AN EXPERIMENTAL STUDY ON FLOW CHARACTERISTICS OF HOMOGENEOUS AND STRATIFIED DEBRIS BEDS

Liangxing Li*, Xumao Zou, Jiaojiao Lou, Huixiong Li and Xianliang Lei
State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University
Xian-ning West Road 28#, Xi'an city, 710049, P.R. China
liangxing.li@mail.xjtu.edu.cn

ABSTRACT

This paper is concerned with reducing uncertainty in quantification of debris bed coolability in a severe accident of light water reactors (LWRs). The experimental results on the flow characteristics of particulate homogeneous and stratified beds are reported here and the objective is to get an idea of how the particles bed characteristics (such as the stratified information and its hierarchical arrangement) affects its flow resistance which is crucially important to the debris bed coolability analysis. Three type 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 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 gradients and its flow 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's model are more comparable with the measured pressure drops. For a bed packed with uniform mixture of particles, the measured pressure gradients 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. Comparing with the homogeneous bed with the same particles, the stratified bed will generate a lower flow resistance, and consequently resulting in a higher dry-out heat flux under boiling conditions.

KEYWORDS
Debris bed, stratified bed, pressure drop, severe accident

1. INTRODUCTION

During a severe accident of scenario a light water reactor (LWR) with failure of all cooling systems, a debris bed may be formed 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 [1-5]. 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

* Footnote, if necessary, in Times New Roman font and font size 10

investigating the dryout heat flux have been reported in previous studies as Li et al. [6], Bürger et al. [7], Schmidt [8] and Lindholm [9]. In general, an extensive dryout heat flux database exists but most of the data are related to top-flooding beds in one-dimensional configuration.

Besides homogeneous debris beds, there were a few experiments to investigate stratified debris bed, as listed in Table I. It can be seen from Table I that the axial stratification of debris bed with fine particles atop coarse particles is most expected. It has been observed that the dryout heat flux in axially stratified beds is reduced significantly [3] but the reason is still unclear. More data is therefore needed to understand/verify the effect of the stratified bed on its coolability.

Table I. Experimental conditions of DHF tests for stratified debris beds

Tests	***Parameters***						
	Particle shape	*Particle size (mm)*	*Bed porosity*	*Bed depth (m)*	*Pressure (bar)*	*Heating method*	*DHF (kW/m^2)*
Boldt et al [10] (axial stratification)	UO_2 particles	1.18+ 4.67 (mean)	0.41	0.1 + 0.4	0.7-69	Internal fission power	117-285
Knonvalikhin [3] (axial stratification)	Sands	0.8 (mean) + 1.0 (mean)	0.26 + 0.36	0.13 + 0.24	1	Embedded heaters	54
Knonvalikhin [3] (axial stratification)	Sands	0.2 (mean) + 1.0 (mean)	0.4 + 0.36	0.13 + 0.24	1	Embedded heaters	87
Nayak et al [11] (radial stratification)	Sands	0.9+ 0.8 + 0.9 (mean)	0.37+ 0.26+ 0.37	0.45	1	Embedded heaters	within 111-222

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 [12]:

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

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 K and η, 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 adapted to the case of two-phase flow through the particulate beds by introducing relative permeability K_r, relative passability η_r, interfacial friction F_i.

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

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

Such approach was adopted in the Lipinski model [13] and its variations [14-18]. 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). Table II shows the most applied models in the field, 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.

