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An experimental study on coolability of a particulate bed with radial stratification or triangular shape

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HIGHLIGHTS

- Dryout heat flux of a particulate bed with radial stratification is obtained.
- It was found to be dominated by hydrodynamics in the bigger size of particle layer.
- Coolability of a particulate bed with triangular shape is investigated.
- The coolability is improved in the triangular bed due to lateral ingression of coolant.
- Coolability of both beds is enhanced by a downcomer.

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ABSTRACT

This paper deals with the results of an experimental study on the coolability of particulate beds with radial stratification and triangular shape, respectively. The study is intended to get an idea on how the coolability is affected by the different features of a debris bed formed in a severe accident of light water reactors. The experiments were performed on the POMECO-HT facility which was constructed to investigate two-phase flow and heat transfer in particulate beds under either top-flooding or bottom-fed condition. A downcomer is designed to enable investigation of the effectiveness of natural circulation driven coolability. Two homogenous beds were also employed in the present study to compare their dryout power densities with those of the radially stratified bed and the triangular bed. The results show that the dryout heat fluxes of the homogeneous beds at top-flooding condition can be predicted by the Reed model. For the radially stratified bed, the dryout heat flux is dominated by two-phase flow in the columns packed with larger particles, and the dryout occurred initially near the boundary between the middle column and a side column. Given the same volume of particles under top-flooding condition, the dryout power density of the triangular bed is about 69% higher than that of the homogenous bed. The coolability of all the beds is enhanced by bottom-fed coolant driven by either forced injection or downcomer-induced natural circulation.

1. Introduction

In the very rare case of a loss of coolant accident in a light water reactor (LWR), the loss of all cooling systems may lead to melting of fuel rods along with the surrounding structure, and the molten corium may form the debris bed at various locations of the reactor: in the core, in the lower plenum and in the reactor cavity. Characteristically, the debris bed is a structure with internal pores which facilitate coolant ingress. Since the debris bed is rather coolable than the molten pool, the coolability of the debris bed plays a crucial role in corium risk quantification, important for the stabilization and termination of a severe accident in light water reactors (LWRs). The debris bed cooling is an exact picture of a two-phase flow in porous media per se, containing the volumetric source of decay heat and complicated bed characteristics. The coolability study mainly aims at finding whether the decay heat can be completely removed by the coolant flowing through the debris bed (Hofmann, 1984; Reed et al., 1985; Lindholm et al., 2006). The dryout heat flux is seen as the limiting parameter to the decay heat removal and it has

Abbreviations: CCFL, counter-current flooding limit; DAS, data acquisition system; DC, downcomer; DHF, dryout heat flux; FCI, fuel (corium) coolant interactions; ID, inner diameter; LWR, light water reactor.

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Nomenclature

d	particle diameter, m
F_i	interfacial friction
g	gravitational constant m/s^2
J	superficial fluid velocity, m/s
K	permeability, m
K_r	relative permeability
p	pressure drop, kPa
s	saturation, $(1-\alpha)$

Greek letters

α	void fraction
ε	porosity of debris bed
η	passability, m^2
η_r	relative passability
μ	dynamic viscosity of fluid, N s/m^2
ρ	density, kg/m^3
σ	surface tension, N/m

Subscripts

g	gas
i	interfacial
l	liquid
r	relative

been subjected to many experimental and theoretical studies since last three decades.

Experimental investigations on debris bed coolability under both in-vessel and ex-vessel conditions have been carried out by many researchers (Hu and Theofanous, 1991; Konovalikhin, 2001; Schäfer and Lohnert, 2006; Li et al., 2012). To analyze the experiments and finally assess debris coolability in reactor scenarios, number of analytical models and empirical correlations were developed for prediction of single/two-phase flow (friction) and heat transfer (dryout heat flux) in particulate beds (Lipinski, 1982; Reed, 1982; Schulenberg and Műller, 1987; Tung and Dhir, 1988; Hu and Theofanous, 1991). Review of the experimental data and empirical correlations can be found in Lindholm (2002) and Bürger et al. (2010).

In porous media, semi-empirical model such as the Ergun equation (Ergun, 1952), due to its acceptable predictions, is widely used for the calculation of frictional pressure drops of single-phase flow

$$-\frac{dp}{dz} = \frac{\mu}{K}J + \frac{\rho}{\eta}J^2 = 150\frac{(1-\varepsilon)^2\mu}{d^2\varepsilon^3}J + 1.75\frac{(1-\varepsilon)\rho}{d\varepsilon^3}J^2 \qquad (1)$$

where dp/dz is the pressure gradient along the height of the bed, the first term of the right-hand side is the viscous loss (proportional to velocity) and the second term is the inertial loss (proportional to velocity squared), where the parameters K and η are called permeability and passability, respectively. In the expressions of Eq. (1), (150) and (1).75 are called the Ergun constants, and d is the diameter of particles, ε is the bed porosity, μ is the dynamic viscosity of fluid, ρ is the density and J is the superficial velocity of fluid.

