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Experimental study of liquid renewal on the sheet of structured corrugation SiC foam packing and its dispersion coefficients

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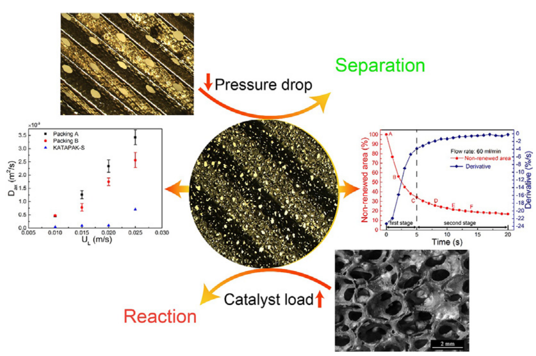
HIGHLIGHTS

- Liquid renewal on the SCFP-SiC sheet was visualized.
- Renewal process was categorized into two stages.
- Effects of liquid flow rate, viscosity and surface tension were considered.
- Axial and radial dispersion coefficients were obtained.

GRAPHICAL ABSTRACT



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ABSTRACT

Developing efficient catalytic packing for reactive distillation can push its application greatly forward. Structured Corrugation SiC Foam Packing is considered an attractive candidate with the rapid development of the coating method. However, liquid flow behavior on the packing and its radial and axial dispersion coefficients remain unclear. We studied herein liquid renewal on the structured corrugation SiC foam packing sheet by photography. The images revealed that the liquid could be constantly refreshed on most of the wetted area and the process can be categorized into two stages by the renewal rate. Effects of liquid flow rate, viscosity, and surface tension on the renewal process were investigated. The renewal results highlight the applicability of the foam packing at low liquid load. Furthermore, axial and radial dispersion coefficients of two foam packing sheets with different pore sizes were characterized, and comparisons with KATAPAK-S showed that the foam packing has better liquid dispersion ability.

1. Introduction

Reactive distillation is an effective means of process intensification considering the reduction of equipment cost and the enhancement in the yield of equilibrium-limited reactions it provides (Noeres et al., 2002). The widely-used contacting devices for reactive distillation are modular catalytic structured packings such as KATAPAK-S (van Baten et al., 2001), Winpak (Xiang et al., 2016) and SCPI (Li et al., 2008). All these packings feature a gas–liquid and liquid–solid separated contact style, attributing to the arrangement of combined separation and reaction elements. However, this structure suffers from a decreased bed porosity due to catalysts loading and a limited gas–liquid interface. Therefore, finding an

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Nomenclature

Latin symbols

L	length of packing sheet (mm)
W	width of packing sheet (mm)
T	thickness of packing sheet (mm)
h	crimp height of packing sheet (mm)
B	crimp base width of packing sheet (mm)
P_t	pixels of red area at time t
$c(t)$	conductivity of liquid at time t (μS/cm)
$E(t)$	residence time distribution (s^{-1})
t_m	mean residence time (s)
x	axial direction (m)
y	radial direction (m)
D_{ax}	axial dispersion coefficient (m^2/s)
D_r	radial dispersion coefficient (m^2/s)
t	time (s)
u_l	superfacial liquid velocity (m/s)

Greek symbols

μ	viscosity (mPa·s)
σ	surface tension (mN/m)
ρ	density (kg/m^3)
β	crimp angle (°)

innovative catalytic packing addressing the aforementioned problems is of vital importance for promoting the advancement of reactive distillation.

Structured packing made of silicon carbide (SiC) open-cell foam material applied in multiphase reactor (Labuschagne et al., 2016; Masson et al., 2015) and separation column (Lévêque et al., 2009; Wang et al., 2016; Xu et al., 2015) has been extensively reported owing to its high porosity, large specific surface area, low pressure drop, excellent heat conduction, and enhanced axial and radial mixing. However, the capacity of monolithic foam packing is restricted because flooding occurs even at lower gas and liquid loads (Lévêque et al., 2009; Stemmet et al., 2005). Structured Corrugation SiC Foam Packing (SCFP-SiC), an integration of foam material into traditional corrugation packing structure, however, is able to exploit advantages from both parties (Zhang et al., 2010). More importantly, the rapid development in catalyst coating technology (Elamin et al., 2015; Jiao et al., 2017; Ou et al., 2017a), enables the SCFP-SiC as an ideal candidate for reactive distillation considering its broader operation range, lower pressure drop, and larger solid–liquid and vapor–liquid interfaces, which promote both reaction and separation.