Table II. Parameters in the models of dryout heat flux in particulate beds

Models	Parameters				
	P_g-P_l	K_r	η_r	F_i	Comments
Lipinski 0D [13]	$\frac{6\sigma(1-\varepsilon)\cos\theta}{d\cdot\varepsilon}$	$K_{r,l}= s^3$ $K_{r,g}=\alpha^3$	$\eta_{r,l}= s^3$ $\eta_{r,g}=\alpha^3$	0	Homogeneous bed
Lipinski 1D [13]	$\frac{\sqrt{150}\sigma(1-\varepsilon)\cos\theta}{d\cdot\varepsilon}J(s)$	$K_{r,l}= s^3$ $K_{r,g}=\alpha^3$	$\eta_{r,l}= s^5$ $\eta_{r,g}=\alpha^5$	0	$J(s)=\frac{(s^{-1}-1)^{0.175}}{\sqrt{5}}$
Reed [14]	0	$K_{r,l}= s^3$ $K_{r,g}=\alpha^3$	$\eta_{r,l}= s^5$ $\eta_{r,g}=\alpha^5$	0	
Lipinski [18]	0	$K_{r,l}= s^3$ $K_{r,g}=\alpha^3$	$\eta_{r,l}= s^3$ $\eta_{r,g}=\alpha^3$	0	
Hu & Theofanous [17]	0	$K_{r,l}= s^3$ $K_{r,g}=\alpha^3$	$\eta_{r,l}= s^6$ $\eta_{r,g}=\alpha^6$	0	
Schulenberg & Műller [15]	0	$K_{r,l}= s^3$ $K_{r,g}=\alpha^3$	$\eta_{r,l}= s^5$ $\eta_{r,g}=\alpha^6$, $\alpha>0.3$ $\eta_{r,g}=0.1\alpha^4$, $\alpha\leq0.3$	$F_i=350s^7\alpha\frac{\rho_l K}{\eta\sigma}(\rho_l-\rho_g)g\left(\frac{J_g}{\alpha}-\frac{J_l}{s}\right)^2$	

* *s=1-α*

It can be seen from above models that the central point in modeling (e.g. Lipinski model, the early accepted model for DHF estimation) was 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 [16]. However, some of the key parameters in above equations such as the steam velocity (J_g) are covered and only can be calculated from the water velocity (J_l) based on energy balance during in the dryout heat flux tests. Also, the measured pressure drops under boiling test conditions were fluctuating extremely compared with the adiabatic two phase flow tests. In order to better understand the effect of debris prototypicality such as the stratification on coolability, the flow characteristics of particulate stratified beds are investigated in the present study and the objective is to get an idea of how the particles bed characteristics (such as the stratified information and its hierarchical arrangement) affects its flow resistance which is crucially important to the debris bed coolabilty analysis. The tests are performed on an adiabatic test facility named Debris bed coolability- low temperature (DEBECO-LT). Three type beds are packed in a cylindrical test section for comparisons. Type-1 bed is a homogeneous bed packed with single size spheres. Type-2 bed is also a homogeneous bed uniformly mixed by two kinds of spheres of different size. 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 gradients and its flow characteristics are measured and recorded during the tests.

2. DESCRIPTION OF EXPERIMENTS

To examine the flow characteristics of single and two phase flow in the packed porous bed, the test facilities of DEBECO-LT (Debris Bed Coolability - Low Temperature) were designed and constructed at State Key Laboratory of Multiphase Flow in Power Engineering (MPFL) to perform adiabatic single/two-phase flow tests in porous media.

2.1. DEBECO-LT Test Facility

DEBECO-LT is a test facility for investigation of adiabatic air/water single or two-phase flow characteristics in porous beds. Fig. 1 illustrates the schematic diagram of the facility, with most parts made of transparent Plexiglas to facilitate visual observation. The test section accommodating the packed bed is made of a Plexiglas pipe of 120mm in inside diameter and 600mm in height. At both the inlet and the outlet of the test section, two pieces of stainless steel wire meshes are applied between flanges to support the bed from below and prevent the particles from leaving the bed. Air is supplied from the bottom and flows up through the packed bed, but water can be supplied from either from the bottom or from the top for bottom-fed (co-current flow) or top-flooding (counter-current flow) tests. All tests are operated under atmospheric pressure.

