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Original Article

An experimental study on two-phase flow resistances and interfacial drag in packed porous beds

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ABSTRACT

Motivated by reducing the uncertainties in quantification of debris bed coolability, this paper reports an experimental study on two-phase flow resistances and interfacial drag in packed porous beds. The experiments are performed on the DEBECO-LT (DEbris BEd COolability-Low Temperature) test facility which is constructed to investigate the adiabatic single and two phase flow in porous beds. The pressure drops are measured when air-water two phase flow passes through the porous beds packed with different size particles, and the effects of interfacial drag are studied especially. The results show that, for two phase flow through the beds packed with small size particles such as 1.5 mm and 2 mm spheres, the contribution of interfacial drag to the pressure drops is weak and ignorable, while the significant effects are conducted on the pressure drops of the beds with bigger size particles like 3 mm and 6 mm spheres, where the interfacial drag in beds with larger particles will result in a descent-ascent tendency in the pressure drop curves along with the fluid velocity, and the effect of interfacial drag should be considered in the debris coolability analysis models for beds with bigger size particles.

1. Introduction

Single and two-phase gas/liquid flow in packed porous media occur in many engineering applications, ranging from agricultural, biomedical, mechanical, chemical and petroleum engineering to food industry [1,2]. Specifically, during a severe accident of a light water reactor (LWR) with failure of cooling systems, a porous debris bed may be formed when melt corium relocates to a water pool in the lower head or in the cavity. The coolability of the debris bed therefore is of great importance in corium risk quantification, which is crucial to the stabilization and termination of a severe accident in LWR. Towards quantitative understanding of debris bed coolability, numerous experiments [3–9] have been carried out and a great number of analytical models and empirical correlations [10–17] are proposed, the central point is to provide the formulation of the friction laws for momentum equations of single and two-phase flow in the particulate beds. It is now generally accepted that satisfactory predictions of pressure drop of single phase flow in packed spheres beds can be achieved by the simple semi-empirical models like the Ergun equation [10].

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

where dp/dz is the pressure gradient along the height of the bed, the first term of the right 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 called permeability and passability, respectively. 150 and 1.75 are called the Ergun constants, d is the diameter of particles, and ε is the bed porosity.

Contrary to single-phase flow, there exist a good number of models and correlations [11–17] to assess the pressure drops of two-phase flow in porous media, and their predictions are quite scattering [8]. Equation (2) shows the general expressions of some models and Table 1 lists the related parameters proposed by different researchers.

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

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Table 1
Different models and their parameter expressions.

Models	Flow patterns	K_{rg}	η_{rg}	K_{rl}	η_{rl}	F_i
Lipinski [11]	All	α^3	α^3	$(1-\alpha)^3$	$(1-\alpha)^3$	0
Reed [12]	All	α^3	α^5	$(1-\alpha)^3$	$(1-\alpha)^5$	0
Hu & Theofanous [13]	All	α^3	α^6	$(1-\alpha)^3$	$(1-\alpha)^6$	0
Schulenberg & Műller [14]	All	α^3	$\alpha^6, \alpha > 0.3$; $0.1\alpha^4, \alpha \le 0.3$	$(1-\alpha)^3$	$(1-\alpha)^5$	Eq.(3)
Tung & Dhir [15]	Bubble flow & Slug flow	$\left(\frac{1-\varepsilon}{1-\varepsilon\alpha}\right)^{\frac{4}{3}}\alpha^4$	$\left(\frac{1-\varepsilon}{1-\varepsilon\alpha}\right)^{\frac{2}{3}}\alpha^4$	$(1-\alpha)^4$		Eq.(4)
	Annular flow	$\left(\frac{1-\varepsilon}{1-\varepsilon\alpha}\right)^{\frac{4}{3}}\alpha^3$	$\left(\frac{1-\varepsilon}{1-\varepsilon\alpha}\right)^{\frac{2}{3}}\alpha^3$	$(1-\alpha)^4$		Eq.(8)
Schmidt [17]	Bubble flow & Slug flow	$\left(\frac{1-\varepsilon}{1-\varepsilon\alpha}\right)^{\frac{4}{3}}\alpha^4$	$\left(\frac{1-\varepsilon}{1-\varepsilon\alpha}\right)^{\frac{2}{3}}\alpha^4$	$(1-\alpha)^4$		Eq.(4)
	Annular flow	$\left(\frac{1-\varepsilon}{1-\varepsilon\alpha}\right)^{\frac{4}{3}}\alpha^3$	$\left(\frac{1-\varepsilon}{1-\varepsilon\alpha}\right)^{\frac{2}{3}}\alpha^3$	$(1-\alpha)^4$		Eq.(9)

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

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, α represents void fraction. Clearly, the total pressure drop consists of three terms: gravity force term, fluid-particles drag term and interfacial drag term. It can be seen from Table 1 that these models can be divided into two groups generally, according to whether the researchers considered the interfacial drag or not.

