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Numerical investigation on hydrodynamic performance of liquid lead lithium bubble column using population balance model

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HIGHLIGHTS

- Flow behaviors with H and V_g were simulated using CFD coupled with PBM.
- Bubble size and gas holdup are mainly determined by vortical flow.
- Interfacial area enhanced by increasing V_g and H, but the enhancement effect is not obvious while the V_g is too fast.

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ABSTRACT

Using bubble column to extract tritium from lead lithium (Pb–17Li) eutectic is an effective way in the process of tritium extraction in liquid blanket system, where the hydrodynamic characteristics of the gas–liquid two-phase flow in the columns play a very important role. In order to understand the two-phase flow details and investigate the influence factors on the hydrodynamic performance, in this paper the flow behaviors in the cylindrical bubble columns with different heights and purge gas inlet velocities using computational fluid dynamics coupled with population balance model were simulated. Liquid flow field, bubble Sauter mean diameter, time-averaged gas holdup and two-phase interfacial area for the different cases were obtained and compared. The simulation results showed good agreement with previous studies, and which indicated that bubble size and gas holdup formation are mainly determined by vortical flow. In addition, interfacial area can be enhanced by increasing the purge gas inlet velocity and column height. However, the enhancement effect will trail away when the gas inlet velocity is too fast, and the contribution of column height is relatively small.

1. Introduction

The liquid lead lithium (Pb–17Li) tritium breeding blanket concept has been studied extensively in the world as a candidate of future demonstration blankets for fusion power reactors [1–3] and a series of Pb–17Li blanket concepts have been designed and assessed by FDS Team in China [4–6]. Bubble columns are widely applied in many industries due to their advantages of simple construction, low cost, efficient mixing and high heat and mass transfer efficiency [7]. Similarly, bubble columns were adopted as one of the recommended devices to extract tritium from liquid Pb–17Li [8–12], in which purge gas (He + 0.1% H_2) was introduced at the bottom via a sparger and Pb–17Li flowed in the opposite direction from the top inlet. The purge gas rose as bubbles through Pb–17Li alloy and took tritium out simultaneously.

In previous works, tritium extraction efficiency was the focus of concern and several experimental studies have been performed to research hydrogen extraction [13–16]. In those experiments, the hydrogen extraction efficiency was calculated by the hydrogen concentration of the inlet and outlet. However, the prediction and evaluation of tritium extraction performance can be carried out by computational fluid dynamic (CFD) simulations. Current knowledge indicated that interfacial area is a key factor affecting the tritium extraction efficiency in Pb–17Li bubble column [17], since it can used to measure the mass transfer rates between gas and liquid phase [18]. Whereas the interfacial area can be computed from bubble mean diameter and gas holdup [19]. Regarding bubble size, Bannari et al. [20] had found that there should be some relations between bubble size distribution and liquid flow behavior. Therefore, to pursue high tritium extraction efficiency, a fundamental understanding and

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investigation of the hydrodynamic characteristics in Pb–17Li bubble column are indispensable. In recent years, numerical simulation has been recognized as a very effective tool for design and optimization of bubble columns. Several studies have been conducted successfully to research the hydrodynamics properties in bubble columns using CFD coupled with population balance model (PBM) [21–24], yet to date research on liquid Pb–17Li bubble column by that means is still lacking.

The purpose of this work is to understand the flow details and investigate the impact factors on the hydrodynamic performance in liquid Pb–17Li bubble column using the CFD-PBM method. Considering column height (H) and purge gas inlet velocity (V_g) are the basic design parameters for Pb–17Li bubble column design [13], the effects of which on the liquid flow filed, bubble size distribution, gas holdup and interfacial area in Pb–17Li bubble column were investigated.

2. Numerical simulation

In order to simulate the flow behavior accurately, three-dimensional cylinder model was adopted. The column dimensions were 150 mm in diameter and 450, 600, 750 mm in height. The columns were initially filled with liquid Pb–17Li. The purge gas was introduced via a sparger with holes at the bottom. The sparger was defined as uniform gas inlet with a specified velocity ranging from 0.15 to 0.65 m/s with the interval of 0.5 m/s. Bubble diameter at the inlet was assumed as 4.5 mm. The top of the column was set as pressure outlet boundary, from which only gas was permitted to escape. The walls were all treated as non-slip boundary. To simplify the simulation process, the purge gas contained only helium and heat and mass transfer were not considered in this work. The material property parameters were calculated by the expressions in Ref. [25].

The simulations were conducted using the CFD code FLUENT incorporated with PBM [26]. The bubble diameter in the columns was discretized into 32 classes range from 0.01 to 26.4 mm according to the discrete method ($d_{i+1}^3/d_i^3 = 2^{1.1}$). The computational domain was divided into relatively uniform triangular prism grid with edge length about 12 mm. The grid size was selected based on the existing study [7]. The $k-\varepsilon$ model was used to model turbulence and drag and virtual mass force were taken into accounted in the simulations. The discretization schemes for all the equations were first order upwind. Based on the optimization of time step [7], the time step was set as 0.01 s.

