



Hydrodynamics of countercurrent gas–liquid flow in inclined packed beds – A prospect for stretching flooding capacity with small packings

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HIGHLIGHTS

- Column obliquity for delaying flooding in countercurrent packed bed is explored.
- Gas–liquid segregation induced by bed tilting is attenuated in pulse flow regime.
- Flooding capacity is sensitive to emplacement of liquid-feed nozzles.
- Lesser pressure drop and liquid saturation are achievable than in vertical packed bed.

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ABSTRACT

Hydrodynamics of the *inclined* bed, which was randomly packed with small packings, was subject to gas–liquid countercurrent flow for different column inclination angles (0–20° from vertical position) and liquid-feed nozzle positions, while sweeping fluid throughputs ranged to encompass trickling flow up to the flooding point, was studied using electrical capacitance tomography. The embedded and overhead nozzles behaved differently with respect to the attainment of the flooding point. In the case of the overhead nozzle, pressure drop and liquid saturation increased with gas and liquid throughputs though leading to considerably widened flooding capacity as the column shifted from verticality. Decreasing pressure gradients and liquid saturations were measured with gradually slanting column axis at the expense of liquid maldistribution inside the bed. The latter effect was the consequence of gas–liquid segregation that accompanied liquid accumulation near the bottommost column wall. One distinction of this flow structure was a peculiar stratified pulse flow regime, which was observed as a prelude to flooding in tilted beds. The inception of this flow regime, stimulated by gas–liquid interactions in the gas-rich upper region, was a function of gas and liquid flow rates. Bed-obliquity, which delayed flooding in this particular flow regime, is regarded as a potential method in prospective catalytic processes that are to be carried out in the countercurrent packed beds which contain small packings.

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1. Introduction

Among the three realizable gas–liquid contacting modes, which are usually dealt with in the operation of fixed bed units, namely, cocurrent downward (trickle beds), cocurrent upward (packed bubble columns) and countercurrent (packed towers) modes, the last mode is ubiquitous and is well-established in industrial processes such as (non-)reactive/(non-)catalytic distillations and gas scrubbing (Ellenberger and Krishna, 1999; Dudukovic et al., 2002;

Kolev, 2006) in addition to being prospectively foreseen as a game-changing device in petroleum refining operations (Trambouze, 1990; Ojeda et al., 2002). There are many appealing characteristics for this contacting mode, which include the ability to maximize the driving force for the gas–liquid mass transfer, to aid in selective removal of by-products or inhibitors and to markedly reduce utilization of catalyst, such as in hydro-desulfurization (Trambouze, 1990; Bertucco and Vetto, 2002; Piché et al., 2001, 2005; Larachi et al., 2012).

A major drawback of the countercurrent operation is the occurrence of flooding, especially when the relatively small packing internals, the size of which is dictated by the mass transfer

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considerations, prevent increased fluid throughputs, thus, ruining possibilities for large-scale processing. For decades, considering the huge stakes at play, prevention of flooding is considered to be the Holy Grail, with numerous proposed strategies. The use of extra-void space in the setting to prevent flooding and to enlarge the flooding capacity in the countercurrent trickle bed was advocated in some studies (Breijer et al., 2008). Other studies proposed the replacement of random packings with structured (Bart and Landschutzer, 1996; Ellenberger and Krishna, 1999; Breijer et al., 2008) or solid foam packings (Banhart, 2001; Fourie and Plessis, 2002; Stemmet et al., 2005) to push the flooding limits towards much higher throughputs in countercurrent mode. In addition, a homogeneous liquid distribution of gas–liquid countercurrent flows in structured packings was achievable up to a high level as determined by Roy et al. (2004) in their tomographic studies. Other investigators, instead of focusing on designing internals with more adapted geometry, explored radial fluid flows in porous media, which were subjected to macro-gravity conditions that resulted from centrifugal fields, to retard inception of flooding. An offshoot of these efforts is the well-known HiGee rotating packed bed contactor (Ramshaw, 1983).

Thus, there is room for developing alternative approaches with innovative configurations. These approaches need to be easy to implement and provide advantages over existing configurations. The conventional counter-current packed beds operate in the vertical position. With the stipulation of a good design of distributors, the liquid and gas phases evenly coexist over the whole bed cross-section. It is speculated that tilting the vessel induces partial segregation of gas and liquid due to gravity. This results in the enlargement of flooding capacity of the packed bed and eventually outweighs the disadvantages of gas–liquid segregation.