By introducing the relative permeability K_r and relative pass ability η_r, Lipinski [11] extended the Ergun equation [10] to the case of two-phase flow through the particulate beds. Such approach was also adopted in Reed model [12] and Hu & Theofanous [13], but different parameters were used. It should be noted that interfacial drag did not take account in These models ($F_i = 0$).

Tutu et al. [16] stressed the importance of gas-liquid interfacial drag of flow in porous beds with coarse particles, especially for large particle sizes ($d_p \ge 6$ mm), where the gas-liquid interfacial drag can be comparable with the gas-solid drag and can't be neglected. Based on measured experimental data and corresponding analysis, Schulenberg & Műller [14] took account of the interfacial drag between liquid and gas (related with buoyancy force, viscous force, inertial force and capillary force), which was expressed as following form.

$$F_i = 350(1-\alpha)^7 \alpha \frac{\rho_l K}{\eta\sigma}\left(\rho_l - \rho_g\right) g \left(\frac{J_g}{\alpha} - \frac{J_l}{1-\alpha}\right)^2 \tag{3}$$

Here σ is the surface tension.

One step further, Tung & Dhir [15] developed a hydrodynamic model including interfacial drag, based on flow regimes and their relationship with flow and porous layer configuration, to predict void fraction and pressure drops for two-phase flow through porous media. Depending on visual observation, they defined three flow patterns: bubble flow, slug flow and annular flow. The expressions of interfacial drag F_i were proposed for different flow patterns. For bubble and slug flow, the interfacial drag F_i was deduced as the following form:

$$F_i = C_1 \frac{\mu_l}{D_b^2 \varepsilon}(1-\alpha) J_r + C_2 \frac{(1-\alpha)\rho_l + \alpha\rho_g}{D_b^2 \varepsilon^2}(1-\alpha)^2 J_r\cdot|J_r| \tag{4}$$

Where J_r is the relative velocity, D_b is the bubble diameter defined by

$$J_r = \frac{J_g}{\alpha} - \frac{J_l}{1-\alpha},\ D_b = 1.35\sqrt{\frac{\sigma}{\left(\rho_l - \rho_g\right)g}} \tag{5}$$

and the friction coefficients were given separately for bubble flow and slug flow

$$\text{Bubble flow } (0 < \alpha < \alpha_1) : C_1 = 18\alpha, \quad C_2 = 0.34\alpha(1-\alpha)^4 \tag{6}$$

$$\text{Slug flow } (\alpha_2 < \alpha < \alpha_3) : C_1 = 5.21\alpha, \quad C_2 = 0.92\alpha(1-\alpha)^4 \tag{7}$$

The interfacial drag for annular flow was expressed as:

$$F_i = \frac{\mu_g}{K.K_{r,g}}(1-\alpha) J_r + (1-\alpha)\alpha \frac{\rho_g}{\eta.\eta_{r,g}} J_r.|J_r| \tag{8}$$

Schmidt [17] modified Tung & Dhir model [15] by revising some expressions of parameters, such as the diameter of gas bubbles or slugs, the flow pattern bounds and the interfacial drag in annular flow, which all mainly affects the formulation of interfacial drag. For Annular flow, the interfacial drag F_i can be deduced as the following form:

$$F_i = \frac{\mu_g}{KK_{r,g}}(1-\alpha) J_r + (1-\alpha)\alpha \frac{\rho_g}{\eta\eta_{r,g}} |J_r| J_r \times \begin{cases} \left(\dfrac{d_p}{6}\right)^2 : d_p < 6\text{mm} \\ 1 : d_p > 6\text{mm} \end{cases} \tag{9}$$