The Ergun equation was modified for the case of two-phase flow through the particulate beds by introducing relative permeability K_r, relative passability η_r, interfacial friction F_i and the capillary pressure $p_g - p_l$.

$$-\frac{dp_l}{dz} = \rho_l g + \frac{\mu_l}{K\cdot K_{r,l}}J_l + \frac{\rho_l}{\eta\cdot\eta_{r,l}}J_l\cdot\left|J_l\right| - \frac{F_i}{1-\alpha} \qquad (2a)$$

$$-\frac{dp_g}{dz} = \rho_g g + \frac{\mu_g}{K\cdot K_{r,g}}J_g + \frac{\rho_g}{\eta\cdot\eta_{r,g}}J_g\cdot\left|J_g\right| + \frac{F_i}{\alpha} \qquad (2b)$$

Above method was initially used in 1D-configuration models like Lipinski model (Lipinski, 1982) and with its modifications (Reed, 1982; Schulenberg and Műller, 1987; Tung & Dhir, 1988; Hu and Theofanous, 1991). These models are principally based on the maximum heat removal out of a 1D-configuration particulate bed with top flooding when coolability is dependent upon Counter-Current Flooding Limit (CCFL). The Lipinski model is the early accepted model for DHF estimation and for most of the similar models the key point in modeling is to provide the formulation of K_r, η_r and F_i used in the momentum equations, based on experimental data. Table 1 shows the mostly used dryout heat flux (DHF) models.

A literature survey shows that the dryout heat flux database exists extensively for particulate beds packed with single-size spherical particles. It is found that most of the experimental data available in literature are related to top-flooding beds in 1D configuration, and limited data are available for the beds packed with multi-size particles. Motivated to enhance the coolability of debris bed, several experimental investigations have been conducted for the debris beds with bottom forced injection and downcomer (Konovalikhin, 2001; Hofmann, 1984; Bang et al., 2005; Miscevic et al., 2006; Takasuo et al., 2011). Interestingly, these experiments showed a significant increase in dryout heat flux (DHF) compared to the top-flooding condition.

On the other hand, there were a few experiments to investigate stratified debris bed. From Table 2 it can be seen that the axial stratification of debris bed with fine particles atop coarse particles is most expected, which leads to a significant reduction in the DHF. Possibly, there can be another type of stratification, i.e. radial stratification, whose effect on DHF is still unclear, since only one piece of study by Nayak et al. (2005) was found in literature which shows that the dryout heat flux in the radially stratified bed is in the range of that observed for the homogenous bed with corresponding porosity. More investigations and data are therefore needed to understand/verify the effect of the radial stratification on coolability of a debris bed.

Table 1
Models for prediction of dryout heat flux in particulate beds.

Model	Parameters			
	$p_g - p_l$	K_r	η_r	F_i
Lipinski (1982)	$\frac{6\sigma(1-\varepsilon)\cos\theta}{d\cdot\varepsilon}$	$(K_{r,l} = s^3)$[a] $K_{r,g} = \alpha^3$	$\eta_{r,l} = s^3$ $\eta_{r,g} = \alpha^3$	0
Reed (1982)		$K_{r,l} = s^3$ $K_{r,g} = \alpha^3$	$\eta_{r,l} = s^5$ $\eta_{r,g} = \alpha^5$	0
Hu and Theofanous (1991)	0	$K_{r,l} = s^3$ $K_{r,g} = \alpha^3$	$\eta_{r,l} = s^6$ $\eta_{r,g} = \alpha^6$	0
Schulenberg and Műller (1987)	0	$K_{r,l} = s^3$ $K_{r,g} = \alpha^3$	$\eta_{r,l} = s^5$ $\eta_{r,g} = \alpha^6, \alpha > 0.3$ $\eta_{r,g} = 0.1\alpha^4, \alpha \le 0.3$	$F_i = 350s^7\alpha\frac{\rho_l K}{\eta\sigma}(\rho_l - \rho_g)g\left(\frac{J_g}{\alpha} - \frac{J_l}{s}\right)^2$

[a] $s = 1-\alpha$.