

PREDICTION OF DRYOUT HEAT FLUX OF VOLUMETRICALLY HEATED PARTICULATE BEDS PACKED WITH MULTI-SIZE PARTICLES

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Abstract

This paper presents MEWA code calculations for the experiments performed on the POMECO-HT facility to investigate the dryout heat flux of various particulate beds, with the objective to interpret the experimental data and validate the code. The code is then applied to coolability assessment for ex-vessel debris beds related to severe accident scenarios of a boiling water reactor (BWR). The characteristics of a prototypical debris bed, such as multidimensionality and multiple particle sizes are emphasized in this study. The volumetrically heated particulate beds of the POMECO-HT experiments are packed with multi-size particles and equipped with a downcomer to investigate the bottom-fed coolability by natural circulation which demands 2D simulation. The results show that the MEWA code is capable of predicting the coolability of the bed with a downcomer (2D) as well as the top-flooding bed whose dryout heat flux can also be predicted by the Reed model (1D). Given the effective particle diameter (1 mm) and porosity (0.45) defined from a few FCI tests, the ex-vessel debris beds for a BWR chosen here are coolable with varied margins: i) compared with a top-flooding bed (spreading over the entire floor of the cavity), the cylindrical configuration with an annular-gap water supply enhances the coolability comparison, but the gain is marginal since the large diameter of the bed prevents the side coolant from flowing into the center of the bed; ii) a heap-like debris bed reduces rather than improves coolability due to its considerable height and base diameter; iii) a stratified debris bed with a fine-particle layer on the top may challenge the coolability.

1. Introduction

This paper is concerned with assessment of debris bed coolability in a postulated severe accident of light water reactors (LWRs), when molten corium is relocated into a water pool, fragmenting and forming a particulate debris bed on the pool bottom.

Various models have been developed to assess the coolability of a debris bed, where the particle diameter and the bed porosity are important input parameters. For a bed packed with multi-size particles, i.e., the case of debris beds formed from fuel-coolant-interaction [1-5], the selection of particle diameter is not straightforward. The widely-accepted practice [6] is to utilize an averaged particle diameter in the modeling calculations, which is called the effective particle diameter. In our recent work [7-11], experimental studies have been carried out to determine the effective particle diameter for various particulate beds. The particulate beds are chosen in such a way that some prototypical characteristics of debris beds analyzed in our previous study [12] can be reflected, so that the data can be used to reduce the uncertainty in quantification of debris bed coolability. The general conclusion is that if the effective particle diameter is represented by the

area mean diameter of the particles in the beds, their dryout heat fluxes can be predicted by the Reed model [11].

However, the Reed model is only limited to coolability analysis of one-dimensional debris beds. In order to find a multi-dimensional simulation tool for two-phase flow and heat transfer in porous media, the present study chooses the MEWA code to analyze the typical tests performed in the above-mentioned works. The idea is to interpret the experiments and validate the computational tool against the experimental data, and then apply it for reactor case. The experimental data are ideal for validation of the code, since the data quality is assured through well-defined characteristics of particulate beds, good instrumentation (including measurement of pressure drops) and controlled thermal-hydraulic conditions. In particular, the coolability of the bed with a downcomer can only be assessed by the multi-dimensional simulation code.

This paper is organized as follows. It first gives the general information of the POMECO-HT tests and the MEWA code. Then, it presents the comparison of the calculated dryout heat fluxes with the experimental data to verify the predictive capability of the code. Finally, the MEWA code is applied to perform coolability analysis for ex-vessel debris beds related to severe accident scenarios of a boiling water reactor (BWR). The multidimensionality of the beds is emphasized in the analysis.

2. Descriptions of POMECO-HT experiment and MEWA code

2.1 POMECO-HT experiment

The details of the POMECO-HT test facility can be found in [9]. The main part of the facility is a stainless steel vessel whose cross-sectional area is 200 mm×200 mm rectangular with the height of 620 mm, used to accommodate the particulate bed and heaters. Over the vessel sits another stainless steel water tank (200 mm×200 mm) which is 1000 mm tall. A tube 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. A total number of 120 electrical resistance heaters are uniformly embedded in the particulate bed, as shown in Fig. 1. Each heater has the diameter of 3 mm and heated length of 195 mm at the power rating of 700 W; thus 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).