From the models discussed above, one can see that the key point in the models is to provide the formulation of the friction laws for momentum equations of two-phase flow in porous beds, since it is believed that the debris coolability is mainly restricted by hydrodynamic limitations of two-phase flow through the debris bed [18]. However, some of the key parameters in above equations such as K_r and η_r are given different expressions by different researchers. What's more, the effects of interfacial drag F_i on the pressure drops of two phase flow are still unsettled. Therefore even for the same flow conditions, the calculated results by different models are different due to the inconsistent parameters. Recent work from Chikhi et.al (2016) [8] stated that there is no definitive conclusion on this subject by now. In order to verify debris coolability analytical models, and to better understand the effect of interfacial drag, experiments are conducted to study the flow characteristics of particulate beds with different sizes particles are performed in the present study, and the emphasis is placed on getting an idea of how the interfacial drag F_i affects the flow pressure drops, which is crucially important to the debris bed coolability analysis.

2. Description of test system

To study the flow characteristics of single and two phase flow in packed beds, the test facilities of DEBECO-LT (Debris Bed Coolability - Low Temperature) is designed and constructed to perform adiabatic single/two-phase flow tests in porous media. 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 120 mm in inside diameter and 600 mm 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 the bottom or the top for bottom-fed (co-current flow) or top-flooding (counter-current flow) tests. All tests are operated under atmospheric pressure. Many types of particles can be packed inside the test to form porous structures, such as spherical/non-spherical particles, single/multi-size particles, particles of homogenous mixture or stratification. Before the signals for pressure and temperature are collected, it is necessary to make sure that the fluid should flood the bed and all the pores inside the bed be access to the fluid. For precise and reliable measurement of pressure drop and flow rates, the Rosemount differential pressure transmitters with an accuracy of 0.04%, pressure sensors with an accuracy of 0.25% and series of flowmeters with different measurement ranges for both air and water are chosen. Before any measurements taken, the facility should work for some time to establish steady-state conditions throughout the system. After the steady-state data are recorded by the data acquisition system(DAS), adjust the operational parameters (i.e, the flow rates) to other values, and the same procedure are repeated.

According to previous studies [8,18–22] in the topic of debris bed coolability, it is known that the particles sizes formed in a debris during a severe accident of Light Water Reactors(LWR) range from hundreds microns to 11 mm, and the mean porosity will highly likely be the order of 0.39 (e.g. ranging from 0.35 to 0.55) and may vary locally. Though many analysis models have been proposed based on the experiments to access debris bed coolability, the predicting results by different models are discrepant due to different choices for the parameters (e.g. the interfacial drag) and there is still no definitive conclusion on this subject [8]. As a follow-on work aiming to reduce the uncertainties in coolability assessment of debris beds, the emphasis of present study is to verify the analytical models for debris coolability analysis and better understand the effect of interfacial drag on the flow pressure drops. Based on this purpose, four particulate porous packed beds consisting of different size particles are constructed. The first two beds (Bed-1 and Bed-2) are packed with relatively smaller size spheres like 1.5 mm and 2 mm in diameter, while the other two beds (Bed-3 and Bed-4) are packed with larger size particles (3 mm and 6 mm in diameter). The detail information list in Table 2. The porosity of packed bed can be obtained by weighing method, as expressed in Eq. (10).

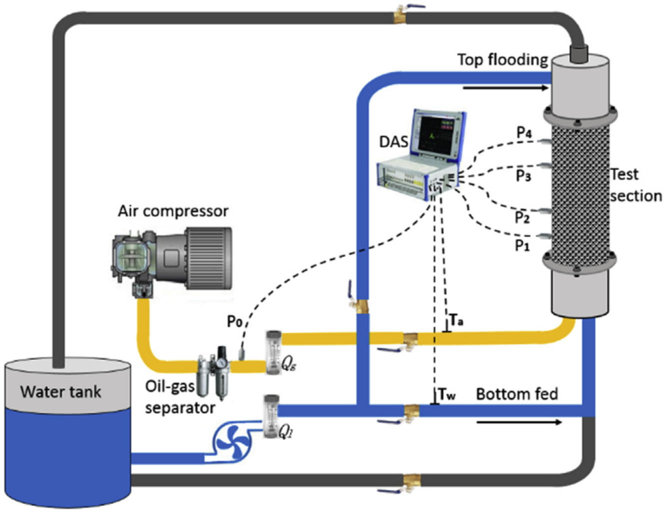

Fig. 1. System diagram of DEBECO-LT.

