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Cross-flow structured packing for the process intensification of post-combustion carbon dioxide capture

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HIGHLIGHTS

- A cross-flow cell of structured packing is inspected for carbon capture.
- Pressure drop and flow repartition are investigated numerically.
- The onset of flooding is shown to be delayed by tilting the cell.

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ABSTRACT

We introduce novel insights into a cross-flow arrangement of structured packings specifically for post-combustion carbon dioxide capture. Gas-liquid dynamics are investigated numerically, with the liquid flowing under the action of the gravity and the gas driven by a horizontal pressure gradient crossing the liquid phase. An elementary packing cell consists of two connected channels: one depicting a co-current gas-liquid flow and the other depicting a counter-current two-phase flow. While flow reversal of the liquid phase can occur in the counter-flow channel at high gas flow rates, the overall flooding point is significantly delayed in comparison to a counter-current flow arrangement traditionally used for structured packings. Varying the gas flow rate and the tilting angle of the elementary cell, a detailed numerical analysis of the flow repartition between channels, the pressure drop, the gas and liquid velocities, and the onset of flooding is presented. The pressure drop is found to be smaller when tilting the cell with respect to the initial scenario at 45°. Flow reversal instead is delayed when lowering the tilting angle, that is when the cell is tilted anti-clockwise. We also reveal the presence of long waves at the edge of the cell at low tilting angles. Finally, data of the wet pressure drop in the cross-flow cell are compared with different commercially available types of packing arranged in a conventional vertical counter-flow configuration, such as several versions of the Sulzer Mellapak™.

1. Introduction

Gas-liquid flows play a fundamental role in many chemical unit operations, such as the carbon dioxide absorption and distillation columns. To enhance gas-liquid contact, common column internals used are structured packings. These optimised geometric structures, made of textured metal sheets to maximise interfacial contact area between a gas phase and a liquid phase, spread the liquid phase as a thin film to extend residence time and allow mass transfer and chemical reactions to complete. The resulting flow occurring in the alignment of these packings is a counter-current flow. Here, a gravity-driven falling liquid film flows downwards along the packing walls in the presence of an upward flowing gas at a constant pressure gradient (driven from the bottom of the column). A typical application being removal of CO_2 from flue-gas using an amine solution in an absorption column.

Any such gas-liquid configuration is inherently unstable and the primary instability is manifested as interfacial waves (Craik, 1966; Yih, 1967). The primary source of the instability is the so-called interfacial mode driven by viscosity contrast between the phases (Boomkamp and Miesen, 1996). Here, the instability kicks off as an infinitesimally small wave, growing exponentially (by virtue of a linear instability) in amplitude both in time and space

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(Lavalle et al., 2017; Schmidt et al., 2016; Tilley et al., 1994; Valluri et al., 2010; Vellingiri et al., 2015). At large amplitudes, growth tends to be non-linear, with energies derived from the inertia of both the phases (the shear modes) in addition to the interfacial mode. This causes the waves to be distorted, leading to formation of ligaments that tend to break-off into droplets carried by the upward gas current. Interfacial waves of this kind play an important role towards enhancing available exchange area, which is crucial for mass and heat transfer (Henstock and Hanratty, 1979; McCready and Hanratty, 1985). However, any counter-current gas-liquid flow is limited by its practical operability. Specifically, at high gas loads, flow reversal occurs in the liquid phase, resulting in the column being flooded by the liquid. This event is called flooding and is characterised by high pressure drops. Therefore, it is common practice in the industry to run the absorption column below the flooding onset point, in order to get the best fruition of the mass transfer at smaller pressure drops. Nevertheless, at the same transfer efficiency, one would delay the flooding onset in order to reduce size and cost of these equipments.

The flow in structured packing has been the subject of many experimental and numerical studies in the past. The experimental works have focussed either on the analysis of performances of novel structured packings (Olujić et al., 2003; Bessou et al., 2010), or the influence of the liquid physical properties on the wetted area (Nicolaiewsky et al., 1999; Bradtmöller et al., 2015); further experimental works have been also performed to measure the liquid spreading in structured packings (Aferka et al., 2011; Fourati et al., 2012). Recently, Computational Fluid Dynamics (CFD) has become an effective tool to complement the experimental works, although the computational cost might still be too expensive for the analysis of complex geometries such as the entire column. Raynal and Royon-Lebeaud (2007) have developed an approach where two-dimensional gas-liquid CFD results are used as basis for three-dimensional one-phase simulations involving the whole column geometry. Subsequently, Fernandes et al. (2009) have performed CFD simulations of a pseudo single-phase model aiming to study the wet pressure drop inside the Sulzer EX structured gauze packing. Several studies have also focussed on the inspection of flow pattern, liquid hold-up and mass transfer occurring in film flows over a packing substrate (Haroun et al., 2010; Valluri et al., 2005; Xu et al., 2008); other works have aimed to characterize the three-dimensional liquid flow over a structured packing element (Ataki and Bart, 2006).

