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Preliminary study of direct visualization of two-phase flow behavior inside porous media using refractive index matching method

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1. Introduction

In the severe accident of a light water reactor (LWR), if In-Vessel Retention (IVR) strategy fails, the molten corium fall into the reactor cavity which is filled with water and the ex-vessel debris bed would be formed on the cavity floor due to Fuel-Coolant Interaction (FCI). However, if cooling performance of debris bed is not sufficient to remove the decay heat of the debris bed, the debris bed may re-melt by a high temperature and it can react with the bottom concrete, which is so called Molten Corium Concrete Interaction (MCCI). Consequently, the coolability of the debris bed has to be reliably evaluated for the analysis of the severe accident.

According to previous researches, the cooling limitation of the debris bed is highly dependent on the hydrodynamic resistance of the bed. Therefore, many researchers investigated two-phase flow behavior and presented two phase friction models between vapor-liquid phase in porous media to predict Dryout Heat flux (DHF) which mean the maximum heat flux without dryout[1, 2, 3]. In 1980s, Tung & Dhir proposed the two phase friction model with three flow patterns concept[4]. They classified two phase flow patterns, which are categorized into bubbly, slug, and annular flow and they reported that two-phase flow pattern is an important phenomenological factor for developing friction model because the each flow patterns have unique characteristics. Unfortunately, however, they did not validate the flow pattern model from a clear experimental data.

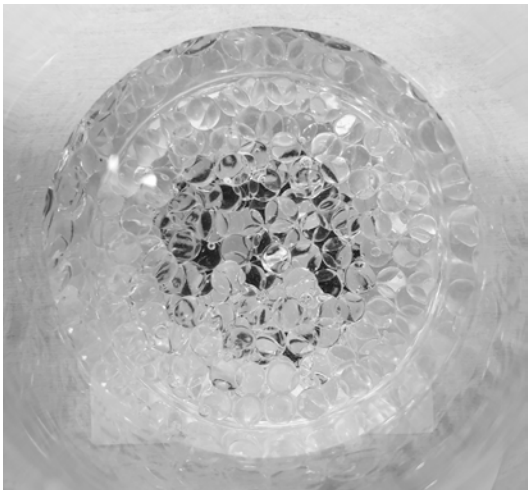
Until now, many researchers tried to observe two-phase flow behavior inside packed particles bed using various methods; visualization with transparent particle[5, 6] and X-ray tomography[7], capacitance tomography[8]. However, the visualization method cannot observe the inside of the particles bed due to difference of refractive index between particles and water. Also, X-ray and capacitance tomography method are not sufficient to attain the pore scale bubble motion in mm-scale particles bed, since the pore diameter is on the millimeter scale and the residence time of bubbles is of the order of several milliseconds. In conclusion, the scientific research work for the two-phase flow behavior in packed particle bed is insufficient.

Therefore, in this study, we conducted preliminary test of direct visualization experiment using Refractive Index Matching (RIM) method in quartz glass particles bed for investigation of the two phase flow behavior inside bed.

2. Method and Result

2.1. Refractive index matching method

The RIM method has been applied in several fields including flow in porous media. The method is can defined as a way to reduce image distortion by aligning the refractive index in a mixed system of two transparent materials. If the RIM method is applied to a packed particles bed with the particles and fluid having same refractive index, the visible light can penetrate through the media without the refraction, making internal flow pattern investigation possible. Fig. 1 is shows an example of RIM method with quartz glass particles and aqueous solution of sodium iodide (NaI).



(a) water-quartz glass particles (index mix matched)

(b) NaI solution-quartz glass particles (index matched)

Fig. 1. Image distortion test

To match the refractive index of the solution with that of the particle, it is essential that the mass concentration of NaI solution should be adjusted. In K. Bai & J. Katz research, they suggested an empirical correlation about refractive index of the NaI solution according to the mass concentration as follows:[9]

$$n = 0.2425c^2+0.09511c+1.335 \quad (1)$$

where n is refractive index of NaI solution and c is mass concentration of NaI solution.

Thus, we found a suitable concentration point of solution, which has same refractive index with quartz glass particles through an image distortion test. The suitable concentration is 55.092% and the refractive index is 1.461.