Table 2
Information for different packed beds.

Particle Sizes(mm)		1.5	2	3	6
Bed Porosity		0.368	0.370	0.371	0.375
Test Section Sizes (mm)	Diameter	120			
	Height	600			
Test Conditions		Single/Two phase flow			

$$\varepsilon = 1 - \frac{M/\rho}{V_0} \tag{10}$$

where M and ρ stand for the quality and density of the packed particles respectively, V_0 represents the volume occupied by all packed particles.

3. Results and discussions

3.1. Single-phase flow tests

In addition to the calibration of instrumentation, the test facility and its measurement system is qualified by measurements of single-phase flow through the beds packed with single-size glass spheres of 1.5 mm, 2 mm, 3 mm and 6 mm in diameter separately. Water is employed as working fluid and the temperature is around 10 degrees when the test system reaches a steady-state condition. The measured pressure drops are then compared with the predicted results by Ergun's equation [10], whose predictable results for packed beds of spheres are generally accepted with satisfactory accuracy [23]. Fig. 2 shows the comparison between the experimental data and the calculated results by Ergun's equation, where triangle symbols represent experimental data, and the solid lines are calculated results. It can be seen from Fig. 2 that the measured pressure drops increase with water flowrates for all packed beds. Besides, the pressure drops of packed bed increase dramatically with the decrease of the packed particle size from 6 mm to 1.5 mm, and the pressure drops of packed bed with 1.5 mm spheres are nearly 10–30 times higher than that of bed with 6 mm spheres, due to the smaller size and porosity of bed with 1.5 mm spheres, which shows that the particle diameter and porosity of packed bed would have significant influence on the pressure drops. What's more, the measured experimental data from all three packed beds are in good agreement with calculated results by Ergun equation, and the mean relative errors between the experimental data and predicted results by Ergun equation have a relatively low average error within 7%. Thus, the quality of experimentation and instrumentation is further ensured by this good agreement.

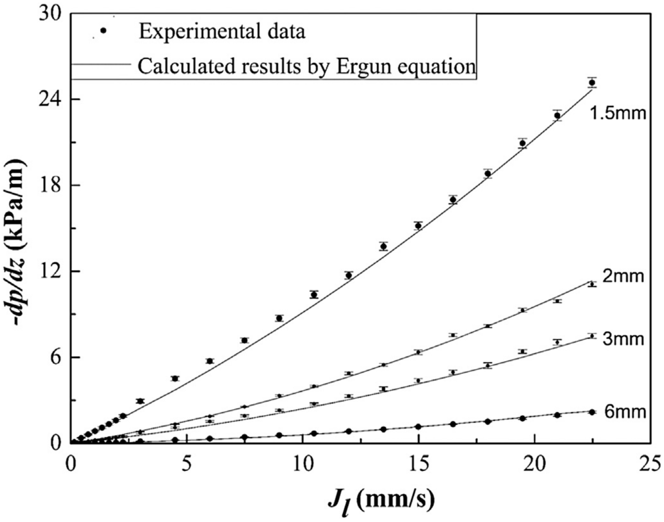

Fig. 2. Pressure drops of single-phase flow through packed beds.

3.2. Two-phase flow tests

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 carried out to investigate the friction laws of two-phase flow through porous beds. On the basis of good quality of experimental apparatus and instrumentation of the test system, the tests of air-water two-phase flow are performed in packed beds with spherical particles of 1.5 mm 2 mm, 3 mm and 6 mm, and the pressure drops are measured. Then the measured pressure drops are compared with the predictions by different models listed in Table 1 to validated the debris coolability analysis models, and in particular, the influence of interfacial drag are analyzed and discussed.

