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Flow patterns and transition criteria in boiling water-cooled packed bed reactors

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ABSTRACT

The flow patterns associated with boiling water-cooled packed bed reactors were investigated via experiments. A bed packed with spheres of different diameters, which were heated by means of electromagnetic induction, was investigated over a range of mass flux values and sphere diameters. Three flow boiling patterns occurred in the packed bed: bubble flow, slug flow, and annular flow. Furthermore, generalized flow pattern maps were plotted in terms of the mass flux versus the vapor quality. The effects of mass flux and sphere diameter on the flow region transition were analyzed, and criteria for transitions between flow patterns were proposed based on certain parameters. These parameters included the Reynolds number, ratio of the glass tube diameter to the sphere diameter, and vapor quality. The results indicated that more than 90% of the data are correctly described by the transition boundary criteria.

1. Introduction

The boiling water-cooled packed bed reactor represents a new conceptual small-scale reactor combining the advantages of a spherical fuel element with the mature technology of a water-cooled reactor and has significant potential for further development (Cuta et al., 2007). Therefore, the flow patterns for flow boiling of water in a volumetrically heated packed bed constitute an important research topic for facilitating this development.

Flow patterns associated with concurrent gas-liquid down-flow and up-flow, and inversion gas-liquid flow through packed beds have been extensively investigated. The results of various studies revealed that the flow patterns vary considerably due to the complex structures of a packed bed, variant flow directions, and diverse liquids. For ease of comparison between the conclusions of the present work and those of previous studies, the following sections review only reports that considered the flow patterns in concurrent gas-liquid up-flow. The flow mode investigated in those studies concurred with the flow mode of the experiment performed in the present study.

Flow-regime classification has focused mainly on classifying flow patterns based on the distribution of two phases (i.e., gas and liquid) in (i) a single pore and (ii) the entire space comprising a packed bed. The reports based on the first classification method are briefly reviewed as follows:

Ford (1960) investigated the flow patterns associated with gas-liquid two-phase flow through a packed bed consisting of 1–2-mm diameter particles. The resulting flow was classified as single-phase and two-phase pore flow, based on the distribution of gas and liquid in a single pore. Single-phase pore flow is described by a flow pattern, where a single pore is traversed by a gas or a liquid solely, and occurs only at low gas flow rates. In two-phase pore flow, a single pore is simultaneously traversed by gas and liquid phases. Saada (1972) and (1975) extended the original concept (Ford, 1960) and proposed criteria for transitions between single-phase and two-phase pore flow. These studies (Ford, 1960; Saada, 1972, 1975; Saada, 1972) have indicated that pore flow usually occurs at small particle sizes. However, the flow patterns will change significantly with increasing particle size and additional criteria are required for investigation of the flow. Several studies (Turpin and Huntington, 1967, Specchia et al., 1974, Molga and Westerterp, 1997; Raghavendra et al., 2011, Gianetto and Specchia, 1992, Varma et al., 1997, Sato et al., 1974, Shah, 1979, Murugesan and Sivakumar, 2002, Liao, 2009, Zhao, 2010; Zhang et al., 2009, 2011) have used a second classification method for the study of flow patterns occurring in a packed bed. The results of these studies are summarized as follows:

According to various studies (Turpin and Huntington, 1967; Specchia et al., 1974, Molga and Westerterp, 1997; Raghavendra et al., 2011; Gianetto and Specchia, 1992; Varma et al., 1997), the regions

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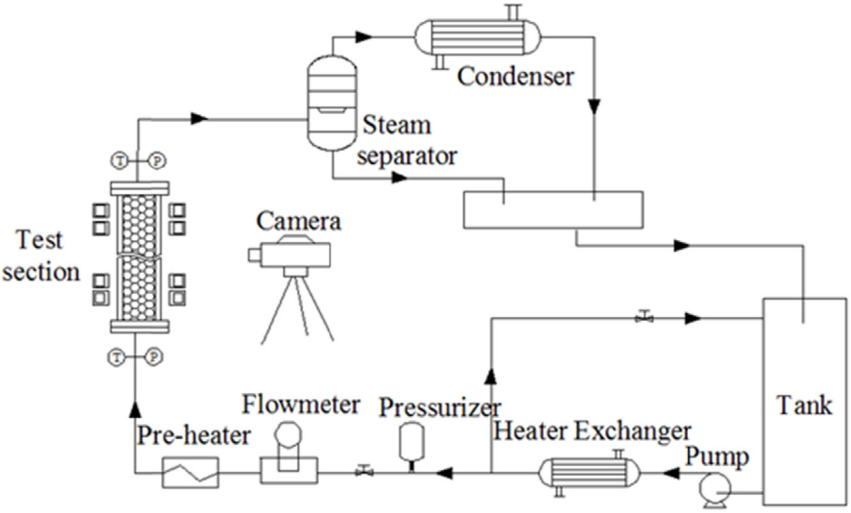

Fig. 1. Schematic of the experimental loop.

