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Flooding limit in countercurrent gas–liquid structured packed beds—Prediction from a linear stability analysis of an Eulerian two-fluid model

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HIGHLIGHTS

- Modeling flooding in structured packed beds.
- Momentum balance includes phase interaction and mechanical dispersion.
- Pressure difference between phases given by capillary dispersion and gravity.
- Gravity unveiled as most dominant stabilization force.
- Mechanical and capillary dispersion have equal significance in dispersion source.

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ABSTRACT

Countercurrent flooding limits in gas–liquid structured packed bed columns were studied using a stability analysis of the solutions of a transient two-zone two-fluid hydrodynamic model around a uniform state. The model is based on the volume-average mass and momentum balance equations and the double-slit drag closures. The source terms in momentum balance equations refer to the total phase interaction and mechanical dispersion forces and the closure expression relating the gas and liquid pressures is given by capillary dispersion and gravity. The model predicts very well the flooding limits for air–water countercurrent flow through various Mellapak structured packings. The incidence on the column-limited flooding point of packing geometry (porosity and specific surface area), fluid throughputs and properties (viscosity, gas and liquid densities) and liquid spreading characteristics was discussed from the perspective of model simulated trends. Gravity was unveiled as the most important factor in the stabilization force which contributes to the attenuation of liquid waves inducing a tendency to make the flow more uniform. Its contribution was factored in using a modified capillary pressure model. Beside gravity, this formulation indicated that the stabilizing role of capillary forces could not be disregarded, particularly for lower values of the gravity scaling factor in liquid-rich regions at relatively high liquid flow rates.

1. Introduction

Packed-bed columns are the workhorse to a wide range of industrial applications where gas–liquid unit operations are essential, such as absorption, desorption, (reactive) distillation and rectification (Strigle, 1994; Dudukovic et al., 1999; Ellenberger and Krishna, 1999; Malone and Doherty, 2000). Despite its long R&D history, the market of internals for developing highly-efficient packings is constantly pressured in the quest of cost-effective units (e.g., good mass transfer efficiency, low pressure drop, and high capacity) capable of meeting ever stringent product specifications and discharge limits. To manage with the constantly growing restriction in cost-efficiency trade-off of packed-bed columns, researchers and manufacturers have studied and developed new types of column internals. As shown in Raynal et al. (2013), almost 50% of the investments costs of a MEA based CO_2 capture process are due to the packed columns, which designs have to be optimized. Structured packings, e.g., corrugated packings of regular type, have received the greatest attention due to their superior performance in terms of pressure drop per theoretical stage to

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achieve high-separation efficiency, reduction in energy dissipation, and improvement in loading capacity at the expense of repelling farther the packing flooding limit (Billet, 1995; Brunazzi and Paglianti, 1997).

Flow patterns in structured packed-bed columns significantly influence their performance through characteristics such as phase holdups, pressure drop and mass transfer rate. Therefore understanding the nature and characteristics of the hydrodynamics in structured packed-bed columns has been a subject of long-standing interest. Accurate prediction of the onset of flooding is of key importance in this regard. The phenomenon of flooding is of considerable technological importance in countercurrent two-phase flow as only its avoidance in a packed-bed column can prevent this latter's dysfunctional operation (Dankworth and Sundaresan, 1989). The onset of flooding can be defined as the maximum flow rate at which one phase can flow counter-currently with respect to the other. Any further increase beyond that maximum will then result in liquid accumulation atop of the bed signaling the column has reached a state of flooding. The flooding point is spotted there by noting the maximum permissible gas and liquid loads per unit area of column cross-section. From experimental observations, and as can be seen from Fig. 1, flooding appearance is linked to a hydrodynamic instability corresponding to a transition from a falling film regime to a bubbly flow regime associated to an important increase of liquid holdup. The impression of a blurred picture at the middle of the picture of Fig. 1b corresponds to the onset of bubbling, which cannot be seen when operating conditions are such that no flooding occurs. The interfacial mass-transfer characteristics of the column significantly improve in the proximity of the flooding point. However, operation of a packed countercurrent column near pre-flooding is risky task as the near-flooding hydrodynamics is unstable and transients as dynamics are little understood.

