Chemical Engineering Science 116 (2014) 398–405

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

Transient liquid holdup and drainage variations in gravity dominated non-porous and porous packed beds

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HIGHLIGHTS

- Dynamics of liquid motion in packed beds of porous and non-porous particles.
- Simple model that is able to predict the liquid dynamics in a packed bed or heap.
- Model accounts for influence of particle porosity.

ARTICLE INFO

Article history:
Received 13 November 2013
Received in revised form
8 May 2014
Accepted 11 May 2014
Available online 17 May 2014

Keywords:
Heap leaching
Liquid drainage
Modelling
Transient liquid holdup
Trickle bed reactors

ABSTRACT

Transient liquid holdup effects are a crucial aspect of the behaviour of many unsaturated packed beds systems. This study examined both a model system consisting of spherical glass beads and a system containing slightly porous (about 5% water accessible porosity) rock particles. Experiments on different column heights show that the initial wetting front moving through the packed bed takes the form of a soliton or standing wave.

The final drainage of the bed when the liquid addition is turned off shows slightly more complex behaviour than that of the initial wetting of the bed. It was demonstrated that if the behaviour of the liquid held around the particles is separated from that held within the particles, the same relatively simple model can be used to describe the drainage of both the model glass bead system and the slightly porous ore system despite the apparent differences in their behaviour, such as a much longer time to achieve the steady state, and a markedly different shape to the initial overall saturation versus time curve.

This simple model assumed that for the liquid between the particles, gravity was the dominant force and that capillarity could be neglected. Neglecting capillarity probably accounts for the slight discrepancy between the experimental and simulated liquid holdup results in the porous ore system at intermediate drainage times.

1. Introduction

The behaviour of unsaturated gravity driven flow of liquid through packed beds of particles is important to a number of different processes ranging from trickle bed reactors (TBRs) to heap leaching.

A trickle bed reactor is a two phase system (liquid and gas) in which fluids usually flow co-currently through a fixed bed of typically porous catalysts or reactant solids (Luciani et al., 2002). The unsteady state operation of TBRs by periodically modulating the liquid or gas supply leads to transient fluid flow characteristics (Khadilkar et al., 1999; Lange et al., 2004; Ayude et al., 2007), which have been reported to increase the reactor performance compared with the steady state flow behaviour (Haure et al., 1989; Lange et al., 1994, 2004; Castellari and Haure, 1995; Tukac et al., 2007).

Heap leaching is another system in which the unsaturated flow behaviour of the liquid through a bed of particles is a crucial aspect of the performance of the system, though they have significant differences compared to trickle bed reactors in terms of the scale and flow rates used (Roman and Bhappu, 1993). This mineral processing technique is used for extraction of base and precious metals from low grade ores by running a leaching solution through an unsaturated bed of ore particles. In heaps, irrigation strategies with alternating solution application periods followed by much longer rest periods have been demonstrated to have the potential to increase the heap performance (Bartlett, 1992).

In this paper the transient variations in the liquid content as the liquid addition rate is varied are studied. In particular the

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http://dx.doi.org/10.1016/j.ces.2014.05.017
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behaviour at relatively low flow rates, when the bed is in the trickle flow or low interaction regime giving droplet and rivulet flow features, is studied. Packed beds consisting of non-porous glass beads as well as slightly porous (approximately 5% porosity) ore particles (a copper ore) are studied in order to ascertain how porosity of the particles affects the behaviour.

Most previous studies in both leaching columns and trickle bed reactors have concentrated on the steady state relationship between the liquid addition rate and liquid holdup as a function of various bed and operating parameters (e.g. Yusuf, 1984; Fu and Tan, 1996; Nemec et al., 2001; de Andrade Lima, 2006). While there have been some previous studies into the transient behaviour of these systems (Standish, 1968; Bartlett, 1992; Tukac et al., 2007; Liu et al., 2008, 2009), the descriptions of the behaviour have typically been qualitative in nature, while the aim of this paper is to develop and validate a model that can describe the transient behaviour of these systems while including the effects of both porosity and the hysteresis observed in these systems.

2. Experimental design

In this study the liquid holdup measurements were performed gravimetrically using a high precision load cell. The gravimetric measurements were compared to an independent measurement based on the volume of drained liquid to obtain uncertainty in the measured holdup values and to verify that the load cell was able to measure the relatively small changes in liquid holdup needed in this work (see Ilankoon and Neethling (2012), for the method and results). It was found out that both methods give virtually identical results thus providing confidence in the load cell based measurements (Ilankoon and Neethling, 2012, 2013).