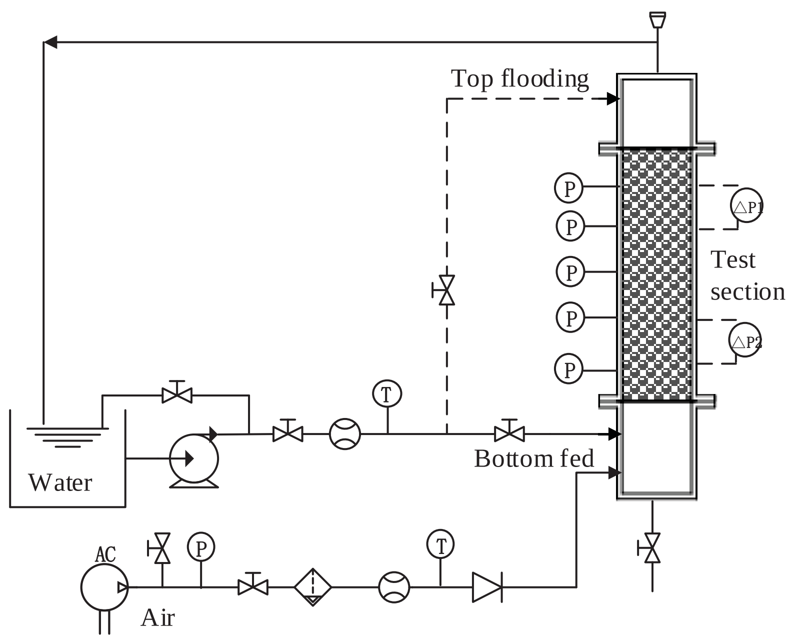


Figure 1. Schematic of DEBECO-LT facility.

Four Rosement-3051 differential pressure transmitters and ten pressure gauges with high accuracy are mounted on the test section to measure the pressures drops of single or two-phase through the bed. Valve manifolds are used with the differential pressure transmitters to perform the block, equalizing and vent requirements of the transmitters. The flowrates of gas and water flows are measured by five OMEGA flowmeters with different measuring ranges. The pressure and temperature are monitored by using OMEGA pressure transducers and K-type thermocouples. The flowmeters and pressure transducers were calibrated prior to experiment. A Data Acquisition System (DAS) is realized through the National Instruments data input instruments and a computer program written in LabView. The program collects the data from thermocouples, pressure transducers and flowmeters.

For operation of the facility, after the well mixed particles are uniformly loaded into the test section, the fluid is supplied to flow through the packed bed at low velocity until there is no change in bed height and in flow resistance, to make sure that the fluid floods the bed and has access to all the pores. For the measurement of pressure drop, the impulse lines of the differential pressure transmitters are filled with single phase fluid by proper operation of the valve manifolds, so that the effect of gravity on pressure drop reading can be excluded. Prior to any measurements taken, the facility is running for no less than half an hour to establish steady-state conditions throughout the system. After the steady-state data are recorded by the data acquisition system, the operational parameters (say, the flowrates) will be adjusted to other values, and the same procedure is repeated.

2.2. Bed Information

As listed in Table III, four particulate beds, denoted as Bed-1 through Bed-4, are chosen in the experiments performed on the facilities DEBECO-LT. Bed-1 and Bed-2 are packed with single size spheres of 1.5 mm and 6 mm in diameter separately, while the porosities are similar as 0.39. Bed-3 is also homogeneous bed packed with uniformly mixing by the two kinds of spheres, one with the diameter of 1.5 mm and another 6 mm. The mass ratio of the 1.5mm particles to the 6mm particles is 1 and the porosity is about 0.32. Bed-4 is a stratified bed consists of two types of glass spheres as used in Bed-3. The lower half is packed with 6 mm spheres while the top half is 1.5 mm sphere. Generally, three types' beds are employed in the present study. Type-1 beds including Bed-1 and Bed-2 are homogeneous beds packed with single size spheres. Type-2 bed is also a homogeneous bed uniformly mixing by two kinds of spheres with different size, corresponding to Bed-3. Bed-4 is belong to Type-3 bed, which is the axially stratified bed composed of two sizes glass spheres. Detail information and the schematic of Beds 1-4 can be seen in Table III and Fig.2.

Table III. Information of the test beds

Bed	Bed information	Sizes(mm)	Porosity	Test conditions
Bed-1	Single size spheres	1.5	0.38	Single / Two phases flow
Bed-2	Single size spheres	6	0.387	Single/ Two phases flow
Bed-3	Uniform mixture of spheres	1.5+6	0.323	Single/ Two phases flow
Bed-4	Stratified bed	1.5/6	0.38/0.387	Single/ Two phases flow

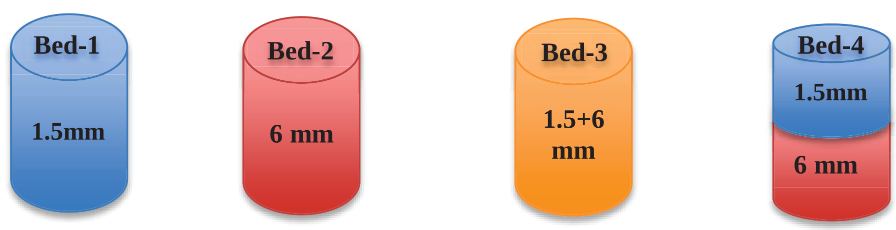


Figure 2. Schematic of Beds 1-4.

