operations. It is essential to further investigate the continuous ELM process in pilot-scale equipment such as column-type contactors. So far, there were a certain number of researches working on the scale-up of the ELM processes. Kinugasa et al. [11] used a spray column as continuous equipment for the removal of phenol by the ELM. Bhowal et al. [12] modified the spray column for the ELM system using centrifugal force rather than terrestrial gravity. Oldshue–Rushton column was applied in the separation of acetic acid from succinic acid by the ELM [13]. Begum et al. [14] investigated the ELM pertraction of Cr(III), Cu(II), and Zn(II) from electroplating wastewater using rotating disk contactor (RDC) as equipment. The RDC and the spray column were also, respectively, tested as continuous equipment to remove cadmium by the ELM [15].

Even though few mathematical models had been established for the continuous ELM processes [11,12], improvements are still needed to evaluate the mass transfer performance more accurate. That is because the parameters in these models were almost estimated by the correlations obtained from liquid–liquid extraction system. To solve this problem, a mass transfer model considering the axial mixing of continuous phase and the polydispersity of emulsion drops in a modified RDC (MRDC) was proposed in our earlier paper [16]. Moreover, the important hydrodynamic parameters of the ELM system were also, respectively, determined using experimental methods in our previous works. The emulsion drop size was measured by photographic method in the absence of mass transfer [17]. Then, emulsion holdup (Φ), axial dispersion coefficient (E_M), and drop size distribution under the ELM mass transfer process in the MRDC were also studied systemically [16]. Generally, the mass transfer rate ($J = K_{oc} \cdot a \cdot \Delta c$) was simultaneously controlled by three important factors including mass transfer coefficient (K_{oc}), specific interfacial area (a, $a = 6\Phi/d$), and mass transfer impetus (Δc). In addition, the mass transfer impetus mainly affected by the parameters of the E_M and partition coefficients (m and n) between phases. Unfortunately, the determination of the mass transfer coefficient for the ELM system was rarely reported. Hence, it is still necessary to further investigate the mass transfer coefficient for the ELM system by experimental or theoretical methods.