The column used is Perspex and has an internal diameter of 243 mm. 3 different column heights were used in the study, namely 300, 500 and 800 mm. A detailed description of the experimental setup including photographs can be found in Ilankoon (2012) and Ilankoon and Neethling (2012, 2013).

Mono-dispersed glass spheres of 10 mm and 14 mm were used for the model non-porous system whereas the slightly porous particle system consisted of 8–11.2 mm copper ore particles (average water accessible porosity of 5%) collected from Kennecott Utah Bingham Canyon Mine. The ore particle properties are described in more detail in Ilankoon and Neethling (2013). The experimentally determined average voidage values for the non-porous and porous systems were about 40% and 35% respectively. For the ore system this is the external voidage excluding the porosity of the particles, which was about 5%.

Using a novel liquid distributor that allowed even liquid addition over the entire bed surface even at the very low flow rates used (Ilankoon, 2012; Ilankoon and Neethling, 2012), the applied liquid flow rates were 1.26, 2.52, 5.04, 10.08 and 20.16 L/h and the corresponding superficial flow were within the range of 0.0075–0.12 mm/s. Deionised water was used as the liquid for all the experiments in this work.

3. Transients during initial liquid addition

The packed column, which was initially dry, was suspended via a load cell to gravimetrically measure the weight of liquid within the column. In addition, a measuring beaker was kept on top a high precision electronic balance in order to continuously measure the drained liquid weight (see Fig. 1). These independent measures of the liquid behaviour within the column were obtained every second until steady state was reached in order to obtain the wetting front movement. Steady state was indicated by a constant load cell reading over a number of minutes. In addition, the wetting of the columns was filmed through the Perspex walls of the column.

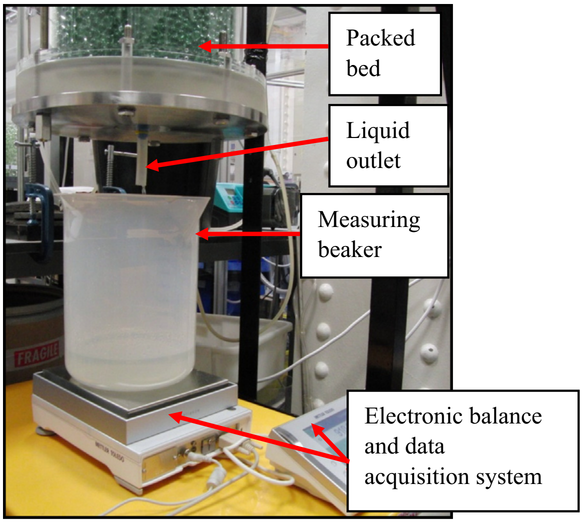

Fig. 1. Experimental setup to measure wetting front movement in the model system.

The liquid within the packed bed moves under the influence of both gravitational and capillary/dispersive effects. If the flow is completely dominated by gravity, a sharp wetting front can be expected, while capillary/dispersive will act to spread out the wetting front. The reason why gravity sharpens the front is that the gravity driven flow rate increases with increasing liquid content. This means that excluding the capillary and dispersive effects, any liquid ahead of the front will be travelling slower than the front and thus will be caught up by the front.

If the gravity effect is strong enough, then the sharpening effect of gravity and the spreading effect of capillarity and other dispersive phenomena will be able to reach an equilibrium that will manifest itself as a standing wave, or soliton, moving through the bed.

Assuming that the particle bed is uniform in its properties in both the vertical and horizontal directions, once established, the shape and velocity of a soliton moving through the bed should be independent of the position of the soliton within the bed. The existence of a soliton moving through the bed can thus be investigated by examining the liquid flow out of the system as a function of time for different bed heights.

If the liquid is moving through the system as a wetting front there will be an initial time period in which liquid does not drain out of the packed bed followed by a rapid transition region towards a uniform drainage rate (linear increase in drained liquid). If there is a standing wave then, in different column heights, the breakthrough time would change, but the shape of the transition region would be the same.

Fig. 2a (10 mm glass spheres) and Fig. 3a (14 mm glass spheres) show the variation of the drained liquid weight as a function of the time (time = 0 indicates initial liquid addition) since the start of the liquid addition into the bed. All these experiments were carried out with a superficial liquid velocity of 0.0075 mm/s (1.26 L/h liquid flow rate). The liquid holdup curves for column lengths of 300 mm, 500 mm and 800 mm are shown and the breakthrough time increases with the packed bed height and decreases with the particle size for the same packed bed height. The average gradient of each line after the transition regions in Figs. 2a and 3a is 1.19 L/h, which is similar to the input liquid flow rate suggesting that the transition to steady state after the passing of the wetting front is indeed very rapid. The subtle differences in