The onset of flooding in packed-bed columns has been described by several empirical and theoretical flooding models. The former one includes the well-recognized generalized pressure drop correlation method by Sherwood et al. (1938) and improved largely by Eckert (1966, 1970), Kessler and Wankat (1988) and Leva (1992). Model-based approaches utilize various concepts of flow pattern and packed bed structure (Hutton et al., 1974; Mackowiak, 1990; Billet and Schultes, 1991, 1995; Dankworth and Sundaresan, 1989). Dankworth and Sundaresan (1989) developed a transient two-fluid model based on volume-average mass and momentum balance equations for the countercurrent gas–liquid flow in random packed-bed columns. The onset of flooding was estimated from stability analysis of the model solution around an equilibrium state. Loss of stability of the uniform state was interpreted in terms of a balance between inertial forces, destabilizing by nature, and capillary forces to counteract this destabilizing effect. When flow channels get large, as in the case of high-porosity and large-packing sizes commonly used in industrial-packed columns, capillary forces, as Young–Laplace equation would foretell, tend to dwarf vis-à-vis inertial forces and thus instabilities emerge. As a consequence, the model developed by Dankworth and Sundaresan (1989) precludes the existence of a stable uniform state for high-porosity and large-packing sizes, which for the context of interest to industry, reflects in an inability to predict the onset of flooding. This would suggest that mechanisms other than those dependent on capillary forces should emerge to counteract the destabilizing inertial forces (Wilhite et al., 2005). Another reason why the model predicts the absence of a stable uniform state in high-porosity packed-bed columns can be the assumption of a uniform flow laterally as required by one-dimensional model formulations. Such supposition may become invalid when the uniform axial solutions are unstable and the resulting flow could easily be two- or three-dimensional, depending on whether stable, laterally-non-uniform flow is possible (Dankworth and Sundaresan, 1989). Additionally, non-uniformity in the flow can produce macroscopic velocity and holdup gradients in the axial and transverse direction which yields viscous and pseudo-turbulence stress terms in the momentum balance equations.

It appears therefore opportune to keep ameliorating and enriching hydrodynamic models dedicated to the prediction of flooding transition in countercurrent gas–liquid packed-bed columns with high-porosity and large packings for better description of alternate mechanisms needed to counteract the inertial forces. The present work is proposed to fill in the gap by developing a new model for predicting the flooding limit of gas–liquid structured packed-bed columns. Flooding point is inferred using a stability analysis of the solutions of a new transient two-zone two-fluid model around the uniform state. In the two-fluid momentum balance equations, source terms refer to total phase interaction and mechanical dispersion forces. The phase interaction forces were evaluated using the model developed by Iliuta et al. (2004) based on the double-slit model approximation. The mechanical dispersion forces were estimated by multiplying the drift velocity and an appropriate momentum exchange coefficient (Lappalainen et al., 2009). The closure for the pressure difference between the phases was given by capillary dispersion and gravity (Wilhite et al., 2005).

2. Modeling of onset of flooding in structured packed beds

The onset of flooding in structured packed bed was determined from a stability analysis of the solutions of a transient two-zone two-fluid model around the uniform state. In order to analyze the stability characteristics, infinitesimal perturbations around the

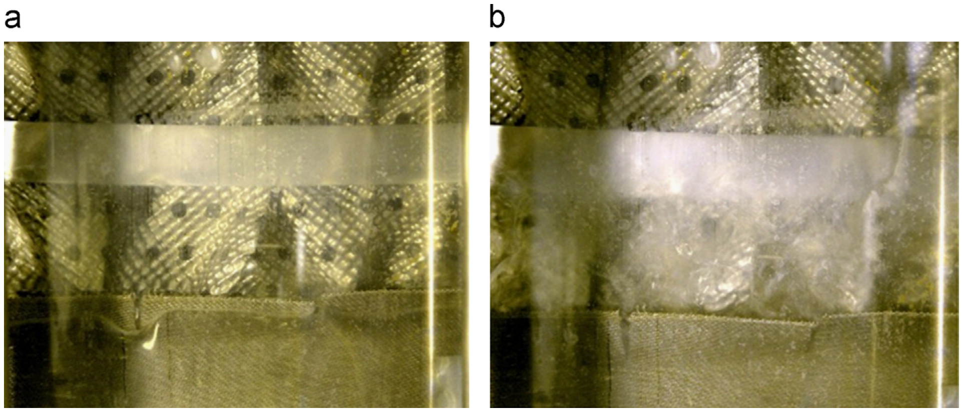

Fig. 1. Pictures of the flow within a structured packing for operating conditions close to the flooding limit: (a) just below flooding and (b) at flooding.