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Electrical capacitance volume tomography for imaging of pulsating flows in a trickle bed

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HIGHLIGHTS

- A pulsating trickle bed is measured by electrical capacitance volume tomography.
- The pulse structures in fully developed and transient conditions are illustrated.
- The pulse frequency, velocity and liquid holdup in various conditions are measured.
- Liquid holdups in gas and liquid zones are solely dependent on the gas flow rate.

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ABSTRACT

Experimental results of the air–water pulsating flows in a trickle bed column were obtained using the electrical capacitance volume tomography (ECVT) system. Detailed 3-D pulse structures in both the fully developed and the transient conditions were illustrated. Pulse frequency, pulse traveling velocity, average liquid holdup and liquid holdup inside the gas-rich and liquid-rich regions, respectively, were measured. Based on a simplified model, the linear liquid velocities inside the gas-rich and liquid-rich regions were estimated. The results revealed that the gas flow rate was the most important parameter in controlling the pulsating flow properties. Discussion on the physical nature of the pulsating flow was also given.

1. Introduction

In a trickle bed reactor (TBR), gas and liquid concurrently flow downward through a packed bed of solid materials. It is a gas–liquid–solid three phase contactor widely employed in petroleum, petrochemical, biochemical, electrochemical, and water treatment industries (Al-Dahhan et al., 1997; Dudukovic et al., 1999). Despite its simple reactor design, the flow structure in a trickle bed is complex. Several different flow regimes are present with different gas and liquid flow rates: trickling flow (gas-continuous flow), pulsating flow and dispersed-bubble flow. At a very high gas flow rate, the spray flow regime may also exist (Tosun, 1984). Among these flow regimes, the trickling flow and the pulsating flow are most commonly encountered in applications. Compared to the relatively steady trickling flow regime, the turbulent pulsating flow regime has intensive interactions between phases, yielding good transport properties for chemical reactions (Boelhouwer et al., 1999). The high interactions between phases can reduce the mass transfer resistance. Furthermore, inside the gas-rich regions, the reaction heat is not thoroughly removed so that controlled hot-spots can be present, raising the temperature periodically to enhance the reactions. Wilhite et al. (2001) compared the catalytic hydrogenation of phenylacetylene in the pulsating flow and trickling flow regimes directly and concluded that the pulsating flow could enhance the reaction rate as well as the yield. To better exploit the benefit of the pulsating flow regime in trickle beds, the pulse properties need to be examined.

Considerable efforts have been made to understand the pulsating flow hydrodynamics inside the TBRs. An area of interest is the trickling-to-pulsating transition. A relatively comprehensive database regarding the transition can be found in Iliuta et al. (1999), and a collection of available empirical correlations on the transition has also been given by Larachi et al. (1999). Anadon et al. (2006)

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employed magnetic resonance imaging (MRI) technique to image the transitioning flow field and concluded that the formation of local instabilities, known as isolated small scale pulsating events, was the key mechanism of the trickling-to-pulsating transition. Llamas et al. (2007) used a wire-mesh device to study the horizontal liquid distribution in a trickle bed operated near the trickling-to-pulsating transition boundary and found that the initial liquid distribution in the bed had a significant effect on the horizontal liquid distribution as well as local flow regimes under this transition boundary condition. A summary of empirical and theoretical models to predict the flow regime transition could be found in Attou and Ferschneider (2000). Compared to the trickling-to-pulsating transition, less attention has been given to the fully developed pulsating flow in trickle beds. In the pulsating regime, results of time-averaged quantities such as overall pressure drop and total liquid holdup are widely available. Nevertheless, data on the pulse properties such as pulse frequency, velocity, length, and ratio between the gas-rich and liquid-rich regions, are still not adequate. In earlier studies, pulse velocity, frequency and unit length were reported by Weekman and Myers (1964). Beimesch highlighted the packing effect on the pulse liquid holdup (Beimesch and Kessler, 1971), and Sato et al. (1973) observed that the maximum pressure along a pulse unit corresponded to the leading edge of liquid-rich region of the pulse. Blok and Drinkenburg (1982) and Rao and Drinkenburg (1983) reported comprehensive data related to the pulse properties in 1980s, using an intrusive cross-sectional electrical conductive mesh method. By employing a pair of conductive ring probes, Tsochatzidis and Karabelas (1995) reported some pulse properties based on non-invasive local measurements , and similar conductive technique was also used by Bartelmus et al. (1998). Boelhouwer et al. (2002) employed the invasive hot-film anemometer to study the gas–liquid distribution.