In order to simplify some expressions to get more clear understanding and facilitate the analysis, the momentum equation on two-phase flow pressure drops (Eq. (2a)) will be converted into dimensionless forms with Dividing by $\rho_l\, g$:

$$P^* = 1 + F_{pl}^* - F_i^* \tag{11}$$

with

$$P^* = -\frac{dp}{dz}\Big/(\rho_l g) \tag{12}$$

$$F_i^* = F_i/[(1-\alpha)\rho_l g] \tag{13}$$

$$F_{pl}^* = \left(\frac{\mu_l}{K.K_{r,l}}J_l + \frac{\rho_l}{\eta.\eta_{r,l}}J_l.|J_l|\right)\Big/(\rho_l g) \tag{14}$$

The P^* represents dimensionless pressure drop, F_i^* means dimensionless interfacial drag and F_{pl}^* is considered as dimensionless liquid-particle drag. Namely, the pressure drop P^* consists of static pressure constant 1, liquid-particle drag F_{pl}^* and the interfacial drag F_i^*.

3.2.1. Tests of two-phase flow in packed beds with different-size particles

Air-water two phase flow up through the porous beds with spherical particles of 1.5 mm, 2 mm, 3 mm and 6 mm are conducted separately. During the tests, the water is first injected from the bottom to fill up the test column. For the same test condition, the water flow is kept fixed while the air flowrates are varied. After that the water flow is changed and the same procedure are repeated. Based on the measured pressure drops at the liquid velocity of $J_l = 0.3$ mm/s, Fig. 3 illustrate the dimensionless pressure drops P^* along with the gas Reynolds number in packed beds with spheres of 1.5 mm, 2 mm, 3 mm and 6 mm, where the Reynolds number is calculated by Eq. (14)

$$\mathrm{Re}_p = \frac{\rho J d}{\mu(1-\varepsilon)} \tag{15}$$

The Re_p is the Reynolds number in porous media. Obviously, the Reynolds number increases as the velocity increases.

It can be seen from Fig. 3, in general there are two-development tendency of the dimensionless pressure drops P^* varying with the fluid velocity. For the beds packed with smaller size particles such as 1.5 mm and 2 mm spheres, the dimensionless pressure drops P^* increase with the Reynolds number gradually. While for the beds with larger size particles (3 mm and 6 mm), the pressure drop curves appear a descent-ascent tendency along with the fluid velocity. Moreover, the pressure drops of bed with 6 mm spheres show greater decreasing scales along with Reynolds number than that of bed with 3 mm spheres. Generally, the packed beds with smaller particles will produce higher pressure drops under the same flow conditions.

In order to verify debris coolabiltiy analytical models, the comparisons between the experimental results and the calculation results by different models are plotted in Figs. 4–7, corresponding to the beds with 1.5 mm, 2 mm, 3 mm and 6 mm spheres respectively. The models both including the interfacial drag such as Schulenberg & Műller model [14] and Tung & Dhir model [15], and excluding the interfacial drag like Lipinski [11] model, Reed model [12] and Hu & Theofanous model [13] are employed to calculate the pressure drops under the test conditions. The calculated results are expressed with different types of lines in Fig. 4 and the experimental results are illustrated as triangle symbols.

It can be seen from Figs. 4 and 5 that for the beds packed with smaller size particles such as 1.5 mm and 2 mm spheres, the calculated results by all predictable models show the same rising trends with that of experimental data, whether the interfacial drag is considered or not. It indicates that the interfacial drag has little

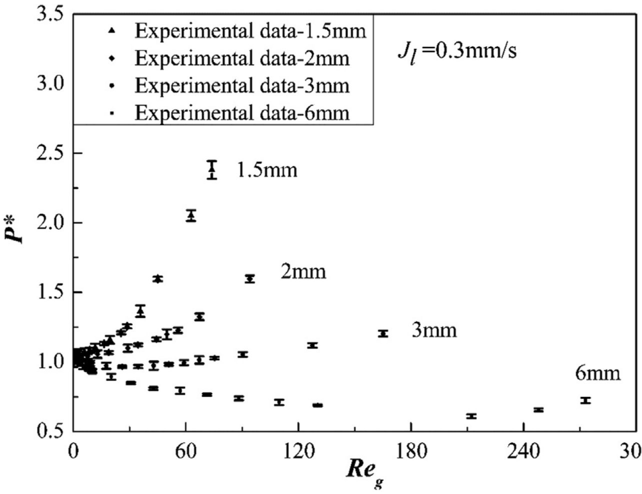

Fig. 3. Pressure drops of two-phase flow through beds packed with different size particles.

