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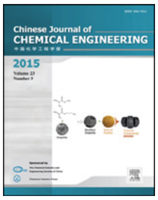

Research Note

Mass transfer characteristics in a rotating packed bed with split packing[☆]

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A B S T R A C T

The rotating packed bed (RPB) with split packing is a novel gas–liquid contactor, which intensifies the mass transfer processes controlled by gas-side resistance. To assess its efficacy, the mass transfer characteristics with adjacent rings in counter-rotation and co-rotation modes in a split packing RPB were studied experimentally. The physical absorption system NH_3–H_2O was used for characterizing the gas volumetric mass transfer coefficient (k_ya_e) and the effective interfacial area (a_e) was determined by chemical absorption in the CO_2–NaOH system. The variation in k_ya_e and a_e with the operating conditions is also investigated. The experimental results indicated that k_ya_e and a_e for counter-rotation of the adjacent packing rings in the split packing RPB were higher than those for co-rotation, and both counter-rotation and co-rotation of the split packing RPB were superior over conventional RPBs under the similar operating conditions.

1. Introduction

Rotating packed bed (RPB) is a new high-gravity gas–liquid mass transfer equipment, which produces a centrifugal force up to several hundred times the gravity [1]. Fig. 1 shows the schematic of RPB, in which liquid enters the RPB through the liquid distributor and is splashed onto the inner edge of the rotor packing, and then it moves outwardly by centrifugal acceleration and contacts countercurrently with gas, producing a large gas–liquid interfacial area, causing intensive mixing and resulted in higher mass transfer efficiency [2–6].

The characteristics of mass transfer in RPBs have been studied extensively. The liquid-side mass transfer coefficient in RPBs has been declared to be several times higher than that of conventional packed columns [7–12]. For example, Ramshaw [7] conducted water-oxygen absorption experiment and found that the liquid-side mass transfer coefficient was 27–44 times higher than that of conventional packed columns. Jiao *et al.* [8] reported the liquid-side mass transfer coefficient was 1–2 order of magnitude higher than that of conventional packed beds. However, Sandilya *et al.* [13] reported the gas-side mass transfer coefficient in RPBs was in the same range as that of conventional packed columns, because the gas involves a large frictional drag in RPBs by the packing, so that the gas undergoes a solid-body-like rotation in the rotor. Rao *et al.* [14] reported that there has been no enhancement in the gas-side mass transfer coefficient in RPBs, because the tangential slip velocity (tangential velocity difference between gas and packing) may be negligible. For the purpose of enhancing the tangential slip velocity, namely the gas-side mass transfer coefficient, Chandra *et al.* [15] proposed a novel rotating packed bed with split foam-metal packing in which the packing is split into annular rings with gaps between them, so that when the alternate rings rotate in the counter-direction mode, a large tangential slip velocity can be achieved.

Many researchers adopted absorption of SO_2 in aqueous NaOH to study the intensification of gas-side mass transfer in a split packing RPB. For example, Reddy *et al.* [16] measured the gas volumetric mass transfer coefficients (k_ya_e) using the SO_2–NaOH absorption system in a split packing RPB, and the results show that gas volumetric mass transfer coefficients are 2 orders of magnitude higher than those reported with a single packing [13,17]. Shivhare *et al.* [18] determined the gas-side mass transfer coefficient (k_y) *via* absorption of SO_2 in aqueous NaOH in the split-packing and conventional single-block RPB, and the results indicate that split-packing RPB was superior to conventional single-block RPB for gas-side mass transfer resistance controlled processes. These previous researches strongly indicate that the gas mass transfer coefficient can be enhanced in a split packing RPB. However, Guo *et al.* [19] used a physical absorption system NH_3–H_2O and a chemical absorption system SO_2–NaOH to study the mass transfer characteristics in a cross-flow RPB, and the results show that the gas volumetric mass coefficient for SO_2 absorption is higher than NH_3 absorption by 70%. The enhancement is possibly due to the effect of chemical reaction, and there may be a chemical acceleration in the mass transfer process. Therefore, more experimental studies on other systems are desired to evaluate the mass transfer and hydrodynamic behavior in the split packing RPB.

The effective interfacial area (a_e) and the gas volumetric mass transfer coefficient (k_ya_e) are two important parameters for characterizing

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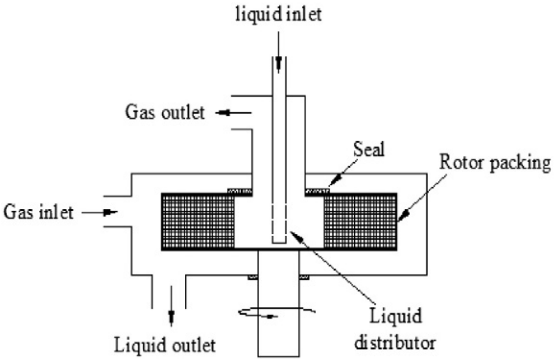

Fig. 1. The sketch of rotating packed bed.

the mass transfer process. In this work, $k_y a_e$ and a_e for counter-rotation and co-rotation modes in a split packing RPB were studied experimentally. The gas volumetric mass transfer coefficient was characterized by a physical absorption system NH_3–H_2O, which is a typical gas-side mass transfer resistance controlled system, where the liquid-side mass transfer resistance is negligible. The effective interfacial area was determined in the chemical absorption CO_2–NaOH system which is used in many works [20,21].

