AN EXPERIMENTAL STUDY ON TWO-PHASE FLOW AND COOLABILITY OF PARTICULATE BEDS PACKED WITH MULTI-SIZE PARTICLES

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Abstract

This paper presents the results of an experimental study on the friction laws of two-phase flow and coolability in a volumetrically heated particulate bed packed with multi-size particles. The pressure gradients and dryout heat fluxes of the bed are measured for both top-flooding and bottom-fed schemes. The bottom-fed scheme is driven by forced injection of water from the bottom of the bed. Moreover, a varied configuration of the bed with a downcomer is employed to investigate the effectiveness of natural circulation-driven coolability (NCDC). The results show that at top-flooding conditions, both the pressure gradient and the dryout heat flux of the bed can be predicted by the Reed model. The coolability is enhanced by the bottom-injection and the downcomer, and the dryout heat flux rises significantly with increasing water velocity of bottom-injection.

1. Introduction

Two-phase flow in porous media is encountered in various engineering and technical processes. Special interest comes from the nuclear power safety, where two-phase flow and heat transfer in a debris bed may occur due to fragmentation of molten corium in coolant, and the coolability of the porous bed is crucial to the stabilization and termination of a severe accident in a light water reactor (LWR). Such a debris bed may take place in the lower head when the melt is discharged from the core to the lower head filled with water. It can also be formed in the rector cavity when the melt is discharged through the vessel failure site to a water pool located under the reactor pressure vessel (RPV) in the containment.

Towards quantitative understanding of debris bed coolability under both the in-vessel and ex-vessel conditions, many experimental an analytical studies have been conducted to investigate two-phase flow and heat transfer in particle beds. The key question in the debris beds coolability study is to answer whether decay heat can be completely removed by coolant flow in the debris bed [1-2]. The dryout heat flux (DHF), the limiting parameter for removal of the decay heat by boiling of the coolant, has been the focus of experimental studies and theoretical developments during the last three decades. Reviews on the experiments investigating the dryout heat flux have been reported by Bürger et al. [3], Schmidt [4] and Lindholm [5].

A good number of models to predict the dryout heat flux are also available in the literature. These models were developed to predict the maximum heat removal out of a one-dimensional particulate bed with top flooding where coolability is contingent upon Counter-Current Flooding Limit (CCFL). For most of the models (e.g., Lipinski model [6] and its variations [7-11]), the central point in modeling is to provide the formulation of the friction laws for the momentum equations:

$$-\frac{dp_l}{dz}=\rho_l g+\frac{\mu_l}{K\cdot K_{r,l}}J_l+\frac{\rho_l}{\eta\cdot\eta_{r,l}}J_l\cdot\left|J_l\right|-\frac{F_i}{1-\alpha} \tag{1a}$$

$$-\frac{dp_g}{dz}=\rho_g g+\frac{\mu_g}{K\cdot K_{r,g}}J_g+\frac{\rho_g}{\eta\cdot\eta_{r,g}}J_g\cdot\left|J_g\right|+\frac{F_i}{\alpha} \tag{1b}$$

where J_l and J_g are the superficial velocities of fluids, K and η are permeability and passability, μ is the viscosity and ρ is the density of fluid, F_i is interfacial friction. For uniform spherical particulate beds, they are expressed as

$$K=\frac{\varepsilon^3 d^2}{150(1-\varepsilon)^2} \qquad \eta=\frac{\varepsilon^3 d}{1.75(1-\varepsilon)} \tag{2}$$

where, d and ε are particle diameter and porosity of the particulate bed, respectively. The formulations of relative permeability K_r, relative passability η_r and interfacial friction F_i vary between different models and the most referenced correlations are listed in Table 1.

Table 1 Models for coolability analysis.

