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Experimental investigation of bubbling in particle beds with high solid holdup

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ABSTRACT

A series of experiments on bubbling behavior in particle beds was performed to clarify three-phase flow dynamics in debris beds formed after core-disruptive accident (CDA) in sodium-cooled fast breeder reactors (FBRs). Although in the past, several experiments have been performed in packed beds to investigate flow patterns, most of these were under comparatively higher gas flow rate, which may be not expected during an early sodium boiling period in debris beds. The current experiments were conducted under two dimensional (2D) and three dimensional (3D) conditions separately, in which water was used as liquid phase, and bubbles were generated by injecting nitrogen gas from the bottom of the viewing tank. Various particle-bed parameters were varied, including particle-bed height (from 30 mm to 200 mm), particle diameter (from 0.4 mm to 6 mm) and particle type (beads made of acrylic, glass, alumina and zirconia). Under these experimental conditions, three kinds of bubbling behavior were observed for the first time using digital image analysis methods that were further verified by quantitative detailed analysis of bubbling properties including surface bubbling frequency and surface bubble size under both 2D and 3D conditions. This investigation, which hopefully provides fundamental data for a better understanding and an improved estimation of CDAs in FBRs, is expected to benefit future analysis and verification of computer models developed in advanced fast reactor safety analysis codes.

1. Introduction

After a hypothetical core-disruptive accident (CDA) in a sodium-cooled fast breeder reactor (FBR), a multiphase flow system comprising a mixture of liquid sodium, molten fuel, molten structure, refrozen fuel, solid fuel pellets, steel particles, control particles and other materials, can form as a consequence of rapid quenching and fragmentation of core materials, the depositing of which leads to the formation of debris beds over the core-support structure and/or in the lower inlet plenum of the reactor vessel (as depicted in Fig. 1) [1]. Due to spatial confinement and drastic rapid cooling from the coolant, these debris beds are likely to be formed with high solid holdup. To achieve in-vessel core retention, post-accident heat removal is crucial. Therefore, as bubbling will play a dominate role in dictating the hydrodynamics and heat transfer efficiency, it is essential to uncover the dynamic characteristics of bubbling generated in particle beds [2].

During the past decades, numerous experimental and model-based studies have been conducted to ascertain bubble rising characteristics in both liquid and solid–liquid mediums. Grace et al., Clift et al., Bhaga et al., and Frank et al. have investigated bubbling characteristics in inviscid or viscous liquid [3–6], while for bubbles moving in solid–liquid systems with lower solid holdup (<0.5), similar experiments have been also performed by Pandit and Joshi [7], Tsuchiya et al. [8], Miyahara et al. [9], Chen and Fan [10], and Glicksman et al. [11]. During their studies, they tried to elucidate the mechanisms and proposed some quantitative correlations to predict bubbling characteristics including bubble velocity, bubble aspect ratio and bubble-induced wake properties.

As solid holdup increases, effects of the solid become more and more predominant as particle–particle and particle–bubble interactions rise in prominence. Mondy et al. and Tsuchiya et al. independently investigated bubbles rising through solid–liquid medium with intermediate solid holdup [12,13]. They tried to recognize the influence of solid phase on the properties of liquid–solid mixture. However, due to limited properties of solid phase encountered in their experimental systems, difference in the findings regarding relative size (bubbles to particles) on effective viscosity of the mixture has been obtained. While for bubbling behavior in packed beds, attentions have also been attracted in the past. Flow patterns in packed beds are known to be extremely complex and depend on gas and liquid superficial velocities, physical properties of fluids, and geometrical characteristics of packed beds [14–20]. Flow regime maps are generally used to categorize flow patterns, such as bubbly, spray, trickling and pulsing flow [14–20]. In

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