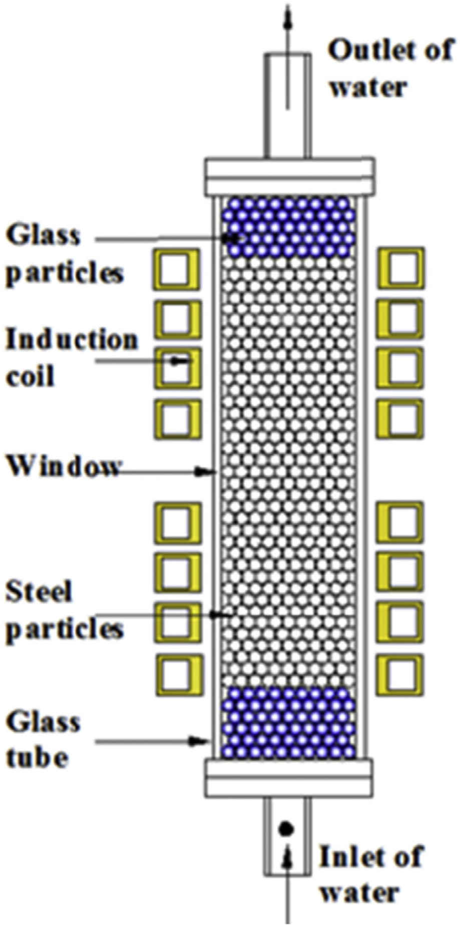

Fig. 2. Schematic of the test section.

Table 1
Detailed parameters of the test section.

No.	Height of glass tube/mm	Inside diameter of glass tube/mm	Height of packed steel particles/mm	Diameter of steel particles/mm
1#	980	75	648	5.09
2#	980	75	700	8.02
3#	980	75	658	12.04

comprising flow patterns are characterized by the occurrence of bubble flow, pulse flow, and spray flow. At a constant liquid flow velocity, the three flow patterns occur consecutively with increasing gas velocity. Bubble flow occurs at low gas flow rates and is characterized by small bubbles dispersed in a continuous liquid. At moderate gas flow velocities, a liquid-rich portion followed by a gas-rich portion flow rapidly flow through a channel, thereby generating a low-density and high-density fluid pulse, i.e., a pulse flow. At high gas velocities, a continuous gas phase with a dispersed liquid flows in a pore flow region and the corresponding liquid film flows along the particle surface. The liquid entrained in the gas increases with increasing gas flow velocity, until the liquid film disappears. In addition to the three aforementioned flow patterns, Sato et al. (1974) have proposed another pattern, i.e., the surging flow occurring between bubble flow and pulse flow. This flow is characterized by the merger of small bubbles into large bubbles, and the corresponding flow pattern usually occurs for particle diameters > 10 mm (Shah, 1979).

Many other studies (Murugesan and Sivakumar, 2002, Liao, 2009, Zhao, 2010; Zhang et al., 2009, 2011) have been conducted, but differing flow patterns have been obtained. Murugesan and Sivakumar (2002) classified the flow into different types, namely: bubble (I) flow, churn flow, pseudo spray flow, bubble (II) flow, pseudo pulse flow, and pulse flow. The results indicated that the churn, pseudo spray, pseudo pulse, and pulse flows correspond to the pulse flow proposed by Sato et al. (1974). Other studies (Liao, 2009; Zhao, 2010; Zhang et al., 2011) have reported that the flow patterns transition from bubble flow to cluster flow when the flow gas velocity increases. They found that, with increasing gas flow rate of the pulse flow, flow patterns of the liquid-rich portion and the gas-rich portion will reveal sub-division of this flow into liquid-pulse flow, churn-pulse flow, and annular-pulse flow.

The aforementioned studies were performed in the absence of a heating source. Zhang et al. (2009) studied flow patterns for the flow boiling of water in a packed bed heated by an external heating source. They observed bubble flow, bubble-slug flow, slug flow, and slug-annular flow, and proposed criteria for transitions between the flow patterns.

Most of the previous studies have focused on the flow patterns associated with gas-liquid flow in the absence of a heat source. Flow patterns for the flow boiling of water in a packed bed subjected to external heating have rarely been considered. Although many fruitful results have been obtained, the experimental conditions for gas-liquid or external heating differ significantly from those associated with a