Since the models for coolability analysis are sensitive to the bed porosity as well as the particle size, yielding results from coolable to non-coolable situations with a relatively small change in the two parameters [2], a great care is taken here in determining the bed porosity. This is achieved 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 porosity is then determined by

$$\varepsilon = 1 - \frac{\sum M_j / \rho_j}{V_0} \tag{3}$$

where ε is the porosity of the bed, M_j is the mass of the particles made of material j and V_o is the total volume the bed occupies (including void). The particles are well mixed prior to filling in the test section so that a uniform packed bed can be obtained.

3. RESULTS

3.1. Tests Results of Beds with Single Size Spheres

In addition to the calibration of instrumentations, the test facility and its measurement system were qualified firstly by measurements of single-phase flow through Bed-1 and Bed-2 packed with single-size spheres. Water is employed as working fluid and the temperature is around 8 degree when the test system reaches a steady-state condition. The measured pressure gradients were then compared with those predicted by Ergun's equation, whose predictions are generally accepted for packed beds of spheres with satisfactory accuracy [19]. Fig. 3 shows the comparison between the measured data and the analytical results of Ergun's equation, where triangle symbols represent experimental data, and the solid lines are analytical results. It can be seen from Fig.3 that the measured pressure gradients are increasing with the flowrates for both beds. While for each flowrate, the pressure drops of bed-1 with 1.5 mm spheres are much higher than that of bed-2 with 6 mm spheres, due to the smaller diameter and porosity of bed-1. Moreover, the measured pressure gradients of both beds are well predicted by the Ergun equation. Thus, the quality of experimentation and instrumentation is further ensured by the good agreement.

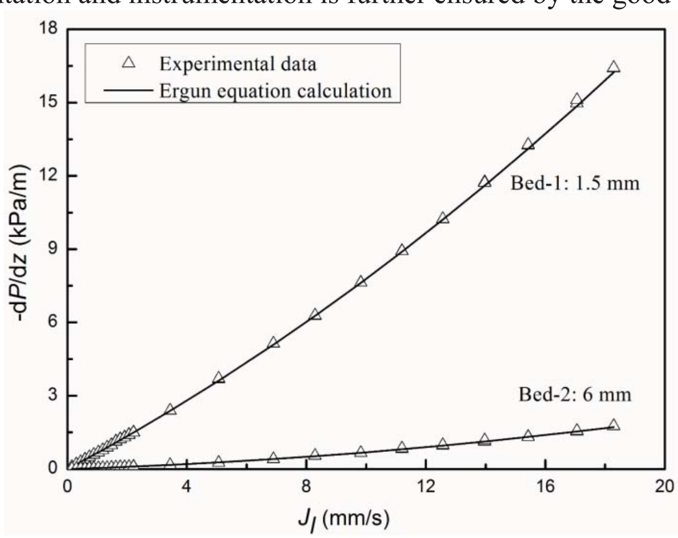
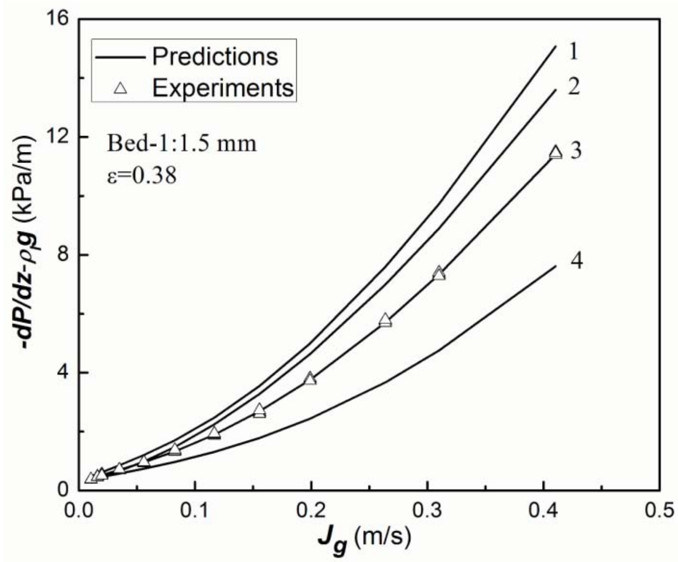