Comprehensive work about hydrodynamics and transport properties including pressure drop, liquid hold-up, flow regime and gas to liquid mass transfer coefficients of foam packing has been published (Dietrich, 2012; Ou et al., 2017b; Parthasarathy et al., 2016). However, detailed liquid flow behavior, especially the renewal process, determining the residence time, reaction conversion and utilization efficiency of foam packing, has not been fully understood. In addition, the radial and axial dispersion coefficients of SCFP-SiC, as critical parameters in column design, have a great impact on interphase mass transfer, concentration and energy distribution, selectivity and yields, but have not been characterized yet. These two gaps constitute the aim of our work.

Several studies have been carried out to investigate liquid flow on both structured packing and foam packing which enlighten our work. By studying liquid flow behavior in an element of KATAPAK-SP, it was found that the flow in the catalyst pocket contributes to the deviation from the plug flow for the packed beds (Behrens et al., 2007). It was also reported that liquid distribution on Mellapak is predominately influenced by packing geometry from the computational tomography reuslts (Fourati et al., 2012). Moreover, Wallenstein et al. (2015) reported that liquid is inclined to flow through sponge packing in the form of rivulets. Li et al. (2015, 2016) found that larger wetted area is achieved on the SiC foam corrugated sheet compared to the gauze sheet, and that pore size and extrusion ratio are two main parameters affecting flow behavior. Nonetheless, all the mentioned work focused on steady flow and cannot reflect the dynamic flow behavior on the packing which is reported in the first part of this paper.

The dispersion coefficients can be obtained by both experimental (Edouard et al., 2008; Saber et al., 2012a, 2012b; Voltolina et al., 2017) and computational methods (Habisreuther et al., 2009; Parthasarathy et al., 2013). However, due to the intricate structure of the foam packing and the limitation of computation capability, most of the work characterized the axial dispersion coefficient experimentally, *i.e.* by fitting one dimensional model to the residence time distribution curves. The fact that the foam packing preserves higher liquid dispersion compared to spherical particles was verified and factors such as foam structure and liquid velocity were also reported (Saber et al., 2012a). Though a two dimensional model was used to describe the dispersion ability, the results were focused on KATAPAK-S and Winpak (van Baten et al., 2001; Xiang et al., 2016). To the best of our knowledge, no publication about the axial and radial dispersion coefficients of the SCFP-SiC sheet has been reported yet, which comprises the second part of our study.

In this paper, liquid renewal process on the SCFP-SiC sheet was visually studied by photographic method and image analysis was carried out to reveal the renewal rate. Effects of flow rate, viscosity and surface tension on the process were also investigated. Furthermore, the two dimensional model was applied to obtain the axial and radial coefficients of the foam packing sheet by fitting its solution to the residence time distribution results.

2. Experimental section

2.1. Materials

Two types of SCFP-SiC sheet, Packing A and Packing B which differ in pore size, were tested. The production procedures of the packing sheet include cutting, extrusion, ceramic slurry impregnation and sintering of polyurethane sponge. Detailed information regarding the packing can be found elsewhere (Zhang et al., 2010). Fig. 1 shows the images of Packing A, in which geometrical features are indicated. The parameters of the two experimental packing sheets are summarized in Table 1, in which SCFP-SiC-350Y means the corrugation angle of the packing is 45° and that the packing specific surface area is 350 m^2/m^3. The surface to volume ratio, window size and strut diameter were obtained from computational tomography whose voxel resolution is 32.65 μm^3.

In visualization tests, red dye was added to the clear distilled water to trace the wetted area. Glycerol (AR, Tianjin Jiangtian Chemical Technology Co., Ltd., China) was added to distilled water to change liquid viscosity and sodium dodecyl benzene sulfonate (SDBS, AR, Tianjin Jiangtian Chemical Technology Co., Ltd., China) was used to adjust liquid surface tension (Zhang et al., 2017). Measurements of viscosity and surface tension confirmed that the adding of the dye did not alter the liquid properties significantly (The