Two particulate beds are selected in the present study, which are packed with multi-diameter glass spheres and multi-size sand particles, respectively. The size distributions of the two types of particles are as shown in Fig. 2, similar to that of the DEFOR-A debris particles [13]. Also the measured particle size distributions from the FCI tests of FARO, CCM and MIRA (data from [5]) are plotted in Fig. 2 for comparison with the present particle size distribution.

The effective particle diameters of the beds are obtained from the experiment [10-11], which are 2.25 mm and 1.75 mm for the glass spheres and the sand particles, respectively; see Table 1. The porosity of the bed packed with glass spheres is 0.29, and 0.37 for the bed with sand particles. The two test beds have the height of 600 mm. There is a 20 or 30 mm thick layer (see figures

below) of large particles (6 mm in diameter) on the bottom of the beds, arranged to facilitate water ingress for bottom-fed tests. All tests are carried out under atmospheric pressure.

Table 1 Parameters of the particulate beds.

Bed	Particles	Size distribution	Porosity	Effective diameter (mm)
1	Glass spheres	see Fig. 2	0.29	2.25
2	Sand particles	see Fig. 2	0.37	1.75

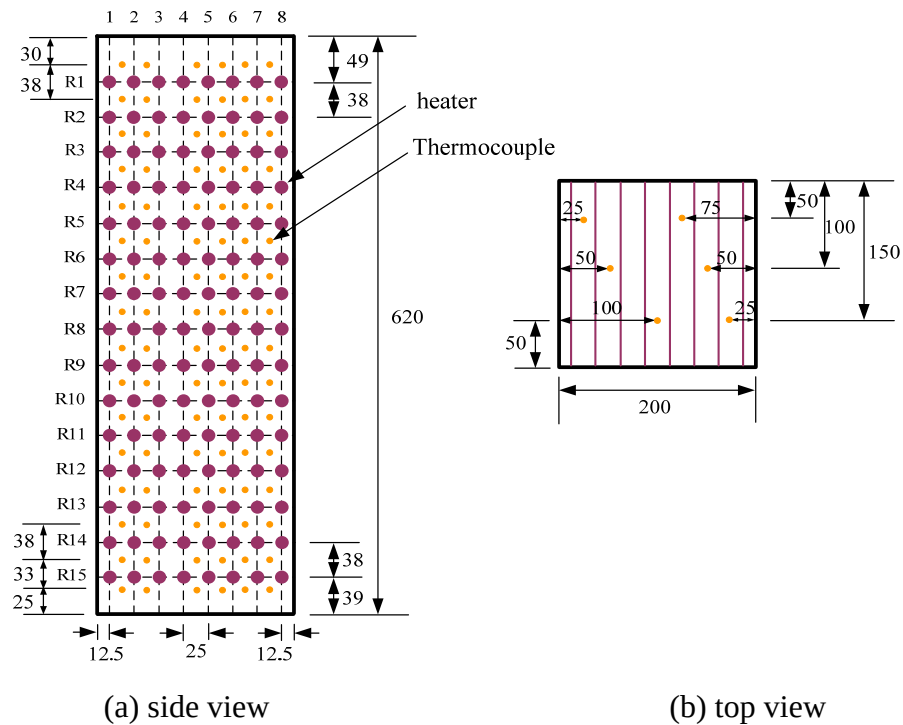


Figure 1 Distribution of heaters and thermocouples in particulate bed.

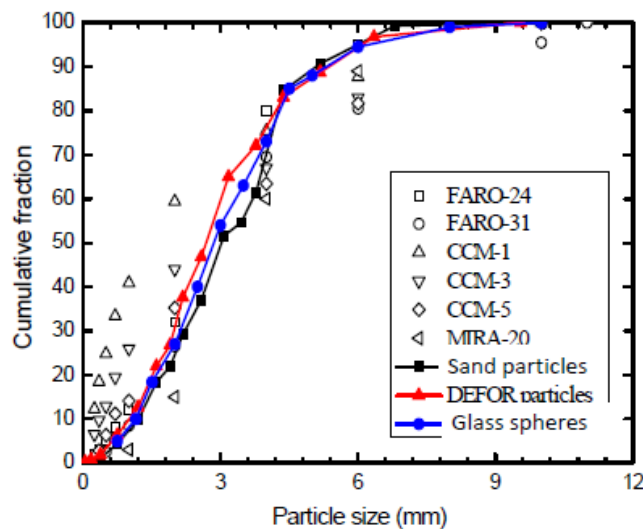


Figure 2 Size distributions of particles in the test beds.