Figure 3. Pressure Gradients of Water Flow through Beds with Single-Size Spheres.

Contrary to single-phase flow, the problem of pressure drop during two-phase flow in porous media is still unresolved. In most cases, the predicted results by different models are scattered. In the present study, the air-water co-current two phase flow tests are also carried out to investigate the friction laws of two-phase flow through porous beds. During the tests, the water flow is fixed while the air flowrate is increasing. Pressure drops are measured when air and-water flow up through the packed beds. Fig. 4 shows the pressure gradients of two-phase flow through bed-1, where the predictions of four models (Reed model [14]; Schulenberg & Műller model [15]; Hu & Theofanous model [17]; Lipinski model [18]) are also plotted in the figures for comparisons. It can be seen from Fig.4, with the increasing of air flowrate, that the measured pressure drops increase gradually. Generally speaking, Reed model [14] predicts well the experimental data.



1–Hu & Theofaneous model[17]; 2–Schulenberg & Műller model [15]; 3–Reed model[14]; 4–Lipinski model[18]

Figure 4. Pressure Gradients of Air-Water Two Phase Flow through Beds with Single-Size Spheres.

3.2. Tests Results of Bed-3 with Mixture Spheres

For mixture of particles with a size distribution, different mean particle diameters were used in previous studies depending on which size distribution function (mass, area, length, number, etc.) chosen [20]. The calculated methods and its value are very different even for the same combination of multi-size spheres,. Generally, there exist among others the mass mean diameter d_m, area mean diameter d_a, length mean diameter d_l and number mean diameter d_n, defined as follows.

$$d_m = \sum x_i m_i = \sum \left(x_i \frac{x_i^3 f_i}{\sum x_i^3 f_i} \right) = \frac{\sum x_i^4 f_i}{\sum x_i^3 f_i} \tag{4}$$

$$d_a = \sum x_i a_i = \sum (x_i \frac{x_i^2 f_i}{\sum x_i^2 f_i}) = \frac{\sum x_i^3 f_i}{\sum x_i^2 f_i} \tag{5}$$

$$d_l = \sum x_i l_i = \sum (x_i \frac{x_i f_i}{\sum x_i f_i}) = \frac{\sum x_i^2 f_i}{\sum x_i f_i} \tag{6}$$

$$d_n = \sum x_i n_i = \sum \left(x_i \frac{f_i}{\sum f_i} \right) \tag{7}$$

where f_i is the number of particles within the given size range (x_i, $x_i+\Delta x$), and the pararmeters m_i, a_i, l_i and n_i are size distribution functions by mass, area, chord length, number of the particles, respectively. For bed-3 consists of 1.5 mm spheres and 6 mm spheres, the four mean diameters calculated according to the equations (4)-(7) are 1.57mm, 1.76mm, 2.4mm and 3.75mm separately.

Figure 5 illustrates the measured pressure gradients of water flow through bed-3 with mixed spheres. For comparison, the calculation results by Ergun equation with different mean diameter are also plotted in Fig.5. It can be seen from Fig.5 that at low flowrate (e.g. Re_p<7), the measured pressure gradients are more comparable with the predictions of Ergun equation with area mean diameter. With increasing

Reynolds number of fluid, the calculate result by the Ergun equation with length mean diameter predicts well the experimental data. Here the Reyonds number in porous media is defined as follows

$$\mathrm{Re}_p = \frac{\rho J d_{sd}}{\mu(1-\varepsilon)} \tag{8}$$

where J, d_{sd} are the superficial velocity of fluid and Sauter mean diameter of particles. The Sauter mean diameter d_{sd} is defined as the diameter of a sphere that has the same volume/surface area ratio as the particle in question.

