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Absorption of ammonia into water-in-oil microemulsion in a rotor-stator reactor

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ABSTRACT

Absorption of NH_3 into water-in-oil (W/O) microemulsion in a rotor-stator reactor (RSR) was investigated in this work. The microemulsion comprised triton X-100, 1-pentanol, cyclohexane and water while the gas phase was a mixture of NH_3 and N_2. Experiments were performed to study the mass transfer process between the gas and the microemulsion. The effects of water content on the physical properties of the microemulsion as well as the influences of operating conditions including water content of the microemulsion, rotation speed, liquid volumetric flow rate and gas volumetric flow rate on the mass transfer coefficient (K_ya) were investigated. The results showed that the density and viscosity of the microemulsion increased with an increasing water content whereas the Henry's constant of the NH_3-microemulsion system decreased. K_ya increased with an increase in water content of the microemulsion, rotation speed, liquid volumetric flow rate and gas volumetric flow rate. A comparison of the K_ya of NH_3 in the RSR and in a packed tower showed that the K_ya of NH_3 in the RSR was 65% higher than that in the packed tower under the same operating conditions, thus, revealing that the RSR has higher mass transfer efficiency than the packed tower.

1. Introduction

Microemulsion is an optical transparent single-phase mixture comprising surfactant, cosurfactant, oil phase and water phase [1–3]. Since its advent in 1943, it has continued to attract a lot of attention due to its unique characteristics of being thermodynamically stable, macroscopically homogeneous and isotropic, but heterogeneous on a microscopic scale [4]. It is therefore widely applied in tertiary oil recovery [5], drug carrier [6], separation engineering [7], synthetic nanoparticles [8,9], etc.

In water-in-oil (W/O) or oil-in-water (O/W) microemulsions, the dispersed phase droplets encircled by surfactant and cosurfactant are dispersed in the continuous phase, and the growth of nanoparticles occurs within them [10]. Thus, the dispersed phase droplets of microemulsions containing soluble metal salts can be used as micro reactors to control the particle sizes for the synthesis of nanoparticles [11]. Since the first application of microemulsion system by Boutonnet et al. [12] to synthesize nanoparticles, it has hitherto been widely used in this field. For instance, nanoparticles have been produced by direct mixing of two microemulsions (or mixing a microemulsion with an aqueous solution) containing appropriate reactants [13–15]. However, the cost of employing two microemulsions is relatively high, and the addition of aqueous solution into a W/O microemulsion results in a rise in the size of the dispersed phase droplets, thereby leading to the increase in the size of nanoparticles synthesized in the droplets.

In order to overcome these limitations, gas-microemulsion reaction systems have been developed and used to prepare nanoparticles [16]. Luminescent ZnSe quantum dots of better photostability have been synthesized by direct reaction of a microemulsion with dilute hydrogen selenide gas [17]. In addition, sulfur nanoparticles of nearly uniform size and higher antimicrobial activity have been prepared by the hazardous H_2S gas and W/O microemulsion system [18]. The mass transfer process between the gas and microemulsion and the micromixing are key steps in this method, and thus, the knowledge of gas-microemulsion mass

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Abbreviations: O/W, oil-in-water; RPB, rotating packed bed; RSR, rotor-stator reactor; VOCs, volatile organic chemicals; W/O, water-in-oil.

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Nomenclature

a	specific interfacial area, m^2/m^3
d	average diameter of the microemulsion droplet in the RSR, m
E	Henry's constant of the NH_3-microemulsion system, kPa
G	molar flow rate of gas stream, mol/s
H	axial length of the casing, m
K_x	overall mass transfer coefficient, $mol/(m^2\,s)$
K_y	overall mass transfer coefficient, $mol/(m^2\,s)$
K_ya	overall volumetric mass transfer coefficient, $mol/(m^3\,s)$
M	molar flow rate of microemulsion stream, mol/s
m	phase equilibrium constant of the NH_3-microemulsion system
N_A	mass transfer rate, $mol/(m^2\,s)$
p_e	partial pressure of NH_3 in the gas stream equalized with the liquid stream, kPa
p_t	total pressure of the gas stream, kPa
R	inner radius of the casing, m
r	radius of the mass transfer zone, m
V	volume of the mass transfer zone, m^3
x	mole fraction of NH_3 in the liquid stream
x_e	mole fraction of NH_3 in the liquid stream equalized with the gas stream
x_i	mole fraction of NH_3 in the inlet liquid stream
x_o	mole fraction of NH_3 in the outlet liquid stream
y	mole fraction of NH_3 in the gas stream
y_e	mole fraction of NH_3 in the gas stream equalized with the liquid stream
y_i	mole fraction of NH_3 in the inlet gas stream
y_o	mole fraction of NH_3 in the outlet gas stream

