Refractive Index matching method for the visualization of two-phase flow behaviour in porous media: A preliminary study

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1. Introduction

In the event of a severe accident in a light water reactor, the molten corium breaches the reactor vessel when an In-Vessel Retention strategy fails. This molten corium will then fall into the reactor cavity which is filled with coolant water and in this process, a porous debris bed will be formed as a result of fuel coolant interaction. Even though the porous debris bed is formed as a result of rapid quenching of falling molten corium, it still possesses decay heat due to the presence of radioactive elements. If this decay heat is not removed by establishing an effective and continuous cooling for the debris bed, then it may lead to remelting, inducing molten corium concrete reaction (MCCI). Any further damage to the bottom concrete bed as a result of this reaction will compromise its integrity which may allow the leaking of radioactive particles in the environment. This scenario will lead to irreparable damage to the environment. Therefore it is of utmost importance to understand the physical process which governs the two-phase flow and heat transfer in porous media. This knowledge is essential for models which assess the coolability of melted core for safety evaluation of light water reactors in severe accidents.

Numerous researchers [1-6] have studied the factors affecting coolability of debris bed from the 1980s. It is reported that the cooling performance of the bed is dependent on the hydrodynamic resistance of the debris bed, which interrupts the coolant flow. The cooling limitation of the debris bed is usually defined in terms of dryout heat flux (DHF), which is the maximum heat flux without dryout condition. The coolable condition of debris bed is achieved when a quantity of supplied coolant matches with the quantity evaporated. Based on the geometry of debris bed the coolant flow configuration can be varied and these flow configuration also affects the DHF.

In early attempts, many researchers [7-10] have proposed two-phase friction models to predict the DHF in porous debris bed. However, some of these models [7-8] failed to consider two-phase flow characteristics and underestimated DHF in passive inflow conditions. While other [9-10] overestimated DHF in multi-dimensional conditions as a result of inaccurate prediction of the two-phase pressure gradient. Later the results of the experimental investigation conducted by Park et al. [11] indicated that the previous friction models fail to predict pressure gradient at high void fractions. Hence, it is inappropriate to use these models for predicting pressure gradient at the wide range of void fractions. Taking cue of this finding Lee et al. [12, 13] studied pressure gradients over wide range of void fraction and proposed a modified two-phase friction model with improved predictability.

From these studies, it is evident that the physical understanding of two-phase flow in porous media is important to improve the predictability of DHF models. Many researchers tried to study two-phase flow behaviour inside a porous bed made up of packed particles by employing different visualization methods such as X-ray tomography [14], capacitance tomography [15] and visualization with clear particles [16]. However, X-ray and capacitance tomography are insufficient to attain pore scale bubble motion inside mm scale bed. Whereas, in case of visualisation with clear particles, due to the mismatched refractive indices of particles and liquid, this visualization method fails to observe the inside of the particle bed. Therefore, there is a great need to explore a suitable visualization method to study two-phase flow behaviour inside a packed particle bed.

In the present study, we tried to employ the refractive index matching method to visualize two-phase flow inside a packed particle bed. We have conducted preliminary tests using water beads and water to visualize two-phase flow behaviour in particle packed bed.

2. Method and Visualisation

2.1 Refractive index matching

The refraction of light passing through a test section is one of the most common difficulties in flow visualization techniques used in fluid dynamics. Refractive index matching (RIM) is used by various researchers as a method to eliminate the refraction of light and to achieve optical accessibility in complex geometries including porous media. In this method, the refractive index of two materials in a mixed system is aligned to reduce image distortion. In the case of a porous bed, if the refractive index of the liquid is matched with the refractive index of particles in the bed, then the light passes through the porous media without refraction making the visualization of a two-phase flow pattern in porous media possible.

Various liquid and solid combinations for refractive index matching are reported in the literature. Here, we have used water beads to simulate a porous bed. The water beads are made up of super-absorbent polymers that absorb water and expand from an initial diameter of 2 mm to a final diameter of 9-10 mm. Since these particles are made up of water and have nearly the same refractive index as water, they eliminate the need for fine-tuning of refractive index for solid and liquid. Fig. 1 shows the example of refractive index matching between water beads and water.

(a) Water beads without liquid

(b) Water beads with liquid

Fig. 1: Image distortion test

2.2 Experimental facility

Fig. 2 depicts the schematic of the experimental test facility developed for visualization of two-phase flow in porous media using the RIM method. The test facility is designed to work at atmospheric pressure and room temperature. The test facility is divided into three main parts namely, a flow control unit, a test section and a visualization unit.