2. Experimental Setup

Fig. 2 is a rotor schematic illustration of a split packing RPB which is made in the laboratory. The rotor of split packing RPB consists of a pair of disks, and three stainless-steel concentric annular rings of different radius are fixed onto each disk. Each annular ring consists of two stainless-steel sheets (2 mm thick each), which sandwich wire gauze packing in between. The diameter of gauze packing wire is 0.4 mm. There are 3 rows of 8 mm holes drilled on each stainless-steel sheet as the fluid pathway, and a small gap (8 or 9 mm) remains between the adjacent concentric rings when the two disks are brought together. The split packing has a specific surface area of 1027 $m^2 \cdot m^{-3}$ and bed porosity of 0.9, and the axial length of the rings is 30 mm. The two disks can rotate in either co-rotation or counter-rotation mode at the control of a switch. When the two disks rotate in counter-direction, a large tangential slip velocity between the gas and the packing is achieved. Table 1 shows the geometric details of the concentric rings of split packing RPB.

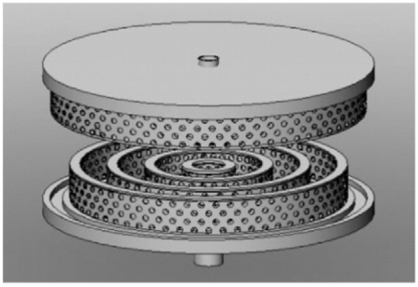

Fig. 2. Rotor schematic illustration.

Table 1
Details of the packing rings

Ring no.	Inner diameter/mm	Outer diameter/mm
1	84	116
2	132	164
3	182	214
4	230	262
5	280	312
6	328	360

Fig. 3 shows a schematic diagram of experimental setup. Air from a roots blower and CO_2 from carbon dioxide cylinder respectively flowed into the split packing RPB by pressure difference through different gas flowmeters. The aqueous NaOH from liquid storage tank measured by a liquid flowmeter flowed into the split packing RPB by of a liquid pump. The aqueous then splashed onto the inner edge of the packing ring through a liquid distributor, moved outwardly by centrifugal acceleration, and countercurrent contacted with mixed gas, finally moved out of the RPB after collected by the casing. The absorption of NH_3 into H_2O was conducted similarly in the same operating conditions. The CO_2 concentration of inlet gas and exit gas was analyzed by CO_2 analyzer (PGM-54, RAE, USA), the NH_3 concentration of inlet gas and exit gas was analyzed by NH_3 analyzer (GT-2000, KEERNUO, China). In this study, the CO_2 concentration of inlet gas was maintained 15700 $mg \cdot m^{-3}$ and the NH_3 concentration of inlet gas was maintained 380 $mg \cdot m^{-3}$.

2.1. Effective interfacial area

In this experiment, the effective interfacial area a_e was measured by chemical absorption of CO_2 in aqueous NaOH. In order to guarantee the absorption of CO_2 in aqueous NaOH to be a first order fast reaction in the liquid film, the experimental conditions were such that the Hatta number $Ha = \sqrt{Dk}/k_L \gg 1$, and the initial concentration of NaOH solution was 1 $mol \cdot L^{-1}$ in all experimental runs. The effective interfacial area was determined from [22]

$$G\mathrm{d}y_{CO_2} = a_e c_A^* \sqrt{Dk} 2\pi r h \mathrm{d}r. \tag{1}$$

The effective interfacial area can be obtained through the integration of above equation from the outer radius to the inner radius.

$$a_e = \frac{G(y_{in} - y_{out})}{\left[c_A^* \pi h (r_2^2 - r_1^2)\right]\sqrt{Dk}}. \tag{2}$$

Here, the non-dimensional number, *Ha*, is the ratio of chemical reaction rate and physical absorption rate in liquid film; k_L is the local liquid-side mass-transfer coefficient, *D* is the solute diffusivity; *k* is the pseudo-first-order reaction rate constant; *G* is the gas flow rate; y_{in} and y_{out} are the CO_2 concentration of gas at inlet ($r = r_1$) and exit ($r = r_2$); *h* is the axial length of the packing rings; r_1 and r_2 are the inner and outer radius of the packing rings; c_A^* is the solute concentration at the liquid interface. The expressions for c_A^*, *D*, k_L and *k* are well established in the literature [22].

2.2. Gas volumetric mass transfer coefficient

The gas volumetric mass transfer coefficient, $k_y a_e$, can be obtained from the physical absorption of NH_3 into H_2O, and the gas volumetric mass transfer coefficient was determined from

$$k_y a_e = \frac{G}{\pi (r_2^2 - r_1^2) h} \ln \frac{y_{in}}{y_{out}} \tag{3}$$

where y_{in} and y_{out} are the NH_3 concentration of inlet gas and exit gas, respectively.

3. Results and Discussion

3.1. Effects of the gas velocity on a_e and $k_y a_e$

Fig. 4 plots the increase of a_e and $k_y a_e$ along with the gas velocity. The tendency of experimental data is in agreement with Reddy *et al.* [16] and Rajan *et al.* [22], a_e and $k_y a_e$ for counter-rotation are larger than those for co-rotation. This phenomenon may be explained by