Model \ Parameter	K_r	η_r	F_i
Lipinski [6]	$K_{r,l}=s^3$ $K_{r,g}=\alpha^3$	$\eta_{r,l}=s^3$ $\eta_{r,g}=\alpha^3$	0
Reed [10]	$K_{r,l}=s^3$ $K_{r,g}=\alpha^3$	$\eta_{r,l}=s^5$ $\eta_{r,g}=\alpha^5$	0
Hu & Theofanous [11]	$K_{r,l}=s^3$ $K_{r,g}=\alpha^3$	$\eta_{r,l}=s^6$ $\eta_{r,g}=\alpha^6$	0
Schulenberg & Műller [8]	$K_{r,l}=s^3$ $K_{r,g}=\alpha^3$	$\eta_{r,l}=s^5$ $\eta_{r,g}=\alpha^6$, α>0.3 $\eta_{r,g}=0.1\alpha^4$, α≤0.3	$F_i=350s^7\alpha\frac{\rho_l K}{\eta\sigma}(\rho_l-\rho_g)g\left(\frac{J_g}{\alpha}-\frac{J_l}{s}\right)^2$

* $s=1-\alpha$

From Eqs. (1) - (2) one can see the particle diameter is an important parameter to determine flow friction (and therefore dryout heat flux) of a particulate bed. However, the real debris particles formed during fuel-coolant interactions (FCI) have a wide range of size distribution [12-14] and such prototypical characteristics play an important role in coolability analysis [15]. There is a clear need to define an effective particle diameter which can then be employed in the models for prediction of frictional drags and dryout heat fluxes.

To identify such an effective particle diameter of multi-size particles in a particulate bed, an experimental study on air/water two-phase flow in a particulate bed packed with multi-size spheres has been carried out [16-17], and the results show that if the effective particle diameter is represented by the area mean diameter of the particles in the bed [16], the frictional pressure drops of two-phase flow in the bed can be predicted by the Reed's model [10].

The present work is a follow-on study to quantify the coolability limits of a volumetrically heated bed packed with multi-size spherical particles under various flow (top-flooding/bottom-fed) conditions. The objective is to verify if the effective particle diameter and the model obtained from adiabatic two-phase flow data are still valid for boiling two-phase flow case.

Moreover, the effect of bottom ingression on coolability is also investigated by either forced injection or natural circulation through a downcomer. In reality, the downcomer represents a retrofit device or coolant access to the bottom of a heap-like bed, which removes the counter-current flow limitation of top-flooding, and thus enhances the coolability of the bed. The forced injection tests were performed to obtain the relationship between the dryout heat flux and the bottom-fed flowrate, which can be used to guide the design of the back-fitting for coolability enhancement.

The test facility POMECO-HT [18] is employed to perform the related experiments. The facility is designed in such a way that has a high power capacity (up to 84 kW or 2.1 MW/m^2) which enables to reach the coolability limit (dryout heat flux) of particulate beds within a broad range of porosity and particle diameters as well as coolability-enhanced measures such as bottom injection of water. The pressure gradients and dryout heat fluxes of such bed are measured for both top-flooding and bottom-fed schemes.

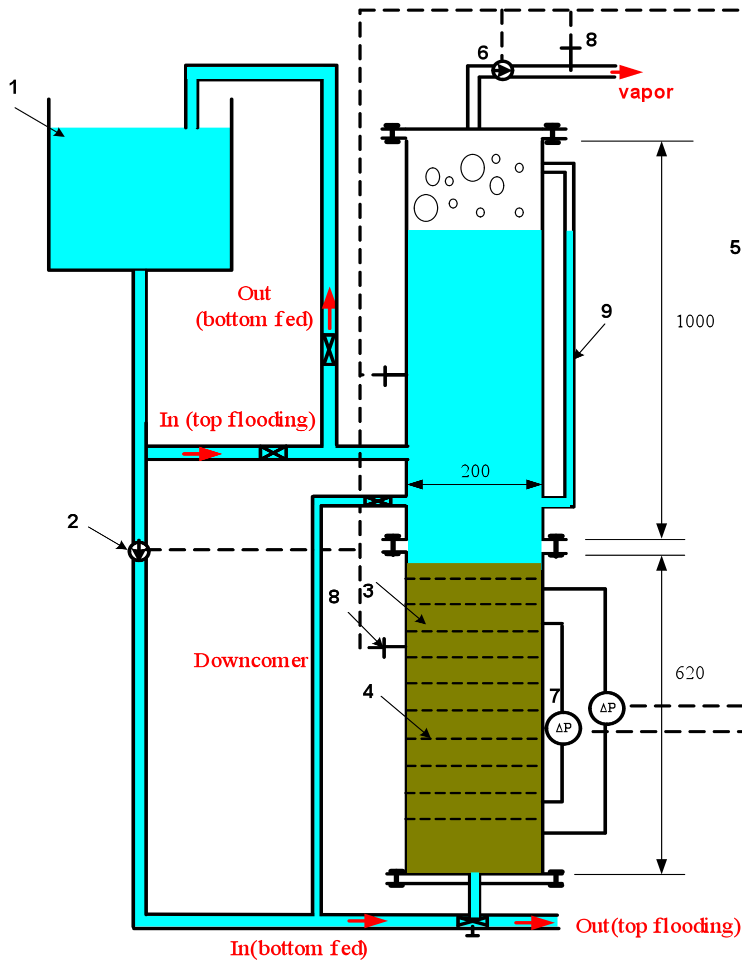
2. Description of test setup and instrumentation