2.2 MEWA code

The MEWA code was developed at IKE-Stuttgart University, Germany for simulating transient behavior of debris bed formed in severe nuclear reactor accidents of LWRs. The code will be integrated into the system code ATHLET-CD. The debris bed is modeled in two dimensions with cylindrical or Cartesian geometry using a quasi-continuum approach. Three separate phases for solid particles, water and vapor are considered. The solid matrix is assumed to be fixed.

The mass conservation is governed by the equations:

$$\frac{\partial}{\partial t}(\varepsilon\alpha\rho_g) + \nabla\rho_g\vec{j}_g = \Gamma, \text{ and } \frac{\partial}{\partial t}[\varepsilon(1-\alpha)\rho_l] + \nabla\rho_l\vec{j}_l = -\Gamma \quad (1)$$

for vapor and liquid, respectively, where α is the void fraction, ε is porosity, $\vec{j}_g$ and $\vec{j}_l$ are the superficial velocity vectors of vapor and liquid, and Γ is the net mass conversion rate (vaporization or condensation) between liquid and vapor.

In the energy conservation equations of vapor and liquid, the mechanical work due to friction and pressure forces is generally neglected. Radiation heat transfer is implicitly considered in the solid energy conservation equation via an effective thermal conductivity.

The momentum conservation equations are simplified by an assumption that the temporal and spatial derivatives of the velocities are neglected, because the dominant force is the friction between the particles and the fluids, and velocity field can be simultaneously adjusted to the pressure field. Especially for quasi steady-state processes, such an assumption is acceptable. As a result, the momentum conservation yields

$$-\nabla p_g = \rho_g\vec{g} + \frac{\vec{F}_{pg}}{\varepsilon\alpha} + \frac{\vec{F}_i}{\varepsilon\alpha} \quad (2)$$

$$-\nabla p_l = \rho_l\vec{g} + \frac{\vec{F}_{pl}}{\varepsilon(1-\alpha)} - \frac{\vec{F}_i}{\varepsilon(1-\alpha)} \quad (3)$$

for vapor and liquid, respectively. Here, $\vec{F}_{pg}$ is drag forces between particles and vapor, $\vec{F}_{pl}$ is drag forces between particles and liquid, and $\vec{F}_i$ is the interfacial drag between liquid and vapor. The drag forces are derived from the Ergun equation [14] and the models for frictional laws of two-phase flow in porous media [15-16]. Details of constitutive laws and correlations to close the conservation equations, including flow and heat transfer, can be found in [17-18].

3. Results of the code validation

3.1 The bed packed with glass spheres

The particulate bed is packed with glass spheres with the size distribution as the blue line in Fig. 2. The effective particle diameter is 2.25 mm and the porosity is 0.29. The bed is 580 mm tall, on a 20-mm-thick bottom layer (Fig. 3a) composed of 6-mm-diameter particles. For the top-flooding case, the bed has an overlaying water pool of 500 mm. The water is saturated at atmospheric pressure. The measured dryout heat flux is 342 kW/m² [11]. In the MEWA

calculation for this case, only the right half of the bed is considered due to the axisymmetric geometry. Since the height of the top water layer does not affect the coolability in such a configuration, only 20-mm-thick water layer is chosen with an open boundary condition. Thus, a two dimensional domain of 100 mm (horizontal) $\times$ 620 mm (vertical) is assumed with a quadrilateral meshing of 70 $\times$ 10 cells. A calculation with a fine grid of double cells is also performed to confirm the solution. Fig. 3b shows the profiles of liquid velocity and particle temperature in the bed after dryout occurs at the bottom of the bed. The dryout heat flux predicted by the MEWA code is 336 kW/m², which is comparable with the experimental value (342 kW/m²).