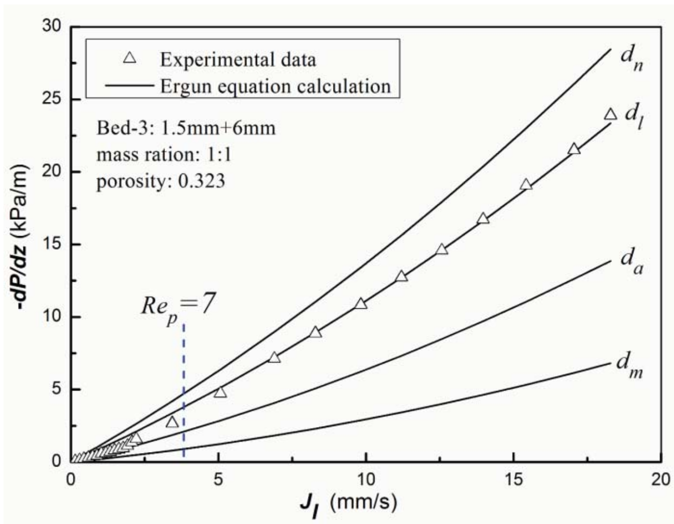
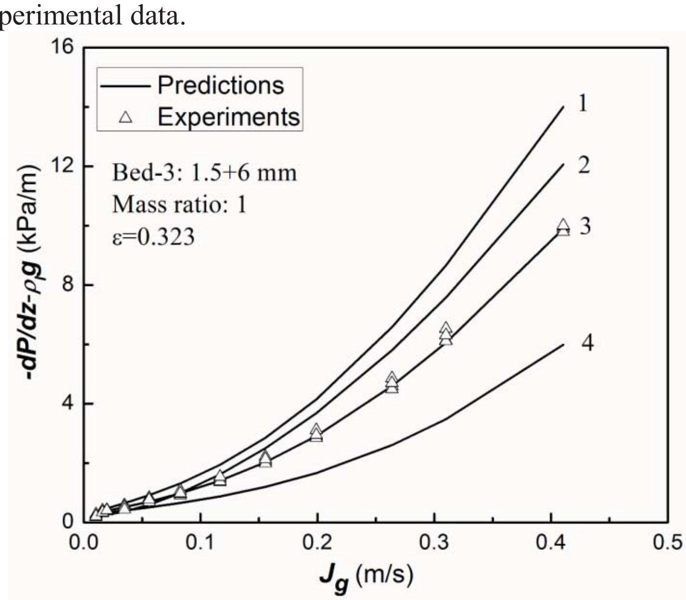


Figure 5. Pressure Gradients of Water Flow through Bed-3 with Mixed Spheres

The test of co-current two-phase air-water flow through bed-3 is also performed. Figure 6 shows a comparison between experimental data and calculated pressure gradients for the bed-3. The liquid velocity is 0.29 mm/s and the area mean diameter of bed-3 at low Reynolds number is used in the calculation by different models. Generally, the prediction of pressure drop by Reed's model is more comparable with the experimental data.