2.1 Test facility

The schematic of the POMECO-HT test facility is shown in Fig. 1, which consists of test section, water supply system, electrical heaters and their power supply system, instrumentation (thermocouples, flowmeters, pressure and differential pressure transducers) and Data Acquisition System (DAS). The test section for accommodating the particulate bed and heaters is a stainless steel vessel whose cross-sectional area is 200 mm×200 mm rectangular with the height of 620 mm. Over the test section sits a stainless steel water tank (200 mm×200 mm) which is 1000 mm tall and connected to the test section through flanges. A level meter is installed on the water tank to monitor the water level during the experiments. A tube with the inside diameter of 8 mm serves as the downcomer connecting the bottom of the bed to the water tank at the level of 100 mm above the bed's top surface. The test section and the water tank are well insulated.

A total number of 120 electrical resistance heaters are uniformly embedded in the particulate bed, as shown in Fig. 2. Each heater has the diameter of 3 mm and the total length of 235 mm, with the heated part of 195 mm. The power rating of each heater is 700 W, so the maximum power capacity of the facility is 84 kW. The temperature profiles of particulate bed are measured by 96 thermocouples installed at 16 vertical levels (Fig. 2a), each having 6 thermocouples at different locations of the cross-section (Fig. 2b).

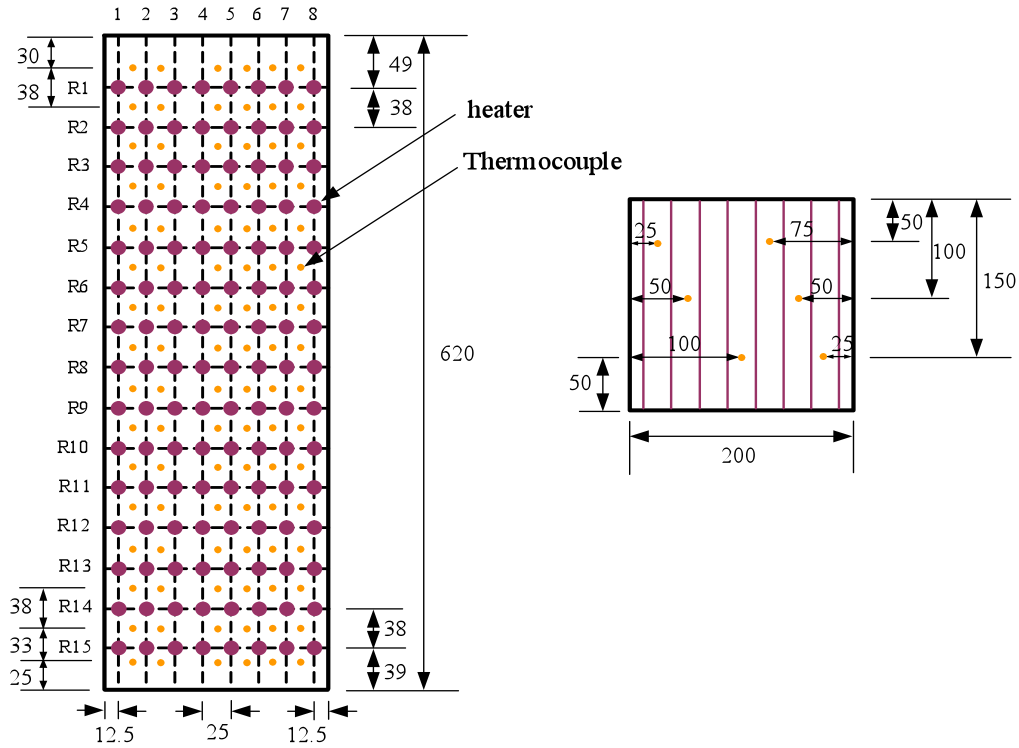
The flowrate of water injection from the bottom of the bed is measured by OMEGA flowmeter (rotameter, FL-2050). The temperatures are monitored by using OMEGA K-type thermocouples. Two Rosement-3051 differential pressure transducers with an uncertainty of ±0.25% of the full scale value (8kPa and 18 kPa separately) are installed to measure pressure drops along the entire and partial heights of the bed, respectively. The differential pressure transducers are connected to the test section through valve manifolds and pressure tapping of 10 mm diameter. A small chamber serving as a steam/water separator is used to prevent steam from entering the impulse lines. The valve manifolds are used with the differential pressure transducers to perform the block, equalizing and vent requirements of the transducers. The Data Acquisition System (DAS) is established by using National Instruments data input instruments and a computer program written in LabView. The program collects the data from the thermocouples, pressure transducers and flowmeters, and employs the indicators to show the numeric data.



