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A two-stage blade-packing rotating packed bed for intensification of continuous distillation☆

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ABSTRACT

A two-stage blade-packing rotating packed bed (TSBP-RPB) was designed and developed for the intensification of continuous distillation. The mass transfer parameters of the TSBP-RPB were investigated using a chemisorption system. Continuous distillation experiments were conducted in the TSBP-RPB by the methanol–water binary system. Experimental results showed that values of the effective interfacial area and liquid-side mass transfer coefficient of the TSBP-RPB were 93–337 $m^2 \cdot m^{-3}$ and 0.05–0.19 $cm \cdot s^{-1}$, respectively. The height of equivalent theoretical plate (HETP) of the TSBP-RPB ranged from 1.9 to 10 cm. Moreover, the TSBP-RPB is easy to be manufactured, which shows great potential for the application of continuous distillation.

1. Introduction

Process intensification (PI) technology includes PI equipment and PI methods [1]. As one of the typical PI equipment, rotating packed beds (RPBs) have been studied and utilized in chemical industries for last 35 years (starting at 1979) [2–6]. An early structure of the RPB's rotor described in the US patent granted in 1981 was shown in Fig. 1(a). The liquid was the continuous phase and the gas was the discontinuous phase in the rotor. Since the rotor was always filled with liquid, the RPB's motor load was very high and a significant amount of energy was consumed [7]. The rotors' structures, shown in Fig. 1(b) [8] and (c) [9], were optimized in the US patents granted in 1983, where the liquid and gas were the discontinuous and continuous phases, respectively. More gas–liquid contacting area can be generated when the liquid is disintegrated by the high speed porous packing packed in the rotor, which benefits the mass transfer process. As a common unit operation of mass transfer in the chemical industry, distillation is carried out by the gas and liquid contacting in a contactor. Because the gas fills the whole RPB space and liquid flows through in the rotor of the RPB as tiny liquid elements, which yields considerable interfacial area, mass transfer between two phases can be enhanced [10–12] in the RPB. As expected, continuous distillation in the RPB became the earliest application, which demonstrated the excellent performance of the RPB [13].

With the purpose of making the RPB a common contactor for continuous distillation, fundamental and application studies were conducted in RPBs by many researchers. The separation efficiency was measured in a one-stage RPB by total distillation experiments [14–17]. Continuous distillation experiments were also conducted in a two-RPB incorporated unit (one RPB as the rectifying section and the other as the stripping section) [13,18,19]. In order to install the intermediate feed along the radial direction of the rotating rotor, a rotating zigzag bed (RZB) was developed [20], which had multi-stage rotors driven by one motor, aiming at putting the continuous distillation in only one RPB unit. Recently, a new counter-flow concentric-ring rotating bed was reported for the continuous distillation which was upgraded from the RZB [21]. A two-stage counter-current rotating packed bed (TSCC-RPB) for the continuous distillation was invented, constructed, and tested by the authors' group [22,23]. Experimental results showed that the TSCC-RPB could provide remarkable separation efficiency. However, the structure of the TSCC-RPB, which had a static disc and a rotational packing in the rotor, was complicated. It required high manufacturing precision and the cost of the TSCC-RPB was 10%–15% higher than that of a conventional RPB.

End effect is a unique phenomenon in a RPB, with mass transfer accomplished in the end zone (radial thickness of 10–15 mm at the inner zone of the rotor) being a magnitude higher than what is achieved in the bulk zone (the rest of the rotor). Based on the visual observation, the liquid was disintegrated into tiny liquid droplets in the end zone, but synchronized with packing in the bulk zone [24]. In order to impinge the

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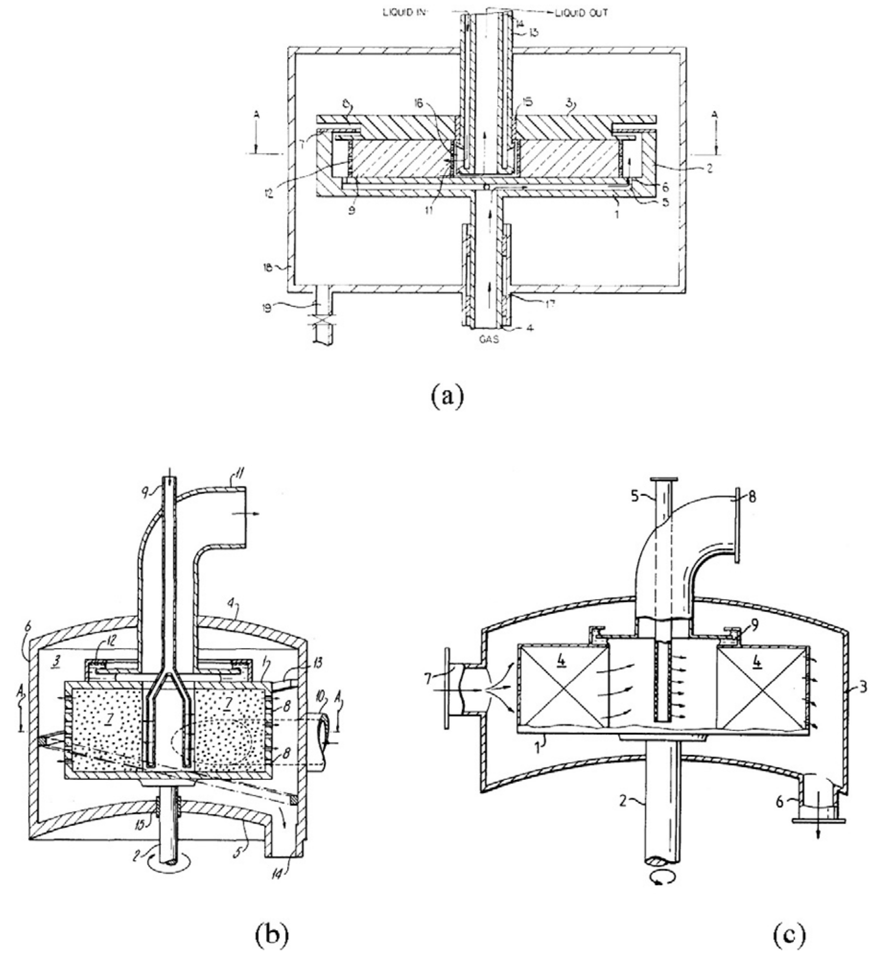