Atta et al. (2010) and Schubert et al. (2010) were the first to describe experimentally and through numerical simulations the hydrodynamics in inclined cocurrent trickle beds. The dependence of segregation in two-phase gas–liquid descending flows and tilt angle was investigated using electrical capacitance tomography. Significant flow behavior alterations, such as phase stratification, liquid saturation reduction as well as two-phase pressure drop, were observed with the tilt angle increase. In addition, these studies revealed qualitative changes in pulse flow regime characteristics, such as pulse frequency and propagation velocity, compared with their vertical analogs. More recently, the hydrodynamics of two-phase gas–liquid ascending flows in inclined packed beds was studied (Bouteldja et al., 2013). The segregation between gas and liquid was observed similar to inclined trickle beds. The change of inception of the transition from the bubble flow regime to segregated flow regime was monitored as a function of the bed tilt angle. The observed segregation led to reduced gas–liquid interactions and thus pressure drop. Other types of inclined multiphase reactors were investigated in the literature. Specifically, the effect of inclination on flow regimes and recirculation patterns in the gas–solid and liquid–solid inclined fluidized beds was the subject of several investigations. Flow regimes and their transitions were characterized for air fluidized beds inclined between 45° and 90° angles, and the inventory of which consisted of different types of powders (O'Dea et al., 1990). For cohesive powders, fluidization heterogeneity was demonstrated to be a major shortcoming of bed inclination, whereby the upper wall was identified as the region of high gas velocity that prematurely prompted localized transition to the bubbling regime (Valverde et al., 2008). Sarkar et al. (1991) studied the effects of connecting pipe length and diameter, its inclination and fluid velocity on the solids flow rate from the fluidized bed to the receiving vessel. In the case of inclined liquid–solid and three-phase fluidized beds, the small inclination angles translated into measurable effects on the solids recirculation pattern and reactor performances (Del

Pozo et al., 1992; Hudson et al., 1996), while the coverage of a broader angular range (Yakubov et al., 2007), from horizontal to vertical, highlighted a strong correlation between bed expansion and tilt angle.

To our knowledge, vessel obliquity as a method to delay flooding inception in countercurrent packed beds has been overlooked in the literature. If the idea proves worthwhile, it will trigger interest in prospective applications of countercurrent packed beds that contain small packing internals for catalytic reactions due to delayed flooding and ensuing enlarged reactor capacity. Remarkably, the brief abovementioned literature survey, which spotlighted hydrodynamic studies for inclined multiphase systems, reveals a lack of investigations devoted to observing behavior of countercurrent flows in inclined packed columns. The knowledge of basic hydrodynamics for the gas–liquid contacting mode opens up a window of opportunities. Therefore, the objective of this study is to scrutinize key hydrodynamic characteristics of gas–liquid countercurrent flow in inclined packed beds (i.e., pressure drop, local and average liquid saturation, flooding capacity, liquid maldistribution, fluid flow morphology, foam inception and pulse formation) as a function of gas and liquid superficial velocities and nozzle liquid-feed modalities. A non-invasive electrical capacitance tomography imaging technique is used to observe liquid distribution as a function of column inclination. The hydrodynamic response to different liquid feed positions is examined to identify appropriate overhead and embedded locations for installing spray nozzles with countercurrent flow in both vertical and inclined columns.

2. Experimental

2.1. Components of the packed bed/ECT/inclined assembly

The hydrodynamic experiments were conducted using air and kerosene at atmospheric pressure and room temperature in an inclined gas–liquid counter-current packed bed (Fig. 1). The fluid properties, operating ranges, internal and column specifications are summarized in Table 1. Kerosene was distributed using a wide-angle full-cone spray nozzle (model # FL-5VS), which was either buried a few cm deep in upper portion of the bed (embedded) or located a few cm overhead. A Plexiglas cylindrical column (internal diameter of 0.057 m) was packed with 6 mm × 6 mm plastic Raschig rings up to 1.4-m height for the overhead nozzle position and 1.43 m for the embedded nozzle. In both instances, the nozzles were aligned centrally with respect to the column revolution axis. Due to the column-particle diameter ratio ≈ 10 , wall effects are expected on some measured hydrodynamic variables. However, even if this ratio is smaller than the ratio typically met for two-phase flow in packed beds, the scope on the specific observations would remain qualitatively valid. The column was placed on a rotatable structure that allowed inclinations between $\theta = 0$ and $20 \pm 1^\circ$ (with respect to vertical position) to be tested. However, the pendular structure was designed to allow bed inclinations up to 50°. A Teflon-metal device tightly fitted at the bottom of the column, shown in Fig. 1 inset, performed a dual function (gas distribution and liquid removal). The device consisted of 22 regularly spaced 0.4-mm-diameter gas-feeding needles, which protruded ca. 10 mm deep inside the lower bed section. The needles were welded in a hair-like manner on a cylindrical cavity through a perforated metallic disk with 9 holes (each hole was 1-mm in diameter), the purpose of which was to ensure a smooth gas–liquid crisscrossing and liquid evacuation. Prior to the countercurrent experiment initiation, the bed was pre-wetted by applying a high throughput of fluids for 30 min according to Kan and Greenfield (1978) pre-wetting method bringing the bed first

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