1 water tank **2 flowmeter (water)** **3 particulate bed**
4 heaters **5 Data acquisition system** **6 flowmeter (vapor)**
7 differential pressure transducer **8 Thermocouples** **9 level meter**

Figure1 Schematic of POMECO-HT facility.

The tests started with preheating of the bed to fully saturated conditions in both temperature and saturation, and afterwards the power input to the bed is increased in small steps to minimize disturbance to the flow regime in the bed. The waiting time is no shorter than 20 minutes at each power step prior to recording the data, being consistent with the approach of Hu and Theofanous [11] to determine the dryout heat flux at equilibrium conditions. When approaching the expected dryout condition, the power increment steps are chosen even smaller to avoid the overshoot of the dryout heat flux. A dryout is considered to be reached in a location where the temperature sensor reading is 10 ^{o}C higher than the saturation temperature. The dryout heat flux is further confirmed if the dryout disappears by slightly reducing the power and waiting a longer time. The system is operating under atmospheric pressure.



(a) side view (b) top view

Figure 2 The distribution of heaters and thermocouples.

2.2 Test bed

The particulate bed employed in the present study is packed with multi-diameter spheres whose size distribution is similar to that of the DEFOR-A debris particles [19], as shown in Fig. 3. Also the measured particle size distributions from the FCI tests of FARO, CCM and MIRA (data from [5]) are plotted in Fig. 3 for comparison with the present particle size distribution.

The test bed has the height of 600 mm and the porosity of 0.29. The porosity is determined by accurate measurement of the material density (double check and verification of factory data) and the particle mass (free of moisture) loaded into the bed.

The effective particle diameter of the multi-diameter spheres is 2.25 mm, which was obtained in our previous work performed for adiabatic single air/water flow in a packed bed with the same particles, where the measurement pressure gradient and also the Ergun's equation are considered [17].

