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Flow resistances characteristics in a particulate bed with the configurations of uniform mixture and stratification

Liangxing Li [a,*], Huasheng Wang [a], Xumao Zou [a,b], Liubo Kong [a]

[a] State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xian-ning West Road 28#, Xi'an City 710049, PR China
[b] China Nuclear Power Technology Research Institute, Shenzhen City 518026, PR China

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ABSTRACT

During severe core melting accidents of light water reactors with failures of all cooling systems, the molten core fuel (corium) would meet and interact with residual coolant water (FCI), then break up and fragment into a porous debris bed. Therefore, the debris bed coolability depending mainly on the flow friction laws, will be in great significance to nuclear reactor safety. This paper is concerned with reducing uncertainty in quantification of debris coolability in a severe accident of light water reactors (LWRs), and the experimental results on the flow resistance characteristics of homogeneous and stratified particulate beds are reported here. The objective is to get an idea of how the particles bed characteristics (such as the stratified information and its hierarchical arrangement) affect its flow resistance which is crucially important to debris bed coolability analysis. Three types of beds are packed in a cylindrical test section with the inner diameter of 120 mm and the height of 600 mm. Type-1 bed is a homogeneous bed packed with single size spheres. Type-2 bed is also a homogeneous bed with uniformly mixing by two sizes of spheres. Type-3 bed is the axially stratified bed which is composed of two sizes of glass spheres same as that in the Type-2 bed. Both single and two phase flow tests are carried out, the pressure drops and its flow resistance characteristics are measured and recorded during the tests. The results show that for gas-water co-current flow through a homogeneous bed, the predictions of Reed model are more comparable with the measured pressure drops. For a bed packed with uniform mixture of particles, the measured pressure drops are close to the predictions of Ergun equation with area mean diameter at low flowrate (e.g. $Re_p < 7$), but the length mean diameter should be considered as increasing of the Reynolds number of fluid. Compared with the homogeneous bed with the same particles, the stratified bed will generate a lower flow resistance, and consequently result in a higher dry-out heat flux under boiling conditions.

1. Introduction

The general field of single/two-phase flow and heat transfer in porous media has received much attention because of its widespread applications in plenty of fields of engineering and science. It is encountered in such basic areas as agriculture, biomedical science, mechanical engineering, chemical and petroleum engineering, food and soil sciences, nuclear engineering and so on (Bejan and Nield, 2006; Jamialahmadi et al., 2005; Holdich, 2002). A special interest comes from the quantification of debris coolability in nuclear power safety analysis, in which particulate debris beds would be formed with failure of all cooling systems when corium melt relocates to a water pool in the lower head or in the cavity, due to fuel (corium) coolant interactions (FCI). The coolability of the debris bed therefore plays an important role in corium risk quantification, which is crucial to the stabilization and termination of a severe accident in a light water reactor (LWR). As a result, many experimental and analytical studies have been conducted towards quantitative understanding of debris bed coolability under both the in-vessel and ex-vessel conditions. 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 (Lindholm, 2002). Dryout heat flux (DHF), the limiting parameter for removal of the decay heat by boiling of the coolant, has been the focus of many experimental studies and theoretical developments during the last decades. Reviews on the experiments investigating the dryout heat flux have been reported in previous studies as Li et al. (2011, 2016, 2017), Bürger et al. (2010), Schmidt (2004, 2007) and Lindholm (2002).

* Corresponding author.
E-mail address: liangxing.li@xjtu.edu.cn (L. Li).

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Nomenclature

A	interfacial area (m^{-1})
d_a	area mean diameter (m)
d_b	bubble diameter (m)
d_i	length mean diameter
d_m	mass mean diameter
d_p	particle diameter (m)
d_{st}	sauter mean diameter
F_i	interfacial drag (Nm^{-3})
g	gravitational acceleration (ms^{-2})
J	superficial velocity (ms^{-1})
K	permeability (m^2)
K_r	relative permeability
M	mass (kg)
P	pressure (Pa)
Re_p	Reynolds number in porous media
s	saturation
V	volume (m^3)
Greek letters	
α	void fraction
ε	porosity
η	passability (m)
η_r	relative passability
μ	dynamic viscosity (Pas)
ρ	density (kgm^{-3})
σ	surface tension (Nm^{-1})
Subscripts	
g	gas phase
l	liquid phase
p	particle
r	relative
Superscripts	
a	annular flow
b	bubble flow
s	slug flow

Table 1 lists a great number of experimental studies on debris coolability by lots of researchers. In general, an extensive dryout heat flux database exists but most of the data are related to top-flooding beds in one-dimensional configuration. It also can be seen from Table 1 that the most experiments were based on homogeneous debris beds with single-size particles, there were only a few experiments to investigate homogeneous beds with multi-size particles or heterogeneous debris beds (e.g. stratified debris bed).