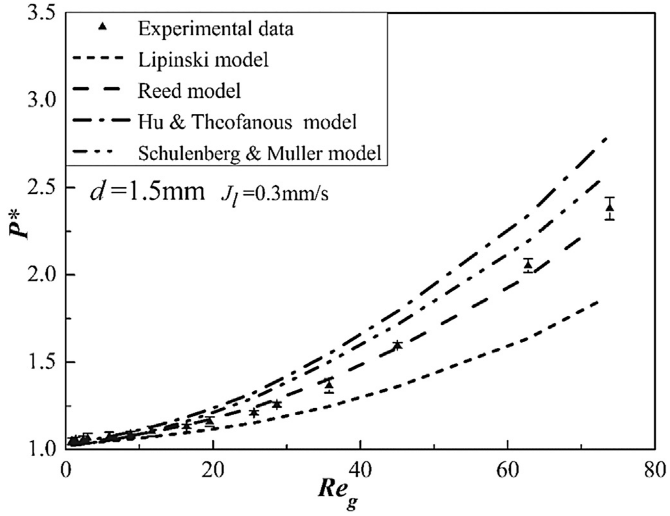

Fig. 4. Pressure drops of two-phase flow through bed packed with 1.5 mm sphere.

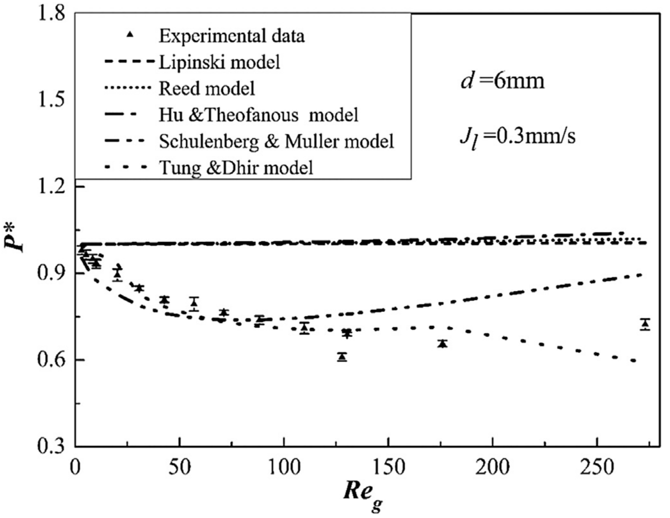

Fig. 7. Pressure drops of two-phase flow through bed packed with 6 mm spheres.

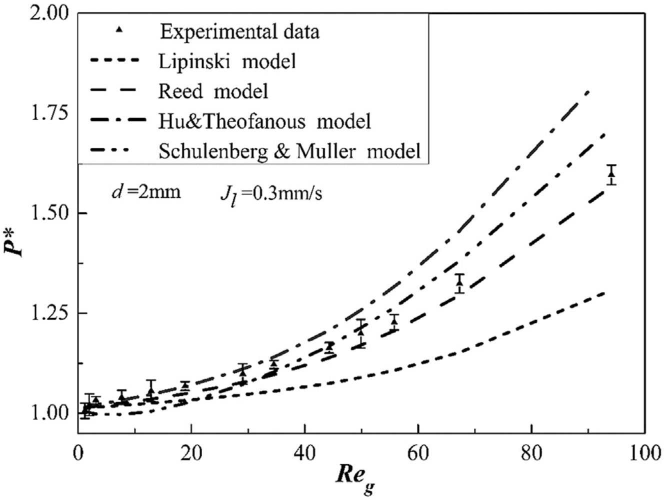

Fig. 5. Pressure drops of two-phase flow through bed packed with 2 mm spheres.

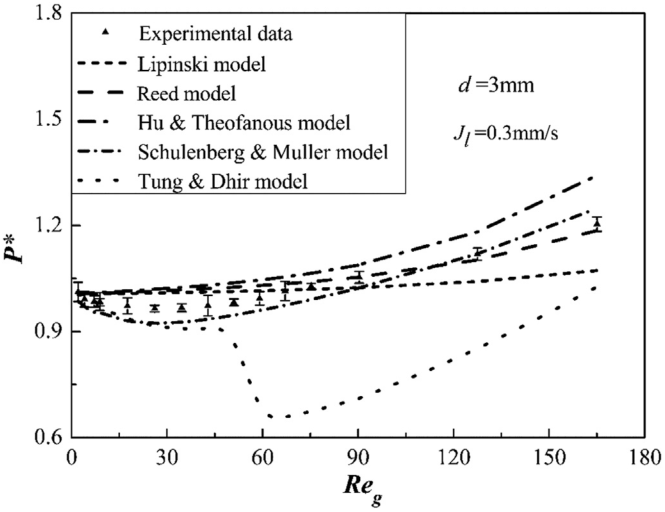

Fig. 6. Pressure drops of two-phase flow through bed packed with 3 mm spheres.