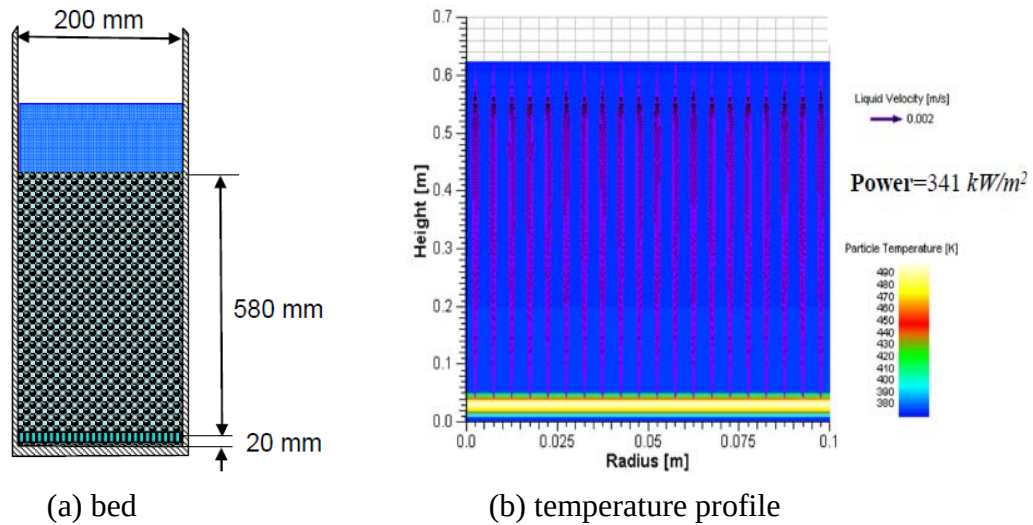


Figure 3 Dryout of the glass sphere bed under top-flooding condition.

For the bed with a downcomer, a tube of 8-mm inside diameter connects the bottom of the bed to the water pool atop. This means the tube works as a downcomer to transport water directly to the bottom of the bed because of the density difference between two-phase flow in the bed and single-phase flow in the tube. The gravity head difference between the downcomer and the particle bed provides a driving force for natural circulation which alleviates the counter-current flow limitation in the top-flooding case and therefore enhances the coolability. The dryout heat flux for the bed with an 8-mm-ID is measured to be 450 kW/m², about 30% higher than that of the top-flooding case [11]. 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 downcomer enable co-current flow of water and vapor at least in the lower part of the bed, which does not only raise the dryout heat flux, but also lifts the first dryout position upward (it occurs at the elevation of 438 mm above the bottom of the bed).

To be able to simulate the influence of the downcomer using the MEWA code, as equivalent bed as shown in Fig. 4a is assumed in the present study, where the downcomer is situated in the center of the bed, instead of outside of the bed in the real setup. This way the same computational domain of 100 mm (horizontal) $\times$ 620 mm (vertical) can be chosen in the simulation, with the corresponding meshing of 120 $\times$ 20. The dryout heat flux predicted by the MEWA code is 428 kW/m², which is 4.9% higher than the experimental value (450 kW/m²). Fig. 4b shows the profiles of liquid velocity and particle temperature in the debris bed after dryout is

initiated. It is observed that the water enters the bed mainly at the bottom of the bed through the downcomer. The dryout begins at the elevation of ~ 400 mm, which is different from the top-flooding case where the bed starts dryout from bottom (cf. Fig. 3b). The dryout position is just a little bit lower than the experimental value (438 mm). The predictions in both the dryout heat flux and dryout position are acceptable, given the approximation in simulation and accuracy in measurement.