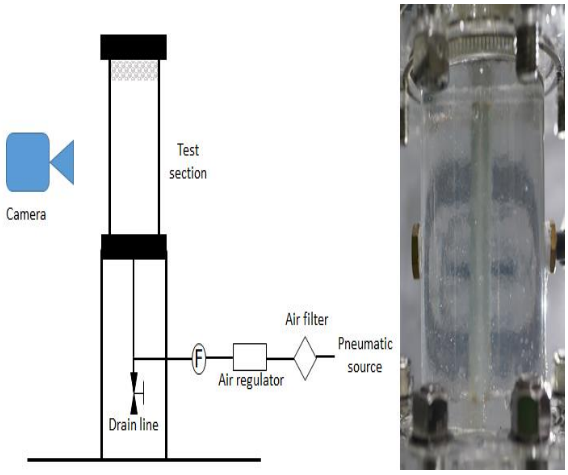

Fig. 2: Schematic of the experimental test facility

The flow control unit consists of an air filter, air regulator and flow controller. The air is supplied to the test section from a compressor line and it is cleaned and controlled using an air filter and a regulator, respectively. The flow rate of the air is measured using a flow meter installed in the line. The test section is made up of acrylic with a cross-section of 50 × 50 mm. A slow-motion camera is used to record flow inside the porous media. The porous testbed is made up of water beads with a diameter of 9-10 mm. Filtered water is used as a liquid to match the refractive index.

2.3 Visualization

In initial tests air is injected in a controlled manner to induce sporadic bubbles inside the porous bed. Fig. 3 depicts the progression of air bubble from porous bed captured by the camera. It is observed that the bubble passes through a path of least resistance in a porous bed. It breaks and merges with the other air bubbles trapped in cavities of porous media. In addition to this, we have conducted a test at increased air mass flow rate (Fig. 4) to visualize and study the two-phase flow pattern. According to our initial test results, we could verify that with matched refractive index, the air bubble growth and flow through cavities inside porous media can be captured using a direct visualization method. Currently, we are establishing the test methodology for estimating the two-phase flow behaviour and transitions in flow patterns at a given mass flow rate in the porous media using the visualization technique. The findings of this study will provide more experimental data for the development and improvement of two-phase flow models to improve their DHF predictability.

Fig. 3: Air bubble growth through porous media

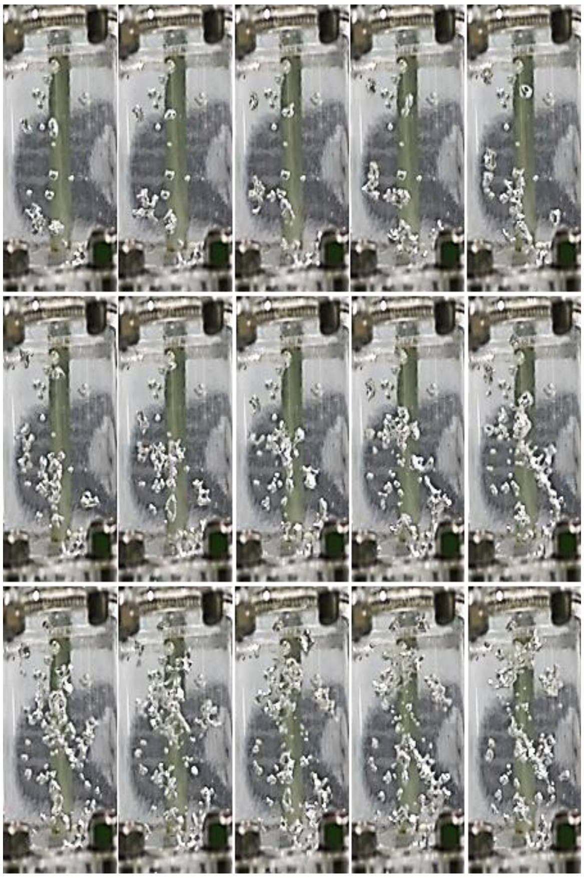

Fig. 4: Air bubble growth through porous media at increased flow rate

3. Conclusion

A preliminary test to investigate two-phase flow in porous bed is conducted using a RIM method. The porous bed was simulated using water bead particles made up of super absorbent polymer and water is used as the liquid. Initial image distortion tests confirmed the matching of refractive index between particles and liquid, allowing complete visual access inside the porous bed. In initial tests, we injected air to develop single bubble and captured their growth in a porous medium using a slow-motion camera. In addition, we conducted tests by increasing the mass flow rate of air to track two-phase flow in the porous matrix. With these experiments, we checked the feasibility of employing the RIM method to study two-phase flow in porous media. In the future, we will use the RIM method to investigate the two-phase flow behaviour inside porous media by varying particle diameters, airflow rates and shape of particles.

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