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Impact of spacer on membrane gas separation performance

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ABSTRACT

Mixing in gas separation membranes has received much less attention than in membrane liquid separation because gas molecules have much smaller viscosity, allowing them to diffuse easily through membranes without requiring significant flow mixing. However, due to advancements in membrane fabrication technologies aimed at improving material properties, concentration polarization (CP) might become an issue in gas separation due to enhanced membrane efficiency and permeability. Consequently, a 2D CFD analysis is conducted to evaluate the impact of spacer-induced mixing on membrane gas concentration polarization for typical CO_2/CH_4 gas separation. Results show that spacers generally enhance flux performance while reducing CP in the membrane channel when compared to the case without spacers. Furthermore, the effectiveness of spacer-flux-to-pressure-loss-ratio (SPFP) reaches a peak for a Reynolds number in the range of $5 < Re_h < 200$ because of the trade-off between flux and pressure drop. This mixing-induced flux enhancement is most effective under high CP conditions (less mixing) within the membrane channel. Similarly, flux enhancement due to spacers can be observed as membrane selectivity, pressure ratio and feed gas concentration increase due to enhanced CP.

1. Introduction

The significance of baffles or spacers in enhancing mixing for liquid separations has been extensively discussed (Guan et al., 2023; Haidari et al., 2018; Lin et al., 2021; Singh et al., 2023; Zhang et al., 2022; Zhou and Ladner, 2022). In these liquid separation processes, spacer filaments are utilized to promote mixing and enhance mass transfer (Foo et al., 2021). On the other hand, membrane-based gas separations function differently, as gas molecules possess much lower viscosity compared to liquid solutes. This allows them to diffuse readily through the membrane without requiring substantial turbulence or mixing (Baker, 2004). Consequently, gas separation membranes are typically thin with a large surface area, facilitating efficient gas permeation. Nevertheless, with the rapid advancement in membrane property research (Castel et al., 2020; Scholes et al., 2012; Siagian et al., 2019), the phenomenon of concentration polarization (CP) may emerge as a significant issue in gas separation, particularly in conjunction with highly permeable membranes. This study addresses the concern of CP in gas separation.

An early study by Chen et al. (2013) found that obstructions installed in the membrane tube would disrupt the gas concentration boundary layer and increase gas permeation across the membrane. In addition, Sharma et al. (2018) reported a nearly 33% increase in gas recovery due to the presence of obstructions in the membrane separator. When spacers (obstructions) are used, it has been observed that mass transfer increases to the extent that the average values of the Sherwood number (Sh) obtained in the spacer-filled membrane channel are three times greater than those reported in the case without spacers (Alkhamis et al., 2015). Overall, applying spacers to gas separation membranes in spiral-wound or hollow fiber modules provides several advantages, including improved mass transfer across the membrane and enhanced overall process efficiency, potentially mitigating issues such as concentration polarization and fouling within the membrane modules (Foo et al., 2023; Lin et al., 2021). However, one of the main issues with including spacers in a membrane channel is the increased pressure loss. Despite this, it is expected that the additional pressure drop has no significant consequences on the membrane performance because of the relatively small pressure drop (of the order of kPa) compared to the inlet pressure, i.e., an inlet pressure in the range of several MPa (Alkhamis et al., 2015). Therefore, the performance of membrane module should

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