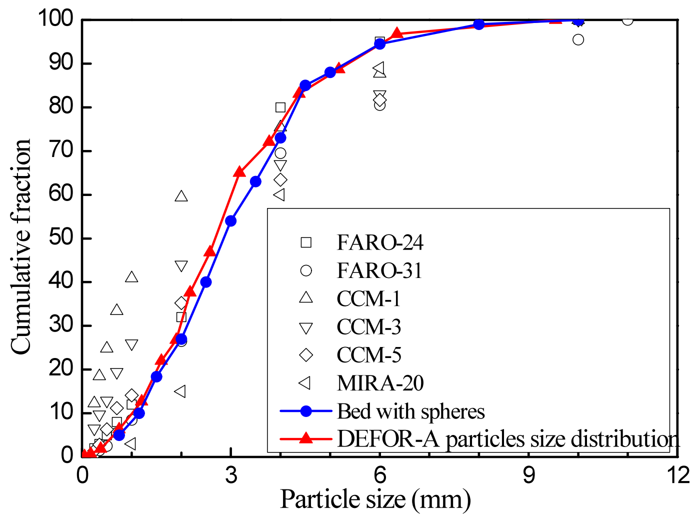


Figure 3 Size distributions of particles in the test bed.

3. Results and discussions

3.1 Friction laws of the bed

Base on the effective particle diameter obtained from adiabatic air/water single-phase flow experiment on the bed [17], two-phase flow tests with the volumetrically bed are also performed. This is to determine which model in Table 1 can be used to predict the frictional pressure drops of boiling two-phase flow in a particulate bed packed with multi-size spherical particles under either top-flooding or bottom-injection condition.

According to the energy balance, the net heating power (Q) for evaporation of water in the test section should be equal to the total power minus the heat loss. Thus, the superficial velocity of steam, J_g can be deduced from Eq. 3. If subcooled water is injected to the bed, it is necessary to add a correction for sensible heat before saturation temperature; see Eq. 4 for calculating the steam superficial velocity. The superficial velocity of water, J_l is derived by the water injection rate J_l^0 and the continuity equation, as shown in Eq. 5. J_l^0 is zero for top-flooding beds.

$$J_g(z) = \frac{\int_0^z Q(z)dz}{\rho_g h_{fg}} \tag{3}$$

$$J_g(z) = \frac{\int_0^z Q(z)dz - Mc_{p,l}(T_{sat} - T_{in})}{\rho_g h_{fg}} \tag{4}$$

$$J_l = J_l^0 - \frac{\rho_g}{\rho_l} J_g \tag{5}$$

Fig. 4 illustrates the measured pressure gradients of the bed packed with multi-diameter spheres under top-flooding condition. The prediction results of different models are also presented in the figure. In top-flooding scheme, water flows from the water pool above the bed down into the porous bed. Vapor generated in the volumetrically heated bed by evaporation, rises up and escapes out of the bed, by which the heat is taken away from the bed. Counter-current flow of water and vapor is established inside the bed.

It can be seen from Fig. 4 that the measured pressure gradients are all lower than the water hydrostatic pressure gradient (9.58 kPa/m) for top-flooding condition. It means the interfacial friction existing between the vapour and water just hinders the water penetrating downward in the heated bed. From the comparisons between the measured pressure gradients and the predicted by different models, it is found that the Lipinski model predicts well the pressure gradients of the bed at low vapour superficial velocity (<0.2 m/s). With increasing the vapour velocity up to occurrence of dryout (see the last two data points in Fig. 4), the prediction of Reed model is more comparable with the experimental data. This implies that the Lipinski model is capable of predicting the drags of boiling two-phase flow before dryout occurs, while the Reed model is more suitable for prediction of the drags in the vicinity of dry out heat flux.

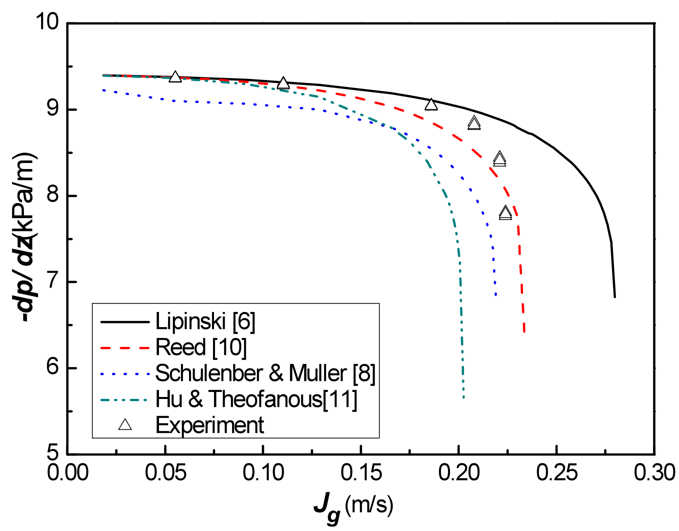


Figure 4 Pressure gradients in the top-flooding bed.