However, most of the experimental results mentioned above were based on local measurements or using intrusive probes. With local measurements only, it is difficult to picture the entire flow field. Intrusive probes, on the other hand, disturb the flow and yield inaccurate results. Recently, a number of non-invasive tomography imaging techniques were applied to the trickle bed reactor study. Schubert et al. (2008) analyzed the liquid flow characteristics inside a trickle bed using a high-resolution gamma-ray tomography and found that the hydrodynamic behavior for a bed of non-porous glass beads and porous Al_2O_3 catalyst support was significantly different. Hamidipour et al. (2009) employed electrical capacitance tomography (ECT) to examine the trickle bed flow properties. They compared the liquid holdup results from ECT with those from residence time distribution (RTD) measurements and investigated the deposition of the fine particles inside a trickle bed. They found that the holdup from ECT was in good agreement with RTD measurements. The bed was observed to transit from the trickling to the pulsating regimes due to fines deposition. They also studied the gas–liquid on–off cyclic operations of the trickle bed using EC and estimated the mean liquid holdup and pulse velocity (Hamidipour et al., 2010). The ECT results indicated that they achieved optimized gas–liquid on–off cyclic operation where the unwanted fines particles deposition inside the trickle bed reactor was significantly reduced. To better understand the flow field inside a trickle bed reactor operating under the pulsating flow regime, a non-invasive real-time 3-D imaging technology is required. Electrical capacitance volume tomography (ECVT), recently developed for multi-phase flow applications, can be used here to study the pulse details (Warsito et al., 2007). ECVT is based on distributing flexible capacitance plates on the peripheral of a flow column and collecting real-time measurements of inter-electrode capacitances. Capacitance measurements here are directly related to dielectric constant distribution, a physical property that is also related to material distribution in the imaging domain. An optimization reconstruction algorithm is employed to map volume images of dielectric distribution in the imaging domain, which in turn can be correlated to the phase distribution. ECVT is suitable for imaging interacting materials of different dielectric constants, typically in multi-phase flow systems.

In this work, fluid dynamic properties of a trickle bed operating under the pulsating flow regime are investigated in an air–water cold flow model column using the ECVT technique. Experimental results of 3-D liquid pulse shape, pulse frequency, liquid holdup, and pulse velocities are reported. The results are found to be in good agreement with the literature work. A simplified model describing the local liquid velocity inside the gas-rich regions and liquid-rich regions is presented. Discussion regarding the physical nature of the pulsating phenomenon is also provided.

2. Experimental setup and procedures

2.1. Electrical capacitance volume tomography (ECVT)

ECVT is a novel process tomography technology recently developed. It is an extension of electrical capacitance tomography (ECT) as it provides direct 3-D imaging (Warsito et al., 2007). By designing capacitance plates with inherit 3-D features, real-time inter-electrode capacitances can be directly related to phase distribution inside the column. There are three major components in the ECVT system: the sensor, the data acquisition hardware, and the computer loaded with the reconstruction algorithm. The ECVT sensor can accommodate irregularities in the flow column through its flexible nature (Wang et al., 2010). The acquisition hardware is tuned to eliminate parasitic and static capacitance in the targeted imaging domain, focusing the system resolution on the varying component which is usually related to phase concentration. The fast acquisition speed of ECVT (in the order of hundreds of images per second) provides real-time visualization of the liquid and gas flows. At this imaging rate, fluid flows can be measured in real-time with quantitative information for both phases. The captured capacitance data is processed offline for image reconstruction and data analysis. The basic measuring technique in ECVT is based on recording changes in current through the capacitance plates as the phases of the flow change their concentrations. The relation between phase concentration and changes in capacitance is based on a non-linear partial differential equation. Thus, the recoded capacitance data can be non-linearly related to the gas or liquid distribution. This non-linearity is further emphasized when liquids of high dielectric constants are used. In this study, water is used as the liquid phase. Water naturally has a high relative dielectric constant of around 80, which further complicates the reconstruction process. To overcome this hurdle, advanced image reconstruction algorithms that can properly map measured capacitance data to phase concentration in the imaging domain are employed. In this effort, an optimization algorithm called neural network multi-criteria optimization image reconstruction technique (NN-MOIRT) is used. This algorithm considers several objective functions that are aimed at finding the most optimum image from the set of measured capacitance data (Warsito and Fan, 2003). The 3-D spatial resolution of ECVT is about 3–5%, depending on the multiphase flow materials used inside the column, with respect to the total imaging domain volume. With the multiphase flow materials used in this study in a liquid-batch packed bubble column, a comparison of the overall liquid holdup in the liquid-batch packed bubble column measured by the ECVT and that by the visual observation of the liquid level in the column indicating that the ECVT measurement error range is within 3%.