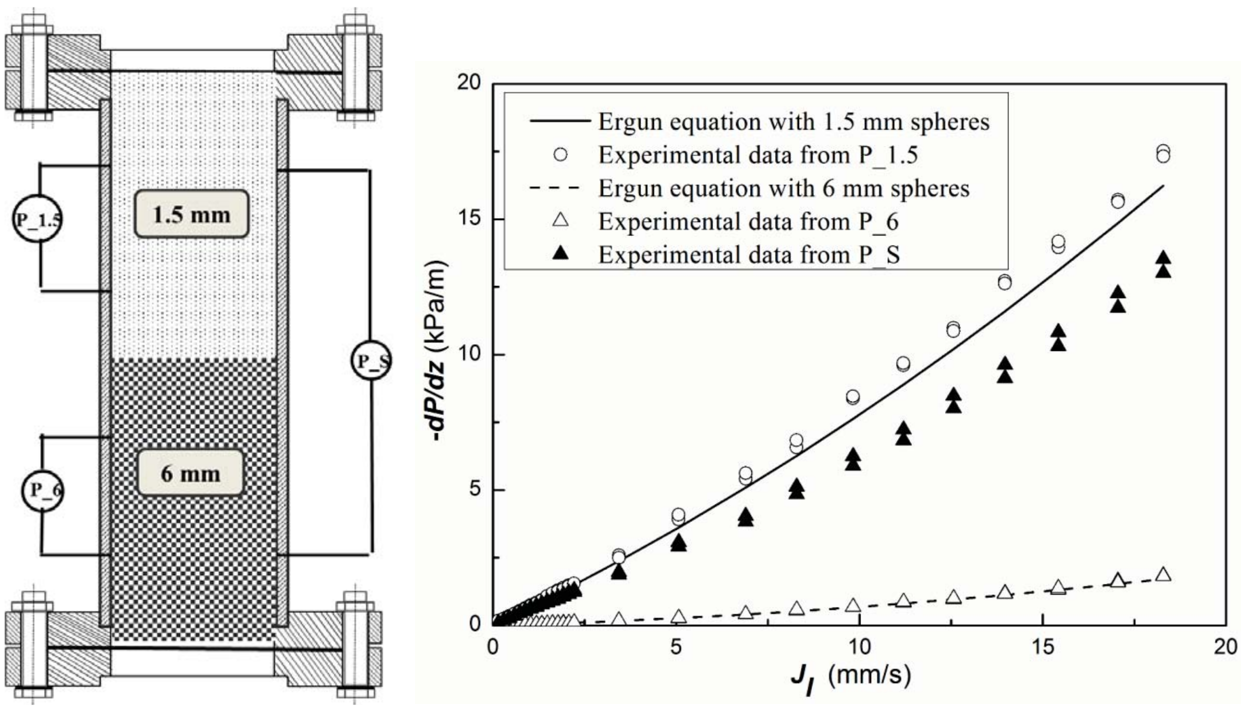


1–Hu & Theofaneous model[17]; 2–Schulenberg & Műller model [15]; 3–Reed model[14]; 4–Lipinski model[18]

Figure 6. Pressure Gradients of Air-Water Two Phase Flow through Bed-3 with Single-Size Spheres.

3.2. Tests Results of Bed-4 with Axial Stratification

Single phase flow tests are performed on the axially stratified bed and the pressure drops are measured for each half part and the whole bed. The detail information can be seen in Fig.7 (a), where P_1.5 is used to measure the pressure drops of top half bed with 1.5 mm spheres, P_6 means the pressure drops of below half bed with 6 mm spheres, and P_S records the pressure drops of whole stratified bed. Fig.7 (b) shows the measured pressure drop of bed-4 during the single phase flow test. For comparison, the predictions of Ergun equation with each part are also plotted in Fig.7 (b).



(a) (b)

Figure 7. Pressure Measurement and Pressure Gradients of Water Flow through Bed-4.

It can be seen from Fig.7 (b) that at bottom part of bed-4, which consists of 6 mm spheres, the measured pressure drops (P_6) are relatively close to the predictions of Ergun equation, while for the top part of bed-4 with 1.5 mm spheres, the Ergun equation underestimates the measured data (P_1.5). Comparing with the measured pressure gradients of Bed-1 with 1.5 mm spheres shown in Fig.3, the data from P_1.5 in Bed-4 is relatively higher too. Obviously, the stratification of particles increases the flow resistance, even if the other part consists of larger particles with higher porosity (6 mm spheres with the porosity of 0.387 versus the 1.5 mm spheres with the porosity of 0.38). From the senses of debris coolability, it is well known that the higher flow resistance in debris bed will results in lower dryout heat flux. Therefore, on the basis of present study, it could be estimated that a little lower dryout heat flux will occur in the stratified bed comparing with the homogeneous bed packed with the smaller size particles.

In addition, the measured pressure drops of stratified bed (P_S) are between the values measured from P_1.5 and P_6. The pressured drop of the whole bed is a little lower than the one with smaller size particles, but higher than the average value of both parts.