3. Results and discussion

3.1. Liquid flow field

Fig. 1 shows the comparison of liquid velocity vector in the bubble columns with different helium inlet velocities. At low helium inlet velocity, the liquid flow was driven by the gas thrust and oscillatory ascending in the column center. Surrounded the central stream plenty of vortical flow regions were distributed, as shown in Fig. 1(a). With increasing helium inlet velocity, the central stream flowed more quickly and the number of vortical flow region decreased (Fig. 1(b)). For the large enough gas inlet velocity, the liquid circulation was hindered. Most part of the central area of the column was filled with the upward liquid flow and it returned to the bottom along the column wall (Fig. 1(c)).

Quantitatively, the mean axial liquid velocity changes with column height and helium inlet velocity are shown in Fig. 2. It can be observed that the influence of column height on the mean axial liquid velocity is insignificant. However, there is an inflection point on each curve at the helium inlet velocity of 0.45 m/s. It may be attributed to a flow pattern transition has occurred at that velocity. When the helium inlet velocity lowers than 0.45 m/s, the flow pattern according to Ref. [27] was churn flow. Although the mean axial liquid velocity was increased with the increasing helium inlet velocity, the rate of increase was relatively slow because of the vortical flow structures inside the column. When the helium inlet velocity reached 0.45 m/s, the flow pattern changed to annular flow. In this pattern, as previously described, owing to the rapid flow of the gas the vortical flow regions almost disappeared. Therefore, the mean axial liquid velocity with helium inlet velocity greater than 0.45 m/s was increased faster. The changes of flow filed with increasing gas inlet velocity are in good accord with Ref. [7].

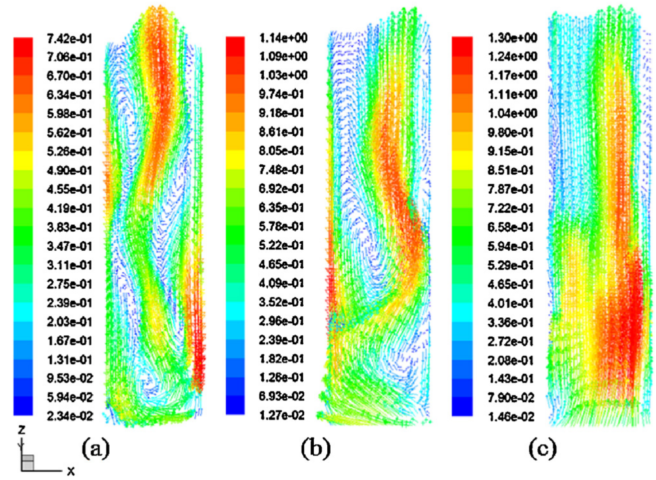

Fig. 1. Comparison of liquid velocity vector in the bubble columns (H = 600 mm) with helium inlet velocities of (a) 0.2 m/s, (b) 0.4 m/s and (c) 0.6 m/s.

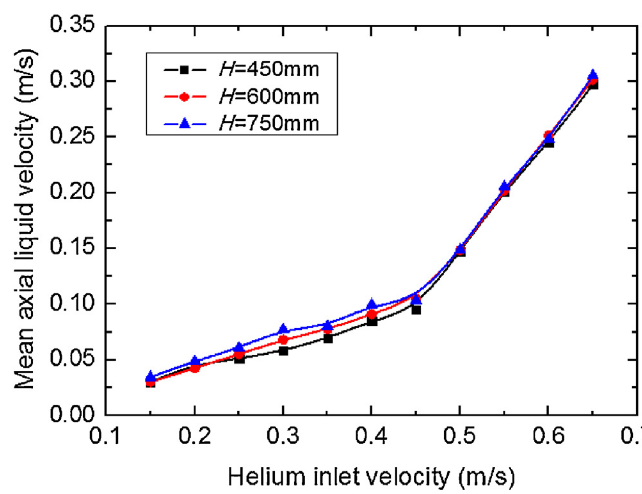

Fig. 2. Mean axial liquid velocity in the columns with different heights and helium inlet velocities.

3.2. Bubble distribution

Fig. 3(a) and (b) show the bubble Sauter mean diameter and gas holdup in the column with helium inlet velocity of 0.2 m/s and column height of 600 mm. Combine Fig. 3 and Fig. 1(a), it is found that the bubble Sauter mean diameter and gas holdup in the vortical flow regions are smaller than in the center stream, which is in agreement with the results in Ref. [20]. It can be explained that the turbulence was enhanced by the reverse flow in the eddy zone, as result the bubble breakup increased and small bubbles were more dominant. For this reason if increase the helium inlet

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