Simultaneously, many studies have investigated the flooding onset in structured packing. Beginning with the empirical method proposed by Sherwood et al. (1938), new analytical approaches have followed (Dankworth and Sundaresan, 1989; Hutton et al., 1974; Iliuta et al., 2014). Meanwhile, flooding has been extensively examined in two-dimensional liquid films sheared by laminar or turbulent gas flows by means of linear stability, Direct Numerical Simulation (DNS) and reduced-order film models (Trifonov, 2010; Tseluiko and Kalliadasis, 2011; Dietze and Ruyer-Quil, 2013; Schmidt et al., 2016; Lavalle et al., 2017; Vellingiri et al., 2015). However, these methods cannot be directly transferred to structured packings due to the flat wall geometries considered in those studies (Hutton et al., 1974).

In this article, we investigate the gas-liquid flow in a cross-flow arrangement of structured packing for post-combustion carbon capture. Post-combustion carbon capture requires removing carbon dioxide from large volumetric flow rates of combustion gas streams at close to atmospheric pressure. One way to achieve process intensification (defined here as a series of design strategies implemented to achieve drastic reductions in the size of existing processes) is to increase gas flow rates to reduce the resulting cross-sectional area and height of CO_2 absorption packed columns. In practice, the cross-sectional area could match a typical heat recovery steam generator structure of a Combined Cycle Gas Turbine or the horizontal ducting downstream of pulverised coal boiler. In this work, we show that horizontal, cross-flow packed column configurations are likely to delay, at increasing gas flow rates, the occurrence of flow reversal in the liquid phase (characterised by high pressure drops) and can be operated at higher gas velocities than conventional, vertical counter-flow configurations. Horizontal absorbers are currently used in smaller scale application in gas-air treating, and at scale for Flue Gas Desulphurisation (FGD) of combustion gases (Klingspor et al., 2002), although with liquid spray systems instead of packing material. The application to carbon capture is novel and is the focus of this article.

While in a conventional vertical packed column the gas is injected from the bottom and ejected at the top, in the cross-flow packing the gas instead flows from left to right under a horizontal pressure gradient. In both scenarios the liquid falls as a thin film driven by the gravity. While vertical counter-flow arrangements are more common, certain applications such as post-combustion CO_2 capture could present favourable characteristics for cross-flow horizontal packed columns: (i) less visual impact at the power plant level because the absorber could develop horizontally rather than vertically; (ii) the absorber could be directly integrated in the flue gas pathway with rectangular ducting.

In order to provide novel insights into the cross-flow arrangement, we present the first detailed CFD study of the gas-liquid flow within a three-dimensional elementary cell of such an alignment of structured packings, as shown in Fig. 1, where the gas flows parallel to the packing sheets. The choice of modeling one single elementary cell aims to reduce the computational cost; this issue has been already discussed by Petre et al. (2003) and Raynal et al. (2004) when simulating the dry pressure drop in structured packings. Also, Said et al. (2011) have shown that modeling the dry pressure drop within a periodic elementary cell is a good representation for the whole packing.

Our two-phase model is based on the Volume-of-Fluid (VoF) method with a Smagorinsky LES (Large Eddy Simulation) model for the turbulent terms. Validation of this transient two-phase VoF-LES model is achieved by comparing the pressure drop of the classical vertical cell under counter-current flow with previous experimental works, and with industrial data from the Sulcol 3.2

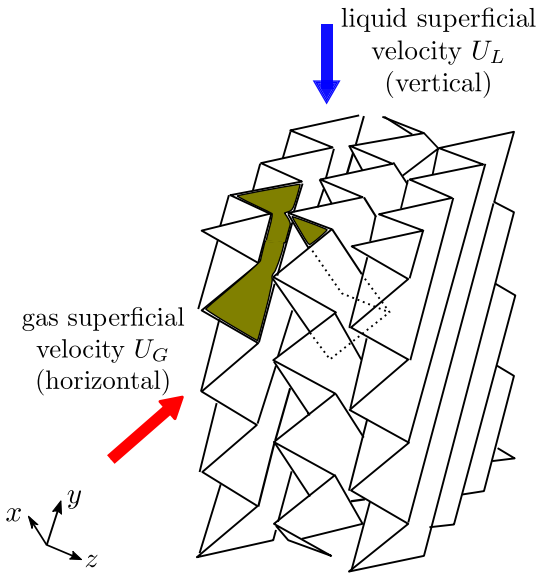

Fig. 1. Representation of the cross-flow structured packing. The highlighted and dashed area corresponds to the elementary cell considered here, and depicted in Fig. 2.