2.2. Experimental facility

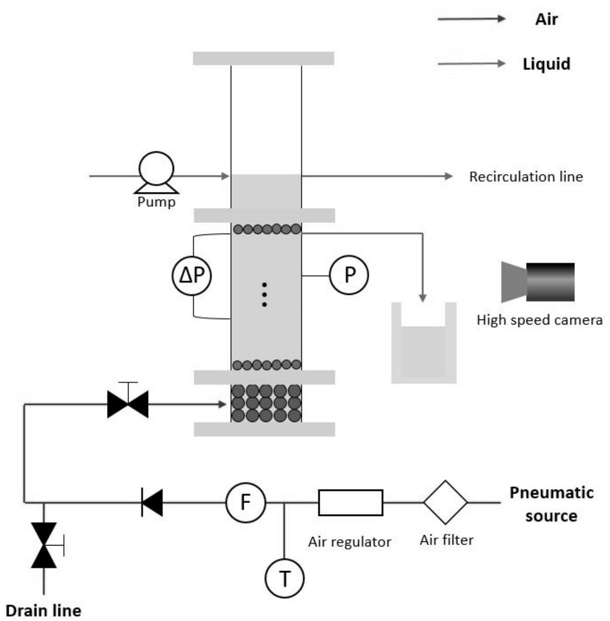


Fig. 2. Schematic design of the experimental facility

The schematic design of experimental facility is illustrated in Fig. 2. The experimental set-up is designed for a pressure of 1 bar and a room temperature. It consists of a filter, a regulator, a flow meter for air, thermocouples and a differential pressure transmitter for measurement of the pressure gradient in particles bed. Air is injected from the bottom of the test section which is filled the NaI solution. The cross section of the acrylic test section is square shape. The length of the test section side is 60 mm and the height is 200 mm. It has 5 pressure ports on the side wall with interval 40 mm. Two ports at the top side of the test section are used to maintain the pool level by injecting and overflowing the solution. On the front side, bubble behavior is visualized using a high speed camera with back light. The test bed is consisted of spherical quartz glass beads whose sizes are 4 mm in this. Figure 4 is a front view of the RIM experimental set-up.

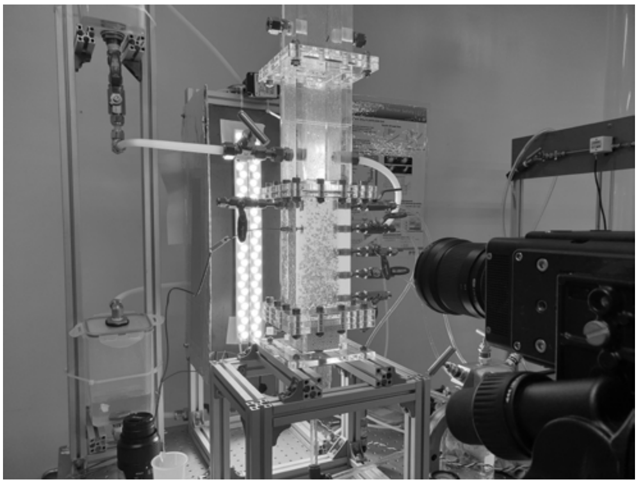


Fig. 3. Front view of the experimental facility

On the experiment, there are two control parameters, which are particle diameter and superficial gas velocity. The main goal of the experiment is two-phase flow pattern map in the void fraction from 0 to 1. Therefore, we will conduct the RIM experiment on the particle diameter 2 – 6 mm and the superficial gas velocity 0 – 1 m/s. That way, each flow patterns like bubble and slug, annular regime will be investigated.

2.3. Structure for visualization

Through pre-test of RIM experiment, there is a problem about visualization of two-phase flow behavior inside particles bed in high superficial gas velocity. The reasons are that many bubble interface prevent the penetration of visible light to the center of the bed, and that gas flow paths are formed due to the relatively high porosity near the wall. Thus, to prevent those problems, the structure for visualization was installed inside test section on the visualization area. The structure is shaped like U to block the bubble coming into the bottom side. (Fig. 4)

