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Investigation of pulsing flow regime transition and pulse characteristics in trickle-bed reactor by electrical resistance tomography

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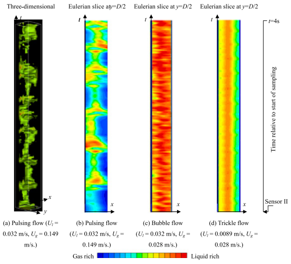
HIGHLIGHT

- Structure of liquid pulse in a lab-scale TBR was non-invasively visualized by ERT.
- Transition boundary from trickle and bubble to pulsing flow was identified.
- Effect of physical property of each phase on pulse velocity was discussed.
- Effective pulse frequency was determined based on numbers of main pulse.
- Effect of physical property of each phase on effective pulse frequency was clarified.

GRAPHICAL ABSTRACT



(a) Pulsing flow (U_l = 0.032 m/s, U_g = 0.149 m/s.)
(b) Pulsing flow (U_l = 0.032 m/s, U_g = 0.149 m/s.)
(c) Bubble flow (U_l = 0.032 m/s, U_g = 0.028 m/s.)
(d) Trickle flow (U_l = 0.0089 m/s, U_g = 0.028 m/s.)

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ABSTRACT

Electrical resistance tomography was applied to non-invasively visualize the liquid distribution in a lab scale trickle bed reactor. Based on the three-dimensional liquid distribution images (time and two-dimensional space) obtained by the ERT system, effect of the physical properties of the fluids and the packed bed, such as column size, particle diameter, gas density and liquid viscosity, on the pulsing flow regime transition and the liquid pulse structures were clarified. The liquid pulses structures were basically dominated by the small local pulses generated in the capillaries between the packed particles. Promotion of the local pulses generation makes the macro liquid pulses evident and well separated, while restriction of the local pulses generation results in the not fully developed or transient liquid pulses. Moreover, basic hydrodynamic parameters characterizing the pulsing flow, namely the liquid pulse velocity and frequency, were also quantitatively discussed. Liquid pulse velocities were calculated by the cross correlation of the conductivity variations of two ERT sensor with certain distance. The effective liquid pulse frequency which only includes the contribution of the main liquid pulse was determined by identified number of main liquid pulse from the 3D liquid distribution images provided by ERT. The measured liquid pulse velocity and frequency by ERT were then compared with the correlation models proposed in previous literatures.

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1. Introduction

Trickle bed reactor (TBR) is one of the widely used three-phase reactors in which gas and liquid flow concurrently downward through a packed bed of catalytic particles. TBR is generally involved in desulfurization, hydrogenation, oxidation, hydrotreating and waste water treatment (Dudukovic et al., 1999; Nigam and Larachi, 2005). Several flow regimes exist in TBR depending on the liquid and gas mass flow rates, the physical properties of the fluids and the packed particle bed (Ng, 1986). Basically four flow regimes can be encountered in TBR, the trickle flow regime, bubble flow regime, pulsing flow regime and spray flow regime (Gianetto et al., 1978). Most commercial reactors commonly operate in trickle flow regime in which liquid flows down the packed particle bed creating liquid films around the particles while gas flows at the remaining gap in the bed (Boelhouwer et al., 2001). However, due to the random nature of packed particle and surface tension of liquid, liquid films around particles tend to merge and flow down through the surface of particles which result in inhomogeneous distribution of liquid in spite of a perfect homogeneous liquid feed on the top of the packing. In addition, stagnant liquid is generated among the contact point of particles, and the stagnant liquid holdup represents about 10–30% of the total liquid holdup (Colombo et al., 1976).

The operation of TBR in the pulsing flow regime is well known for its advantages in terms of higher mass and heat transfer rates, complete catalyst wetting and a decrease in axial dispersion compared to trickle flow (Boelhouwer et al., 2002; Burghardt et al., 1995). Moreover, the alternating passage of liquid-rich and gas-rich pulses continuously mobilizes the stagnant liquid, and reduces the unwanted consecutive reactions to a lower level (Duduković et al., 2002; Saroha and Nigam, 1996). Understanding the nature and characteristics of the hydrodynamics in the pulsing flow regimes and the transition from trickle or bubble flow regimes are subjects of long-standing interest for design and scale-up of commercial units operated in the natural pulsing flow regime. Much information has been reported on the characteristics of pulsing flow through hydrodynamic experiments, and correlation models of the liquid pulse velocity and frequency were also developed (Bartelmus et al., 1998; Boelhouwer et al., 2002; Burghardt et al., 1999, 2004). Conductance technique is the major measurement method used in the above literatures. In this method, the local liquid holdup is estimated by the measured resistance between a pair of electrodes inside the wall of column by utilizing the difference in electrical conductivity between liquid and gas phase. However, such measurement technique mainly gives only a global view on the pulsing flow, and thus many small-scale details such as the liquid pulse structure, which actually affect the reactor performance and safety, cannot be assessed.