Fig. 1. Rotor structure in the US RPB patent granted in (a) 1981 (b) and (c) 1983. (a) 1 — stainless steel base; 2 — wall; 3 — transparent plastic lid; 4 — hollow shaft; 5 — radial channel; 6 — port; 7 — lip; 8 — annular groove; 9 — glass bead; 11 — radially inwardly disposed wire mesh; 12 — radially outwardly disposed wire mesh; 13 — outer concentric tube; 14 — inner concentric tube; 15 — gas — tight seal; 16 — fan sprays; 17 — bearing housing; 18 — stationary housing of stainless steel; 19 — port. (b) 1 — rotor; 2 — drive shaft; 3 — chamber; 4 — cover; 5 — base; 6 — chamber wall; 7 — packing; 8 — aperture; 9 — liquid feed pipe; 10 — gas feed pipe; 11 — by-passing of the packing; 12 — liquid seal; 13 — spiral; 14 — liquid discharge pipe; 15 — seal. (c) 1 — rotor; 2 — shaft; 3 — case; 4 — packing; 5 — liquid feed pipe; 6 — liquid discharge pipe; 7 — gas feed pipe; 8 — gas discharge pipe; 9 — seal.

liquid in the bulk zone and generate more liquid interfacial area, a new designed RPB with blade packing (here called one-stage blade-packing rotating packed bed, OSBP-RPB) was reported, which enhanced the mass transfer in the whole rotor [25]. Experimental results showed that the 60° blade-packing had the highest mass transfer efficiency. Combining the advantages of the TSCC-RPB and OSBP-RPB to develop a two-stage blade-packing rotating packed bed (TSBP-RPB) seems therefore a potential improvement. The aims of this development are: (1) to simplify the structure and (2) to maintain the same separation efficiency of the TSCC-RPB by replacing the static disc and rotational packing in the TSCC-RPB with the high efficiency 60° blade-packing in the OSBP-RPB. In this work, mass transfer parameters, presented in terms of the effective interfacial area (a_e) and liquid side mass transfer coefficient (k_L), of the TSBP-RPB were measured by the system of CO_2 chemisorption into NaOH solution. Then the TSBP-RPB was utilized in the continuous distillation of a methanol–water binary system to test the separation efficiency, presented in terms of the number of theoretical plates (N_T).

2. Experimental Section

The TSBP-RPB, having two rotors with blade-packing in one rotational shaft, was constructed as shown in Fig. 2(a). Dimensions of the TSBP-RPB are shown in Table 1. Fig. 2(b) shows the structure of the blade-packing. Each blade-packing has three packing rings and two blade rings. The detailed structure of the blades can be found elsewhere in a previous paper [25]. The inner and outer blade rings had 30 and 48 pieces of blades, respectively. The liquid distributor in the upper or lower rotor consists of four pipes configured in parallel with the axis and each pipe has four nozzles aligned along the axial direction. The stainless steel wire mesh was used as the packing and has a specific surface area of 500 $m^2 \cdot m^{-3}$ and a porosity of 96%.

Fig. 3 shows a sketch of the experimental setup for measuring mass transfer parameters of the TSBP-RPB. The NaOH solution (about 1 $mol \cdot L^{-1}$ or 0.05 $mol \cdot L^{-1}$) at room temperature (20–25 °C) was pumped into the inner edge of the rotor from the stock tank. The mixed gas of CO_2 and air was tangentially introduced from a gas inlet and contacted the liquid counter-currently within the packing. The volume fraction of CO_2 in the mix gas was set on about 10% or 2%. Gas samples at the gas inlet and outlet were measured by two infrared gas analyzers (GXH-3010F, Huayun Analytical Instrument Company, China), respectively. Four liquid sample collectors were used and liquid samples were analyzed by an Automatic Potentiometric Titrator (Beijing Xianqu Weifeng Technology Development Co., ZDJ-2D). The calculations of a_e and k_L were reported elsewhere in a previous paper [22].