In order to further illustrate the effects of particles bed characteristics on its flow resistances, Fig.8 shows the measured pressure drops of beds1-4 when water flow through the packed bed. It can be seen from

Fig.8 that the flow resistances in bed-3 is the greatest one among the four beds for the same flowrate, due to the lowest porosity exists in bed-3, as seen in Table III. Moreover, it is known that the bed-3 and bed-4 are composed of the same size particles together with the same mass ratio, the only difference is that the bed-3 is a uniform mixture with the two size particles but bed-4 is a stratified bed. Obviously the stratified bed generated a lower flow resistance, and consequently resulting in a higher dryout heat flux under boiling conditions. In this sense, the stratification of particles is more welcome during the severe accident scenario since the stratified bed will come to a safer cases.

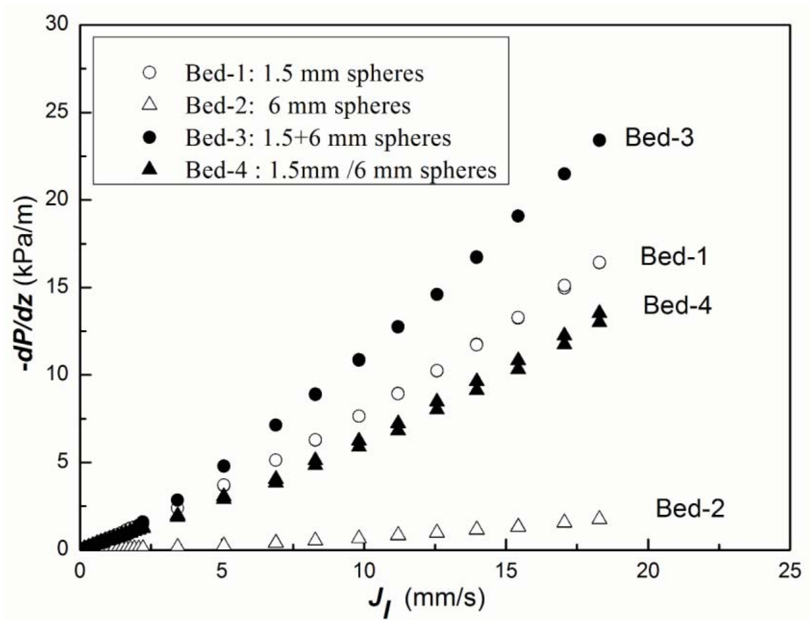


Figure 8. Comparisons of the Measured Pressure Gradients of Water Flow through Beds 1-4.

4. CONCLUSIONS

In order to better understand the effect of debris prototypicality such as the stratification on coolability, the flow characteristics of particulate homogeneous and stratified beds are investigated in the present study. Three type beds are packed in a cylindrical test section for comparisons. Four beds are employed in the present study and both single and two phase flow tests are carried out, the pressure gradients and its flow 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's model are more comparable with the measured pressure drops. For a bed packed with uniform mixture of particles, the measured pressure gradients 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. Comparing with the homogeneous bed with the same particles, the stratified bed will generate a lower flow resistance, and consequently resulting in a higher dryout heat flux under boiling conditions.

NOMENCLATURE (IF NEEDED)

Symbol	Quantity	SI Unit
d	Particle diameter	m
d_a	Area mean diameter	m
d_l	Length mean diameter	m
d_m	Mass mean diameter	m

d_n	Number mean diameter	m
d_{sd}	Sauter mean diameter	m
F_i	Interfacial friction	
g	Gravitational acceleration	m/s^2
J	Superficial velocity	m/s
K	Permeability	m
K_r	Relative permeability	
M	Mass of particles	kg
P	Pressure	Pa
Re_p	Reyonlds number in porous media	
s	Saturation	
V_0	Volume of the porous bed occupied	m^3
Greek letters		
α	Void fraction	
ε	Porosity	
η	Passability	m^2
η_r	Relative passability	
μ	Dynamic viscosity	Pa s
ρ	Density	kg $/m^3$
σ	Surface tension	N/m
Subcsript		
g	Gas	
l	Liquid	

ACKNOWLEDGMENTS

This work is supported by National Natural Science Foundation of China (grant no. 51406143). The authors thank the staffs at the Division of Two Phase Flow and Heat Transfer in High Pressure and High Temperature for their constructive discussions and suggestions.

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