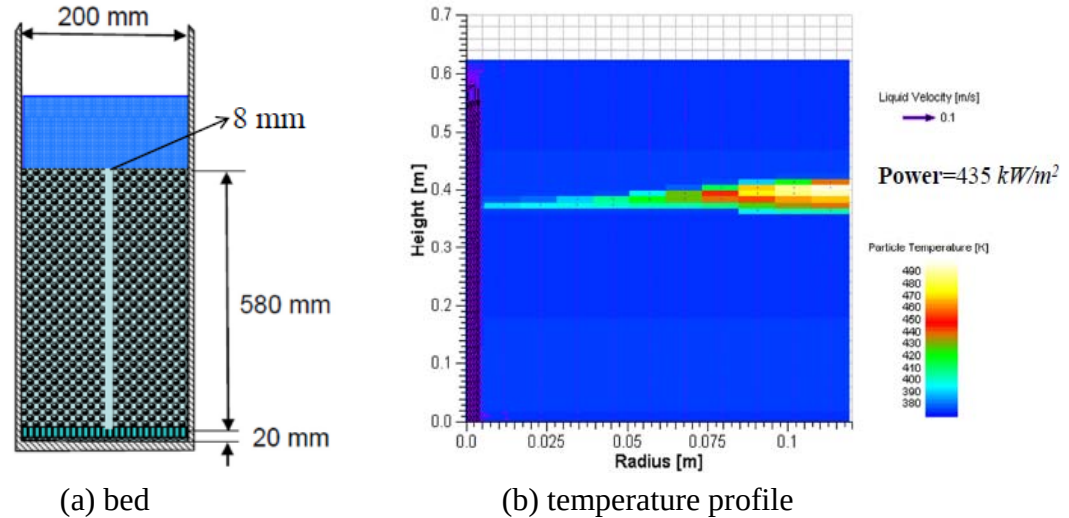


Figure 4 Dryout of the glass sphere bed with an 8-mm-I.D. downcomer.

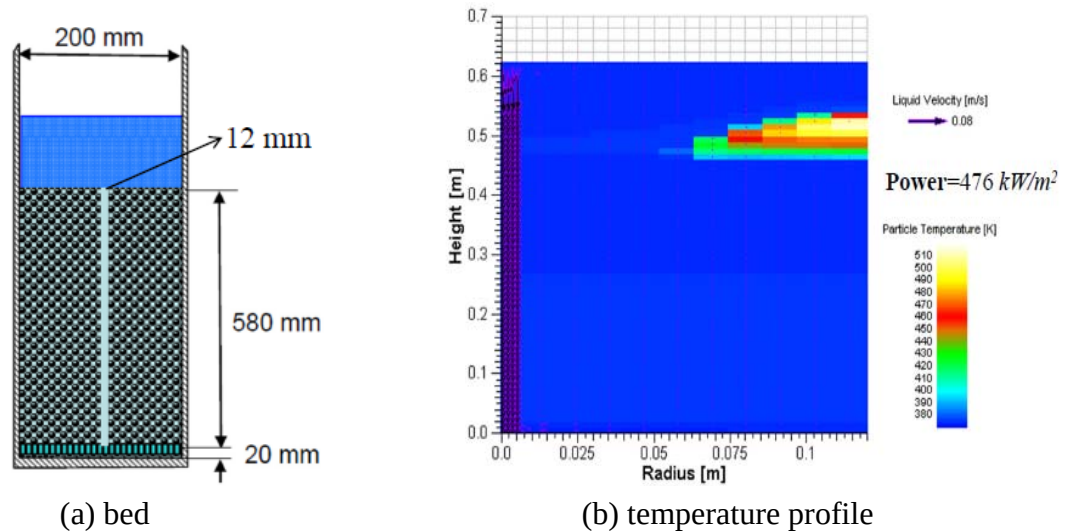


Figure 5 Dryout of the glass sphere bed with a 12-mm-I.D. downcomer.

If the inside diameter of the downcomer increases to 12 mm (cf. Fig. 5a), the dryout heat flux predicted by the MEWA code is 468 kW/m^2 , which is 9% higher than that of the bed with an 8-mm-ID downcomer (428 kW/m^2), while the dryout starts at the elevation of ~ 500 mm (see Fig. 5b), which is also higher than the position of ~ 400 mm for the bed with the 8-mm-ID downcomer. It appears that the gain in the dryout heat flux is not proportional to the increase in flow area of the downcomer, since the flow area of the 12-mm tube is 2.25 times of that of the 8-mm tube. This means there is a threshold value for the downcomer size, above which the further

coolability enhancement will be dismissing. The reason is that the flow resistance is governed by the two-phase flow in the particulate bed.