Tests were carried out with water injection from the bottom of the bed. In bottom injection conditions, co-current flow establishes in the lower or entire height of the bed, depending on the injection rate. Fig. 5 shows the measured pressure gradients for the injection rate of 0.125 mm/s. One can see that the experimental data have a good agreement with the predictions of the Lipinski model at low vapour superficial velocity. When the heating power is approaching the dryout heat flux (DHF), the Reed model predicts better the pressure gradients of the bed.

It should be pointed out that in the present study the pressure drops were not recorded when the heating power is lower than 6 kW, corresponding to 0.08 m/s for vapor superficial velocity. Thus, it is not clear if the S-shaped pressure gradient obtained in [4] will appears at low vapor velocity for the particulate bed here. This is to be confirmed in the subsequent tests.

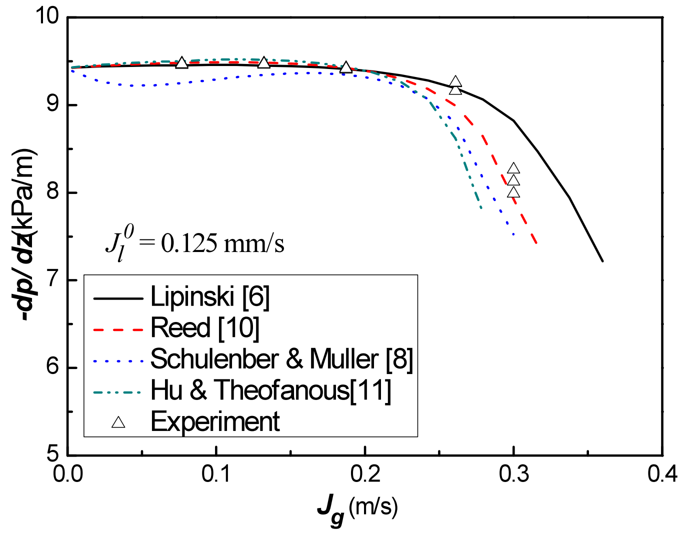
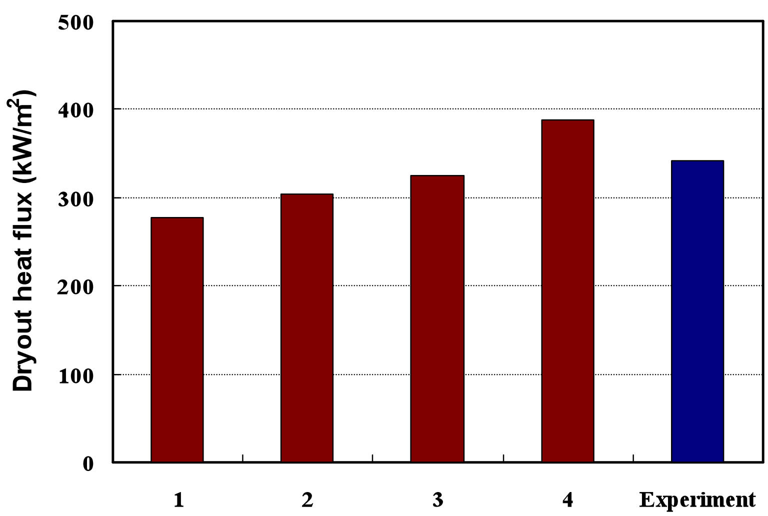


Figure 5 Pressure gradients in the bottom-injection bed.

3.2 Dryout heat flux of the top-flooding bed

The bed is flooded from the top, with overlying water pool of 500 mm. The water is at saturated temperature under atmospheric pressure. The heating power at which the dryout takes place is 13.68 kW, resulting in the dryout heat flux of 342 kW/m^2. As illustrated in Fig. 6, this value is relatively close to the prediction of the Reed model for dryout heat flux in a top-flooding bed with the effective particle diameter of 2.25 mm and porosity of 0.29. This is consistent with the prediction of frictional pressure drops, as stated above.