Greek letter

ρ	density of the microemulsion, kg/m^3

transfer process is highly necessary. However, studies on the mass transfer process between gas and microemulsion phases are scarce. Liu et al. [19] employed the volatile organic chemicals (VOCs) and O/W microemulsion system as the gas and liquid phases respectively to evaluate the absorption process, and found that the mass transfer process was controlled by liquid film [20]. Also, gas absorption into AOT-based microemulsions has been investigated in a double stirred-cell absorber by Gómez-Díaz et al. [4], and the results revealed that the ternary microemulsions showed a faster absorption process than the CO_2-water system, which could be explained on the basis of the internal dynamics of microemulsions.

In the above research, the concentration of the gas components dissolved in microemulsion was reduced by the reaction between the dissolved gas components and salts in the microemulsion, leading to an increase in the mass transfer driving force. Consequently, the reaction itself can intensify the mass transfer process. However, the intensification of the reaction is limited by the mass transfer resistance and interfacial area between the gas and microemulsion in the absorption-reaction process. Also, the above approaches have the limitations of uneven distribution of the reactants. The possible application of a novel multiphase reactor: rotor-stator reactor (RSR), which was invented in 2006 [21], to overcome these drawbacks is described herein. It can greatly intensify mass transfer and micromixing effects of the gas-microemulsion system due to a highly intensified gas-liquid interfacial area and fast surface renewal rate of the gas–liquid interface, which can be attributed to small liquid droplets and thin liquid films formed as a result of the great centrifugal force generated by the rotating rotor and the violent turbulence of the gas and liquid streams. In comparison with a rotating packed bed (RPB), the RSR demonstrates advantages of uniformity in circumferential distribution of liquid, no need for internal sealing for gas–liquid reaction, etc. Micromixing time in the RSR has been studied and calculated to be about 10^{-5} s, which is an order of magnitude less than that in the RPB (about 10^{-4} s) [22,23], suggesting that the RSR can significantly alleviate the problem of uneven distribution of the reactants. Besides, the RSR has shown good performance in the preparation of oil-in-water emulsion [24] and nano-$CaCO_3$ [25].

This study employed the RSR as a reactor to investigate the mass transfer coefficient of gas (NH_3) in the absorption process of NH_3-W/O microemulsion in the RSR. The effect of water content on the physical properties of the microemulsion was studied, and the variation of mass transfer coefficient (K_ya) under different operating conditions was also investigated.

2. Calculation of K_ya

The equations for the experimental K_ya values in the RSR can be obtained as follows.

An infinitesimal mass transfer zone is isolated (as shown in Fig. 1) for investigation and the following equation (Eq. (1)) is derived in terms of material balance:

$$Gdy = Mdx = N_A a dV \tag{1}$$

$$dV = 2H\pi r dr \tag{2}$$

Substituting Eq. (2) to Eq. (1), the solution is:

$$Gdy = Mdx = 2N_A a H\pi r dr \tag{3}$$

$N_A a$ can be expressed as:

$$N_A a = \frac{Gdy}{2H\pi r dr} \tag{4}$$

Eq. (5) can be obtained by the gas–liquid mass transfer rate equation:

$$N_A a = K_y a(y - y_e) = K_x a(x_e - x) \tag{5}$$

Substituting Eq. (5) to Eq. (4), the solution is:

$$N_A a = \frac{Gdy}{2H\pi r dr} = K_y a(y - y_e) \tag{6}$$

Since K_ya values were obtained by the inlet and outlet gas/liquid concentrations in the RSR, the integral path was from the center of

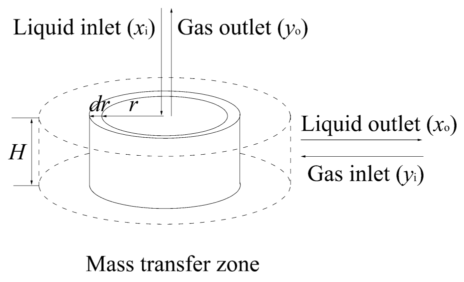

Fig. 1. Diagram of integral path for material balance in the mass transfer zone.