In fact, scoping studies on debris bed formation and configuration based on FCI experiments (Karbojian et al., 2009; Magallon, 2006; Konovalikhin, 2001) indicated that the stratification of debris bed with fine particles atop coarse particles would be most expected, as shown in Fig. 1. It has been observed that the dryout heat flux from experiments of stratified debris beds is reduced significantly (Konovalikhin, 2001; Thakre et al., 2014), but the reason is still unclear. More data is therefore needed to understand/verify the effect of the stratification configuration of debris bed on its coolability.

To analyze the experiments and finally assess debris coolability in reactor scenarios, a great 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. It is generally accepted and widely used by engineers that satisfactory predictions of frictional pressure drops of single-phase flow in the porous media can be obtained with the use of semi-empirical models such as the Ergun equation (Ergun, 1952):

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

where dp/dz is the pressure gradient along the height of the bed, the first term of the right side is the viscous loss (proportional to velocity) and the second term is the inertial loss (proportional to velocity squared). μ is the dynamic viscosity of fluid, ρ is the density, J is the superficial velocity of fluid, the parameters K and η are permeability and passability, respectively. In the expressions of K and η, 150 and 1.75 are the Ergun constants, d is the diameter of particles, and ε is the bed porosity.

Contrary to single-phase flow, there exist lots of models and correlations to assess the pressure drops of two-phase flow in porous media, but their predictions are quite scattering (Li et al., 2011; Clavier et al., 2015; Chikhi et al., 2016). Different from single-phase flow in porous media, the mutual influence between the fluid phases on the pressure drops for two-phase flow in porous media should be considered additionally. In general, the parameters of relative permeability K_r, relative passability η_r and the interfacial drag F_i are introduced into the Ergun equation (Ergun, 1952) to develop a balanced momentum equation for two-phase flow in porous media. Eq. (2) shows the general expressions of the models for two-phase flow in porous media.

$$-\frac{dP_l}{dz} = \rho_l g + \frac{\mu_l}{KK_{r,l}}J_l + \frac{\rho_l}{\eta\eta_{r,l}}J_l|J_l| - \frac{F_i}{s} \quad (2)$$

$$-\frac{dP_g}{dz} = \rho_g g + \frac{\mu_g}{KK_{r,g}}J_g + \frac{\rho_g}{\eta\eta_{r,g}}J_g|J_g| + \frac{F_i}{\alpha} \quad (3)$$

where l and g represent the liquid and gas phases respectively, and the parameters K_r and η_r are called relative permeability and relative passability respectively, F_i is called interfacial drag, a represents void fraction, s is the saturation, equal to 1-a. Clearly, the total pressure drops consist of three terms: gravity force term, fluid-particles drag term and interfacial drag term. Table 2 shows the most applied models in debris coolability, whose correlations are developed upon the data of dryout heat flux (DHF), i.e., the maximum heat removal criterion of a 1D top-flooding bed. Such approach was adopted in the Lipinski model (1981) and its variations (Reed, 1982; Tutu et al., 1984; Schulenberg and Müller, 1987; Tung and Dhir, 1988; Hu and Theofanous, 1991; Schmidt, 2007; Taherzadeh and Saidi, 2015; Clavier et al., 2017). These models are mainly based on the maximum heat removal out of a one-dimensional particulate bed with top flooding when coolability is contingent upon Counter-Current Flooding Limit (CCFL).

It can be seen from above models that the central point in modeling (e.g. Lipinski model, the early accepted model for DHF estimation) is to provide the formulation of the friction laws for momentum equations, since it is believed that the coolability is mainly restricted by hydrodynamic limitations of two-phase flow through the debris bed (Tung and Dhir, 1988). However, some of the key parameters in above equations such as the steam velocity