effect on the pressure drops of two-phase flow through the packed beds with small size particles. In detail, the calculated values by Hu & Theofanous model [13] and Schulenberg & Műller model [14] are significantly higher than the experimental values, while the calculated values by Lipinski model [11] is lower than the experimental values. Generally, the predicted values by Reed model [12] is more comparable with the experimental data especially at higher Reynolds number.

While for the curves of larger size particles (3 mm and 6 mm) shown in Figs. 6 and 7, the measured pressure drop appears a descent-ascent tendency along with the Reynolds number. Different with the descent-ascent tendency of the measured pressure drop curves, the calculated results by the models like Lipinski model [11], Reed model [12] and Hu & Theofanous model [13] show a rising trend gradually with the fluid velocities. Such kinds of models did not include the interfacial drags and the contribution of interfacial drag to the pressure drops is neglected. While the predictions of Schulenberg & Műller model [14] and Tung & Dhir model [15] show the similar descent-ascent tendency with that of experiments. In other words, the predictable models like Lipinski model [11], Reed model [12] and Hu & Theofanous model [13] which ignore the interfacial drag can not predict the descent-ascent trend for experimental pressure drops of large-size packed beds, while only Schulenberg & Műller model [14]and Tung & Dhir model [15] which include the interfacial drag item could predict this trend. Therefore, it is believed that the interfacial drag plays an important role to the variation of the pressure drops when two phase flow through the beds with larger particles. Consequently, the effect of interfacial drag should be considered in the debris coolability analysis models for beds with bigger size particles.

Based on the comparisons between the experiments and calculations with different models, as shown in Figs. 4–7, it seems that no one model can predict well all the experimental data in present study. The prediction of Reed model [12] are relatively close to the experimental data for the beds with smaller size particles like 1.5 mm and 2 mm spheres, corresponding to Figs. 4 and 5. While for pressure drops in the beds with larger particles of 3 mm and 6 mm spheres as shown in Figs. 6 and 7, the Reed model [12] does not even predict the downward tendency of the measured pressure drops and the predicted values are far from the experimental data especially at lower Reynolds number, because of ignoring the effects of interfacial drag in the model. On the other hand, the models considering the interfacial drag like Schulenberg & Műller model [14] and Tung & Dhir model [15], predict the similar trends as experimental data, but the calculated values are not agreement well with the experimental data, especially for the beds with smaller size particles. In summary, there is a clear need to modify and improve the debris coolabitly analysis models.

As discussed above, the difficulty in modeling such flows are lack of information on interfacial drag. As known from Eqs. (12)–(14), the dimensionless pressure drop P^* consists of hydrostatic pressure constant 1, liquid-particle drag F_{pl}^* and the interfacial drag F_i^*. When the water flow is zero, the liquid-particle drag F_{pl}^* would also be zero and could be almost neglected. So, the interfacial drag F_i^* can be derived from dimensionless pressure drop P^* based on the experimental measurements. In other words, for the special cases of zero water flow, $J_l = 0$

$$P^* = 1 - F_i^* \tag{16}$$

Obviously, if the interfacial drag $F_i{}^*$ is neglected ($F_i{}^* = 0$) too, Eq. (16) will be $P^* = 1$, meaning that the pressure drops would keep an invariable hydrostatic pressure and independence of air flow. Otherwise, the interfacial drag should be considered and may not be neglected.

To better understand the effect of interfacial drag on the pressure drops of two phase flow through packed beds, the special two-phase flow tests with a zero water flow are performed in present study. Fig. 8 shows variation of the dimensionless pressure drops (upper part) and interfacial drag F_i^* (bottom part) along with air flow in beds of 2 mm and 6 mm particles, based on the experimental data under the conditions of zero water flow ($J_l = 0$), where the solid triangle symbols represent the data from bed with 2 mm spheres while that of bed with 6 mm spheres are plotted as empty triangle symbols.

