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Liquid drainage in inclined packed beds—Accelerating liquid draining time via column tilt

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ABSTRACT

The dynamics of liquid drainage in inclined packed beds was studied experimentally using electrical capacitance tomography. The evolution of textural flow regimes and liquid saturation profiles were monitored as a function of bed tilt angle and bed height. Film and droplet textural regimes were discriminated during bed drainage tests. They consisted of a rapid step discharging, virtually at constant flow rate, ca. 80% of the poral dynamic liquid followed by as lower step of partially-saturated pores discharging the remaining 20%. The drainage time was markedly reduced upon tilting the column resulting ultimately in virtually bed-length independent drainage times. Bed inclination reduced the droplet paths to the vessel wall, stimulating migration and coalescence of liquid droplets towards the lower mostarea of the column cross-section. This ensured sufficient hydraulic pressure nearby the high-porosity wall area to maintain enhanced liquid outflows. As a prospective process intensification artifice, inclining packed beds way exhibit superior advantage in stimulating drainage of tall vessels especially if emergency circumstances arise.

1. Introduction

In comparison with classical flows through vertical porous media, the flow of fluids in inclined porous media has indisputably been the poor sibling which thus far has received less attention in the literature. Applications where flows of such type abound include drilling and pumping during oil recovery and geothermal engineering applications, marine oil fields where inclined wells are drilled from a single platform towards different directions, and non-vertical flows of natural gas and crude oil from geological formations with high-permeability inclined fractures [1]. Furthermore, the industry of fossil-fuel offshore extraction and processing is also increasingly interested on this particular type of flows where the hydrodynamic behavior of floating reactors and separators on embarked ships such as floating production, storage and offloading systems is a crucial aspect of their design [2].

Use of inclined gas–liquid packed beds as cold-flow models to gauge the divergences in hydrodynamics with respect to vertical beds has been the subject of very few studies. Atta et al. [3] and Schubert et al. [4] were the first to describe experimentally and numerically the hydrodynamics of inclined trickle beds. Their studies demonstrated the strong correlation between phase segregation in gas–liquid descending flows and vessel tilt angle. Reduction in liquid saturation and two-phase pressure drop was observed with an increase in tilt angle. More recently, the hydrodynamics of two-phase gas–liquid descending flows in inclined rotating tubular fixed beds was also investigated by Härting et al. [5]. Four different flow regimes, namely, stratified, sickle, annular and dispersed flows were identified. These studies also revealed that as long as inclined rotating fixed beds operate either in stratified or sickle flows, the pressure drop was lower compared to vertical trickle beds. Similarly, the hydrodynamics of gas–liquid ascending flows in inclined packed beds was also studied [6]. The same segregation between gas and liquid was observed as in inclined trickle beds resulting into reduced pressure drops.

Gravity-driven drainage is an important operation in various industrial fields [7]. This operation consists in clearing the free-draining extra-granular poral liquid present in the packed bed aided by mere gravitational effects. For instance, despite being costly, this step is crucial in cleanup and maintenance of acid mine drainage to meet the regulated effluent limits [8,9]. Likewise, acid-base reactions of alkaline solids with acidic solutions or biological acid main drainage with sulfate-reducing bacteria are further examples where the liquid drainage dynamics is an important subject of study [8,10].

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Gravity-driven drainage in inclined packed beds is identified as a further step in our investigations. There is in our opinion room for alternative approaches with innovative configurations that must be researched. Such approaches need to be easily implemented while potentially bringing some advantages over existing configurations. Conventional packed beds operate in vertical position; with the stipulation of a good design of distributors, fluid phases usually flow evenly over the entire bed cross-section. It is speculated that tilting the vessel could induce, due to the gravitational force, lateral displacements in addition to the streamwise drainage flow along the column. The resultant would be to alter the textural properties of the draining liquid to an extent to eventually highlight a prospective usefulness of inclining packed beds.

The study of drainage dynamics in porous media is a very classical problem in reservoir engineering, hydrogeology, fuel cells though often concerned with low-porosity or very small (submillimeter) grains [11]. In absence of pressure gradients, the only driving force for drainage is gravity. It is sufficiently important in medium-to-high porosity beds and coarse particles to induce an outflow such as for the packed bed systems which are of interest to us here. During the drainage process, the resisting drag forces manifest themselves in the form of viscous and inertial dissipations in terms of relative (linear and quadratic) velocity of liquid with respect to the packing. Concomitantly and upon inception of partially saturated pores in the bed, interfacial forces arise and start acting in concert with the drag forces to oppose liquid drainage. Governing the distribution of interfaces in the porous medium, these capillary forces are responsible for the residual or static (or capillary) liquid holdup which is retained, after the outflow dies out, mainly in the form of pendular menisci nearby the throats or constrictions [12].