3.2 The bed packed with sand particles

The particulate bed is packed with sand particles with the size distribution as the black line in Fig. 2. The effective particle diameter is 1.75 mm and the porosity is 0.37. The bed of the height 570 mm is sitting on a 30-mm-thick bottom layer (Fig. 6a) filled with 6-mm-diameter particles. For top-flooding of the bed with saturated water at atmospheric pressure, the measured dryout heat flux is 450 kW/m^2 [9], while the predicted value by the MEWA code is 471 kW/m^2 . It can be seen that the difference between the measured and the predicted is marginal.

To investigate the influence of a cake formed in a debris bed on its coolability, a simulant cake is embedded in the upper part of the sand particle bed. The simulant cake is formed by a fine-particle ($<0.5\text{mm}$) layer surrounded by an aluminum foil. The thickness of the cake is $\sim 30 \text{ mm}$, with the cross-sectional area of $160 \times 160 \text{ mm}^2$. It is centrally located 385 mm above the bottom of the bed. The measured dryout heat flux is 198 kW/m^2 [9], while it is predicted to be 185 kW/m^2 by the MEWA code. The location of dryout takes place underneath the simulant cake in the experiment, but the first dryout position is situated in the simulant cake in the simulation. This may be because no heaters are embedded in the cake of the experiment, but the bed in the simulation is uniformly heated everywhere.

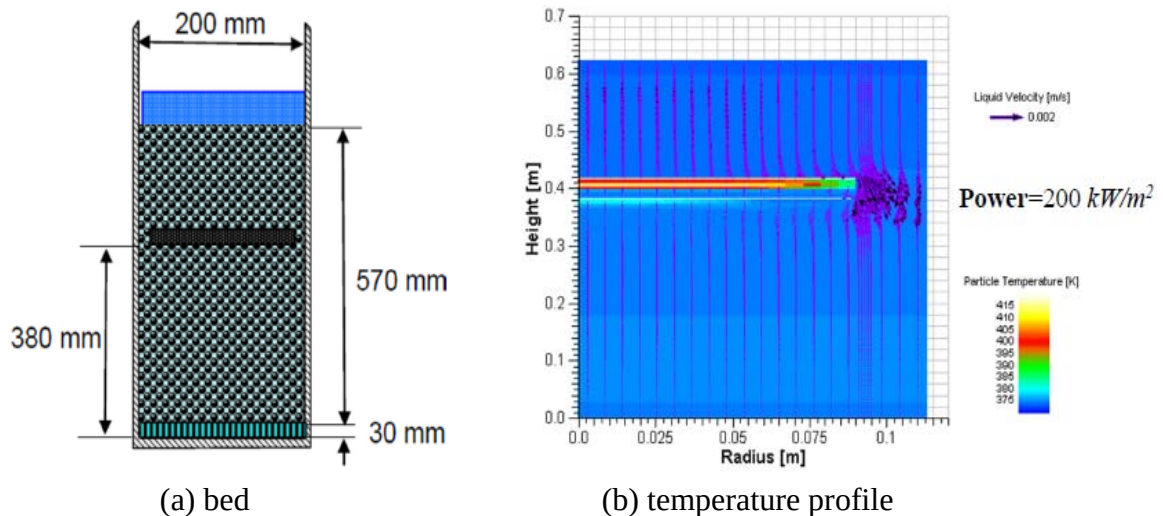


Figure 6 Dryout of the sand particle bed with a simulant cake.

4. Reactor application analysis

For application of the MEWA code to coolability analysis of a prototypical-scale debris bed, we investigate the effect of debris bed configurations (multidimensionality) on its coolability. The analysis is performed for an ex-vessel debris bed formed in the reactor cavity flooded with water during hypothetical severe accident scenarios of a boiling water reactor (BWR). The reactor has the thermal power of 3900 MW and the cavity diameter of 12 meters (see Fig. 7). The maximum mass of the corium melt ejected to the reactor cavity is 256000 kg, with the solid volume of 29.1

m³ (without void). The depth of the water pool in the cavity is 8 meters, and the melt is assumed to be well fragmented in the deep water pool due to fuel coolant interactions (FCI).