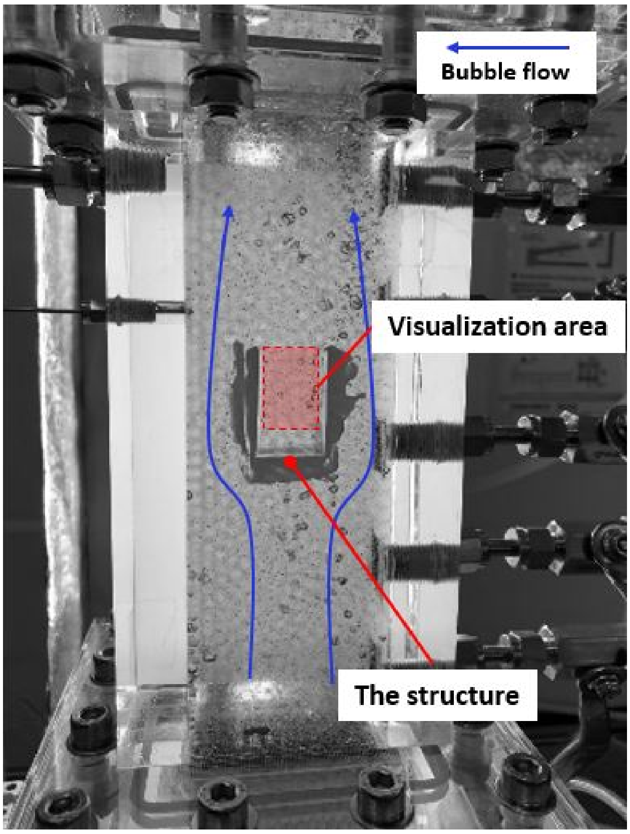
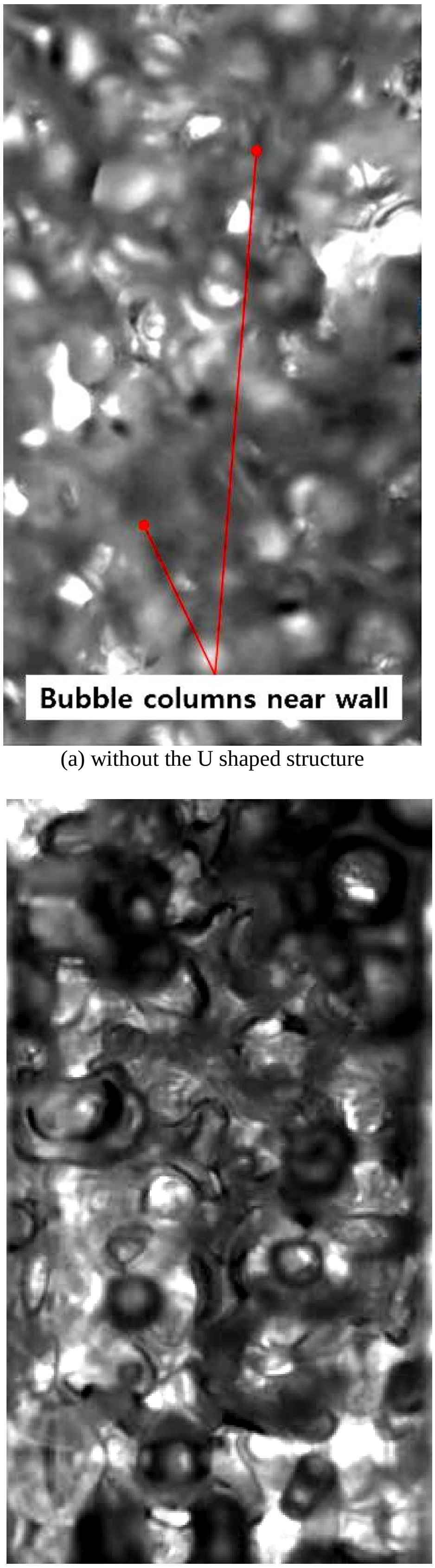


Fig. 4. Test section image with the structure for visualization

Then, we conducted visualization experiments in the case without the structure and in the case with the structure to confirm the effect of the structure. Figure 4 shows the result of the visualization experiments when superficial gas velocity is 0.463 m/s. As previously explained, Fig. 5 (a) shows that, in normal case visualization is not possible due to the front bubble columns. On the other hand, in Fig. 5 (b), the bubbles behavior inside particles bed is observed, because there are no bubble columns on front side due to the structure. According to the result, we could verify that the direct visualization inside the particles bed with visible light can be possible even in two-phase flow condition. However, the optimization of the structure like structure shape and size is needed for clear visualization of bubble behavior except for trap bubble inside particles.



(a) without the U shaped structure

(b) with the U shaped structure

Fig. 5. Bubbles behavior images

3. Conclusion

For investigation two phase flow behavior in porous media, preliminary test of direct visualization inside quartz glass particles bed was conducted using RIM method. Through the pre-tests, we found the suitable concentration of NaI solution for matching the refractive index. In addition, the U-shape structure was added to enable visualization of bubbles behavior inside the particles bed in high superficial gas velocity and the effect was verified through the comparison with the non-structure case. Consequently, we checked the feasibility of RIM method at two-phase flow experiment in porous media. In the future work, we will investigate two-phase flow behavior inside particles bed using RIM method on the experiment facility.

Acknowledgements

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