Liquid drainage behavior in vertical packed beds was investigated experimentally and through modeling by Urrutia et al. [13], and very recently by Hamidipour and Larachi [14] and Ilankoon and Neethling [15]. Unlike the study by Urrutia et al. of an initially partially-saturated two-phase flow, the two latter studies considered an initially full bed with still liquid in their gravity-driven drainage tests. The effect of bed porosity and particle size on the transient free-draining liquid saturation was investigated by Hamidipour and Larachi. They highlighted the reduction in drag force between liquid and packing when particle size was increased resulting in faster draining sequences. These authors also identified the role of wall area in easing liquid drainage due to the higher local porosity depending on column-particle diameter ratio. Particle sizes including porous and non-porous particles were studied by Ilankoon and Neethling. They demonstrated the strong correlation between gravity and behavior of liquid held in the extra-granular void while the intra porous liquid was governed by capillary effects.

To the best of these authors' knowledge, vessel obliquity as an artifice to control drainage time in packed beds has hitherto been overlooked in the literature. Remarkably, the brief literature survey above in spotlighting the studies relevant to packed beds reveals a total absence of investigations devoted to the observation of the drainage behavior in inclined packed columns. Therefore, the objective of this study is to scrutinize some key characteristics of liquid drainage in inclined packed beds such as local and average liquid saturation, textural morphology, drainage velocity and rate, and liquid distribution as a function of bed tilt angle and bed height. Use is made of a non-invasive electrical capacitance tomography imaging technique to observe liquid distribution as a function of column inclination.

2. Experimental

The experimental set-up built to investigate the effect of packed bed obliquity on liquid drainage is illustrated in Fig. 1. Its main part

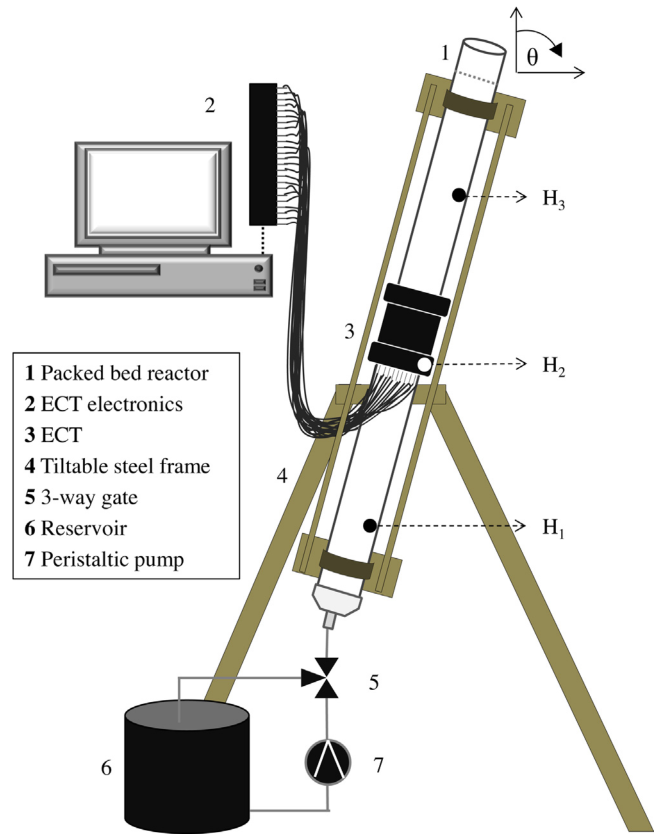

Fig. 1. Layout and components of the packed bed/ECT/inclined assembly.

consists of a 5.7 cm inner-diameter and 150 cm high Plexiglas column packed with glass beads (d = 3 mm, ε = 0.395). The bed was positioned on a steel pendulum-like frame which can be tilted in the full angular range from horizontal to vertical position. Bed drainage was performed under various inclined positions by varying the inclination angle in small increments of 5° in the range of 0° (vertical) to 25° with an angular accuracy of 0.1°. To prevent motion of the uppermost layer particles while assigning slanted positions to the bed, the glass beads were firmly immobilized using a stainless steel grid inserted from the top. Kerosene was used as a liquid phase which was circulated upwardly by means of a peristaltic pump from a reservoir to ensure that complete flooding of the bed interstices was achieved. Prior to initiating the drainage phase, the column was pre-wetted then filled with kerosene until bed heights up of 150 cm. After the liquid supply was cut off and the column was paused for ca. 3 min, the liquid was allowed to drain freely from the bed back to the reservoir via gravity upon re-opening a 3-way gate located beneath the column. The experimental conditions and the physical properties of kerosene are summarized in Table 1.

Table 1
Packed bed and liquid properties.

Property	Value/range
Size of glass spheres (mm)	3
Bed porosity (-)	0.395
Maximum bed length (m)	1.5
Columninner diameter (mm)	57
Inclination angle (°)	0–25
Kerosene density (kg/m^3)	789
Kerosene viscosity (mPa s)	1.05
Kerosene surface tension (mN/m)	25.3