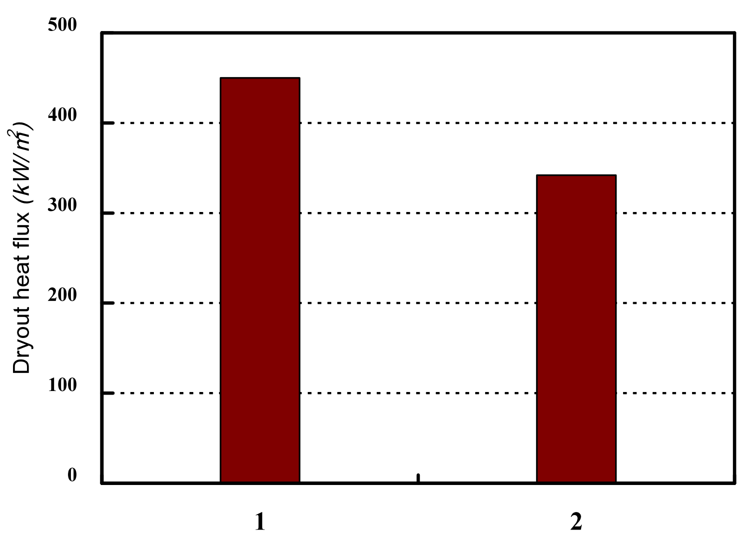
1–Hu & Theofaneous model [11]; 2–Schulenberg & Műller model [8];
3–Reed model [10]; 4–Lipinski model [6]

Figure 6 Dryout heat flux measured and predicted by various models.

3.3 Dryout heat flux of the bed with a downcomer

For the bed packed with the same particles as the top-flooding experiment, the dryout heat flux of the bed with an 8-mm-ID downcomer was measured to be 450 kW/m^2, about 30% higher than that of the pure top-flooding bed; see Fig.7. The coolability enhancement by the downcomer is quite significant, considering that the flow area of the downcomer is only 0.5% of the total flow area of the bed.

The reason for the contribution of the downcomer is straightforward. In the top-flooding bed, the vapor flowrate increases with raising the heating power. The increased vapor flowrate requires a higher water ingression rate to balance the mass in the bed. On the other hand, the flow of vapor also acts as a resistance to water flowing downward. At a certain level of heating power, the upward vapor flowrate is sufficient to prevent the water ingression from further increasing, reaching the so-called Counter-Current Flooding Limit (CCFL) results. The downcomer can break the CCFL, and thus increases the dryout heat flux. The water can be directly transported from the top water layer to the bottom of the bed by natural circulation. Therefore the co-current flow of water and vapor takes place least in the lower part of the bed. Consequently, not only does the dryout heat flux increase, but also the dryout location move upward (it initially occurs at the position of 438 mm above the bottom of the bed).



1–with downcomer; 2–without downcomer

Figure 7 Dryout heat flux measured with/without downcomer.

3.4 Dryout heat flux of the bed with bottom-injection

From the experiment with the downcomer, it is obvious that the bottom-fed flowrate is the key to enhance the coolability. There are many parameters affecting the bottom-fed flowrate, such as the size of the downcomer, the geometry (e.g., height) and characteristics (e.g., porosity and particle size) of the bed, etc. Instead of varying all the parameters, here we investigate the effect of the bottom-fed velocity on the dryout heat flux by varying the bottom injecting flow rates. This gives the quantitative data for the design of any coolability enhancement measure.

Figure 8 shows the measured dryout heat flux with increasing rate of bottom injection flowrate, while Fig. 9 is the dryout position in vertical direction at different bottom flowrates. As illustrated in Fig. 8, the dryout heat flux rises with increasing the water velocity of bottom injection. The dryout heat flux of the bed can be more than the double of that in top-flooding case, if the superficial velocity of water injection is greater than 0.21 mm/s. From Fig. 8, one can also conclude that the bottom-fed velocity for the case with the downcomer is around 0.09 mm/s.