In the previous studies (e.g., [5], [12]), the effective particle diameter of debris beds is assumed as 3 mm and the bed's porosity as 0.4. However, the recent works [2-3] indicate the porosity tends to be higher than 0.4, while the effective particle diameter is smaller than 3 mm. Based on the recent data of DEFOR and POMECO research at KTH and the findings elsewhere [6, 19], here we define the effective particle diameter of the debris particles as 1 mm and the bed's porosity as 0.45. If the pressure in the containment is 1 bar and the water in the cavity is assumed to be saturated (long-term coolability), the dryout power density of top-flooding such bed is 910 kW/m³ predicated by the code. Since the decay heat is within the range of 0.5~1% the thermal power of the reactor, which is 375~750 kW/m³ in term of the debris bed volume, the debris bed is coolable by only top-flooding (i.e., the debris particles evenly spread over the entire floor of the cavity, to form a bed with 1D counter-current flow in it). The coolability margin is getting smaller for the high decay case.

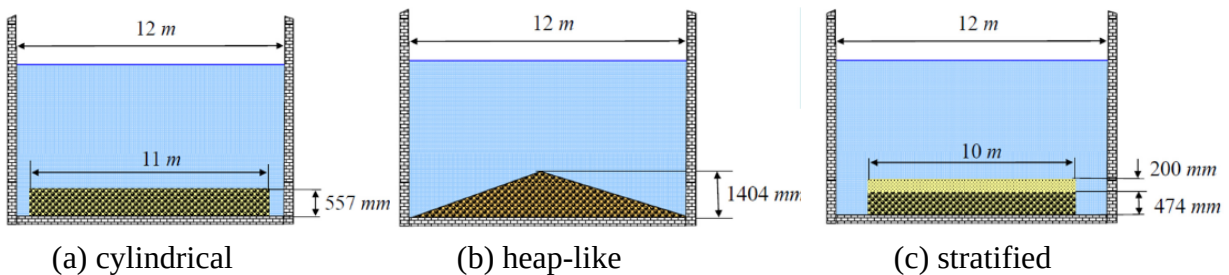


Figure 7 Configurations of an ex-vessel debris bed.

What if other configurations of the debris beds are formed to allow multi-dimensional flow? A few of representative beds are as shown in Fig. 7 where Fig. 7a represents a scenario where the debris does not occupy the entire floor of the cavity, leading to an annular gap between the bed and the cavity wall. This is more realistic than the uniform spreading assumption, due to the large area of the cavity floor. In this case, the dryout power density is 956 kW/m³, 9% higher than that of the top-flooding bed, due to water supply from the annular to the bottom of the bed. The gain in coolability appears marginal since the large diameter of the bed prevents the side coolant from flowing into the center of the bed. If the bed is formed atop an unheated layer, for example, due to the first release of stainless steel melt following vessel failure, the coolability enhancement by the annular-gap formation will be more pronounced [12].

For the bed with a heap-like shape (cone) as shown in Fig. 7b, the dryout power density is 535 kW/m³. Surprisingly, instead of increase in dryout power density, it decreases by 41%, compared with the value of the top-flooding bed (910 kW/m³). This is because the heap-like bed has the height of around three times the top-flooding bed, given the same mass of the debris. The special geometry results in a high void zone near the tip of the cone, where dryout occurs first. Notably, due to the high rate of steam flow through the tip, the dryout zone and its temperature do not vary rapidly with increasing power load. In other words, the steam flow plays a role in coolability.

An axially stratified debris bed (cf. Fig. 7c) may be formed in a severe accident, with a fine-particle layer settle atop a larger-size particle layer, due to the consequence of steam explosion.

The coolability of such bed is determined by the top layer in top-flooding scheme, since the capillary force across the interface of the two layers prevents coolant from reaching the lower layer. Such a barrier, however, can be alleviated if coolant is supplied from the bottom through the annular gap as shown in Fig. 7c where it is assumed that a 200-mm-thick layer with 0.5-mm-diameter particles sits atop a 474-mm-thick layer with 1-mm-diameter particles. The porosity is 0.45 for both layers. The dryout power density is calculated to be 356 kW/m^3 , which is 63% higher than the values (218 kW/m^3) of the top-flooding bed packed with the 0.5-mm-diameter particles.