Therefore, considerable effort was spent in the past to introduce tomographic imaging techniques to the study of trickle reactor hydrodynamics, such as magnetic resonance imaging (MRI) (Koptyug et al., 2005; Nguyen et al., 2005), X-ray tomography (Marchot et al., 2001; Van der Merwe et al., 2007), gamma-ray tomography (Boyer et al., 2005; Schubert et al., 2008) and electrical tomography(Hamidipour et al., 2010; Reinecke and Mewes, 1997). Since MRI is limited to small vessels made of nonmagnetic materials, X-ray and gamma-ray suffer from low temporal resolution; electrical tomography technique is rather attractive to the application for pulsing flow due to its high temporal resolution, low cost and less complexity. Depending on the electrical property that is to be imaged, there is a choice between electrical resistance tomography (ERT) and electrical capacitance tomography (ECT). ECT is based on the measurement of capacitance patterns to produce permittivity images and especially fit for electrically non-conductive liquid. Wang et al. (2014) applied ECT for imaging of the pulsing flow in air-deionized water TBR with 2 mm glass beads, and successfully visualized the liquid pulse structures. However, effect of the physical properties of the fluids and the packed bed, such as the column size, particle diameter, gas density and liquid viscosity, on the flow regime transition process and the pulsing flow properties, especially the small-scale local details like liquid pulse structure, has not been clearly addressed. Moreover, in some application of TBR like the water treatment process, ERT is better suited due to the high conductivity of liquid phase such as the sea water used in the present study (Dickin and Wang, 1996).

In the present work, due to quite distinct difference between the conductivity of gas and liquid phase used in the experiment, ERT is applied. Through appropriate sensor's calibration, the conductivity distribution in the sensed cross-section of TBR is obtained without disturbing the flow, and then converted into the real-time liquid holdup distribution. Effects of column size, particle diameter, gas density and liquid viscosity on pulsing flow regime transition are clarified on the basis of the visualization results from ERT. The hydrodynamics properties of pulsing flow involving the liquid pulse structure, liquid pulse velocity and liquid pulse frequency are also discussed and quantitatively evaluated by the correlation proposed in a previous literature.

2. Experimental setup

2.1. Electrical resistance tomography

The methodology of electrical resistance tomography (ERT) is to detect the higher and/or lower conductivity objects in the conductive bulk phase by change in measured voltage. In order to obtain the cross-sectional conductivity distribution, two major processes should be carried out. One is voltage measurements and the other is to construct the tomographic image which represents the conductivity distribution in the cross-section. Schematic diagram of voltage measurements strategy of ERT is shown in Fig. 1. In ERT, a constant current is injected into a pair of adjacent electrodes arranged on boundary of measurement target. And the potential difference between all remaining pairs of electrodes is measured. The current injection electrode pairs are then switched to next adjacent electrode pair, and measurements are carried out between other remaining electrode pairs. This measurement strategy provides one set of measured voltage for one image. This type of measurement philosophy is guided by the

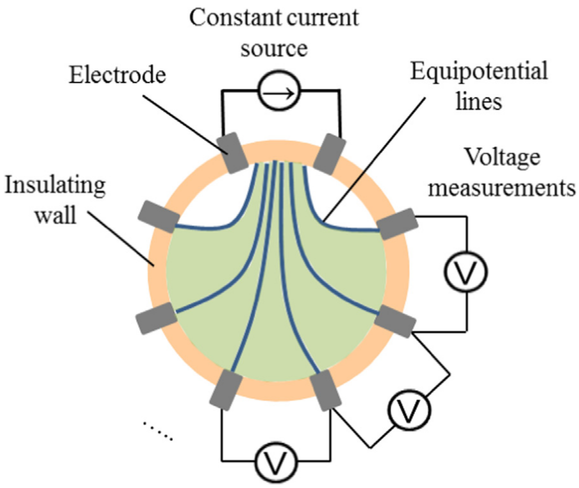

Fig. 1. Schematic diagram of sensor geometry and measurement strategy.