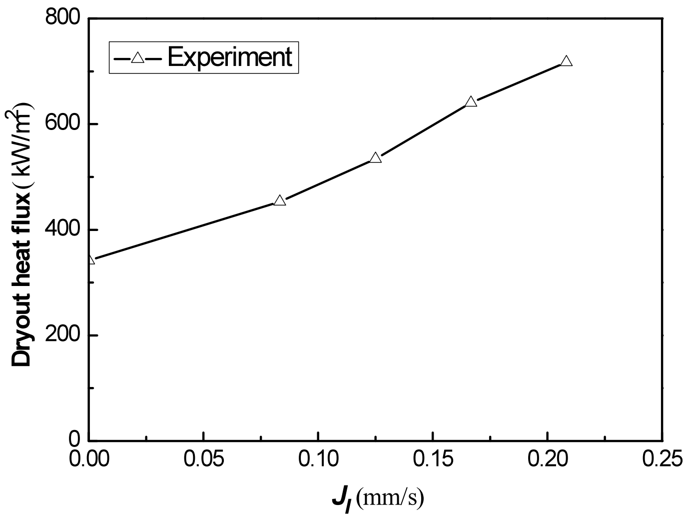


Figure 8 Dryout heat flux measured at different bottom injection flowrate.

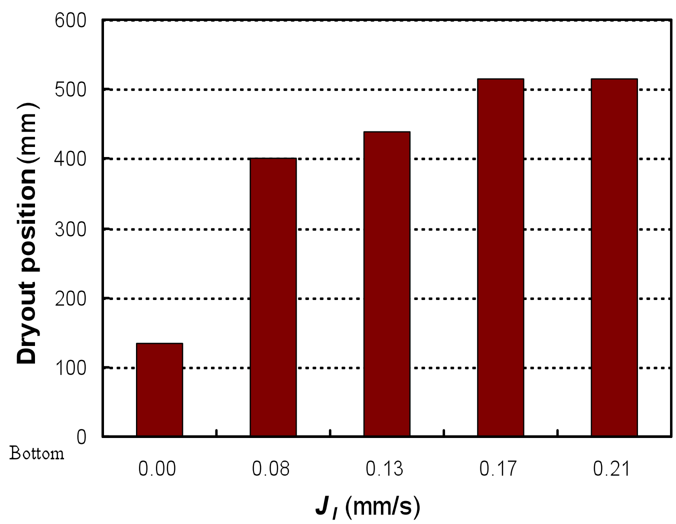


Figure 9 Dryout locations (vertical direction) at different bottom injection flowrate.

4. Conclusions

Motivated by the uncertainty reduction in coolability assessment of debris beds formed during a hypothetical severe accident, an experimental study were performed on the POMECO-HT test facility to investigate the flow resistance and dryout heat flux of a particulate bed packed with multi-diameter spheres which have the similar size distribution to the debris particles obtained in the FCI tests. The results show that given the effective particle diameter obtained from adiabatic air/water single-phase flow experiment on the bed, the Reed model well predicts the pressure drop of two-phase flow through the volumetrically bed when it is about to dry out, while the Lipinski model appears more suitable for the flows far before the dryout occurs. The measured dryout heat flux is also well predicted by the Reed model for the top-flooding bed. The bottom-fed coolant improves the dryout heat flux significantly. For instance, the dryout heat flux of the bed with an 8-mm-ID downcomer is elevated by 30%, comparing with the top-flooding bed. Through the forced injection of water from the bottom of the bed, the relationship between the dryout heat flux and bottom-fed flowrate is obtained, as shown in Fig. 8. Later, the effects of non-spherical particles on dryout heat flux will be studied, where the shape factor of non-spherical particles should be considered.

ACKNOWLEDGEMENT

This study is supported by the research programs of APRI7, SARNET2, ENSI and NKS. The discussions with the MSWI team members at KTH are gratefully acknowledged. The authors thank the staff at the NPS Laboratory of KTH for their technical support in the experimental setup.

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