The dryout positions for the three beds can be seen in Figure 8. Generally speaking, the dryout never occurs first at the bottoms of the beds with multi-dimensional ingress of coolant, which is distinct from the pure top-flooding bed. The co-current two-phase flow in the multi-dimensional beds always raise the vulnerable location of dryout upward.

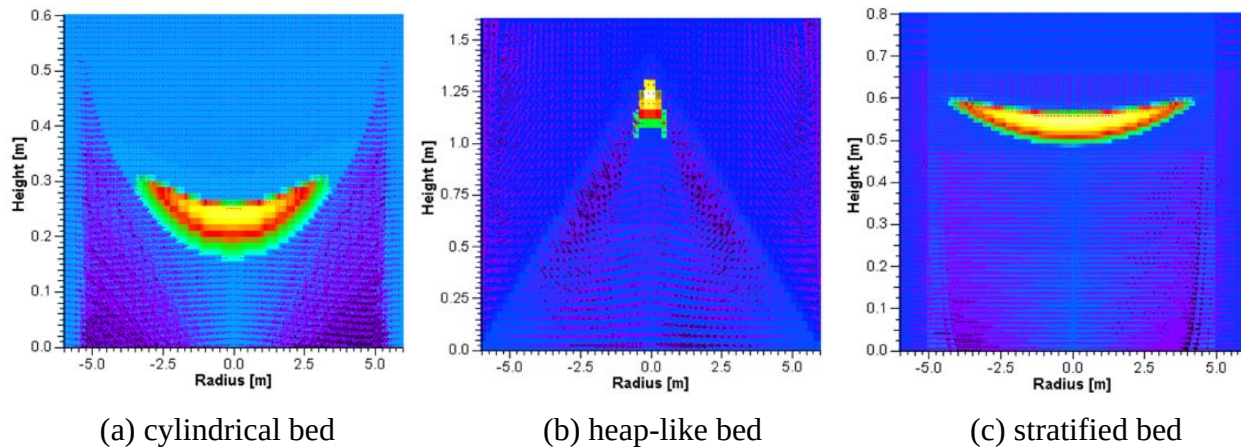


Figure 8 Temperature profiles of the various debris beds as illustrated in Figure 7.

5. Conclusions

Motivated by the interpretation of the POMECO-HT experiments and validation of a simulation tool for coolability analysis of a debris bed formed in a hypothetical severe accident, the MEWA code is chosen in the present study to calculate the tests performed on the POMECO-HT test facility. After the calculations for the POMECO-HT experiments, the code is employed to investigate the coolability of a prototypical-scale debris bed formed in the reactor cavity of a 3900 MWth BWR during severe accident scenarios. Based on the existing data from experiments of fuel coolant interactions (FCI), the effective particle size and porosity of the debris bed is assumed as 1 mm and 0.45, respectively.

The dryout heat fluxes measured in the POMECO-HT tests are predicted by the MEWA code with differences within an acceptable range (<5%), for the bed with a downcomer and the bed with a simulant cake embedded as well as top-flooding beds. Considering the approximation in simulation and accuracy in measurement, it is concluded that the code is capable of coolability assessment of the particulate beds chosen. The code also predicts the dryout positions reasonably well.

The ex-vessel debris bed spreading uniformly over the cavity of the BWR is coolable. If the bed is formed in a cylindrical shape with a surrounding annular-gap between the bed and the cavity wall, the water supply through the gap will enhance the coolability, but the gain in dryout power is marginal since the large diameter of the bed prevents the side coolant from flowing into the center of the bed. A stratified debris bed with a fine-particle layer on the top may challenge the coolability, but water supply through the surrounding gap to the bottom significantly increases the dryout limit. If a heap-like debris bed is formed, it reduces rather than improves coolability due to its considerable height and base diameter, compared with the uniform bed spreading over the cavity floor.

It should be noted that more scrutiny is needed for the reactor-scale calculations, since the scale-up may pose a challenge on the capability of the code. This calls for more experiments with real multidimensionality and enlarged-scale tests, as well as sensitivity and uncertainty analysis.

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