It can be seen from Fig. 8 that, for the bed with 6 mm spheres, the dimensionless pressure drops P^* are not maintain in hydrostatic pressure but decrease from the hydrostatic pressure gradually along with air flow during the test in present study. Correspondingly, the interfacial drag increases gradually from zero value according to Eq. (16), see the empty triangle symbols in Fig. 8. Therefore, the interfacial drag cannot be neglected and should be considered in the analysis of two-phase pressure drops in the beds with large particles. Comparing with that of 6 mm spheres, the variation of P^* and $F_i{}^*$ in bed of 2 mm spheres are fairly minor, especially at the conditions of lower Reynolds number.

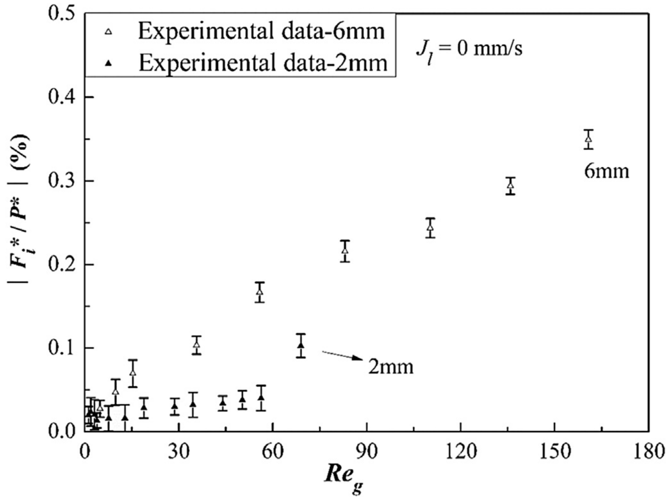

Fig. 9. F_i^*/P^*along with air flow.

Furthermore, the contribution of interfacial drag F_i^* on two-phase pressure drops P^* are also conducted by calculating the rates of F_i^*/P^* under the conditions of zero liquid flow rate, and the results are plotted in Fig. 9. It can be seen from Fig. 9 that the rates of F_i^*/P^* in bed of 6 mm spheres rises gradually with the air flowrate, and the max value is around 40%. In contrast, the rates of F_i^*/P^* for bed with 2 mm spheres are within 5%. It suggests that the influence of the interfacial drag on two-phase pressure drops of bed with smaller size particles is weak and ignorable, while the effect of interfacial drag should be considered in the debris coolability analysis models for beds with bigger size particles.

In addition, related data from published literature [8,16] are also collected and sorted to quantify the influence of the interfacial drag on two-phase pressure losses. Based on the experimental measurements for pressure losses and void fractions, the proportions of interfacial drag in pressure losses are calculated and plotted in Fig. 10, together with the related data from present study.

As seen from Fig. 10, in general, the proportions of interfacial drag in pressure losses of different-size beds show great distinctions. The proportions will become more significant with greater particle sizes of packed beds. The proportions of 3.18 mm packed

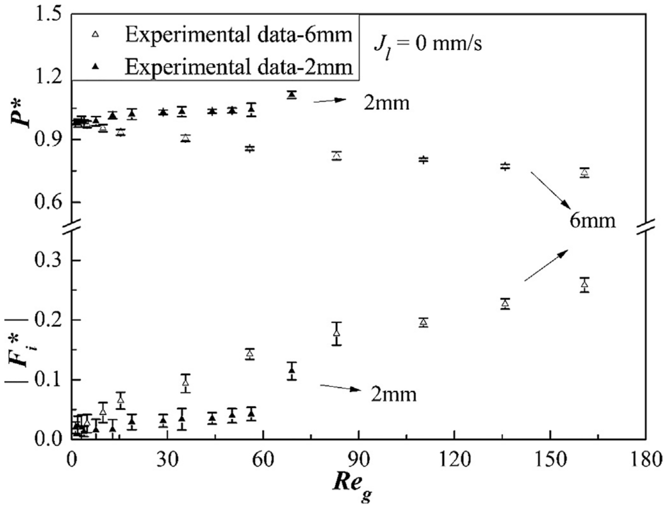

Fig. 8. Variation of P^* and F_i^*along with air flow.

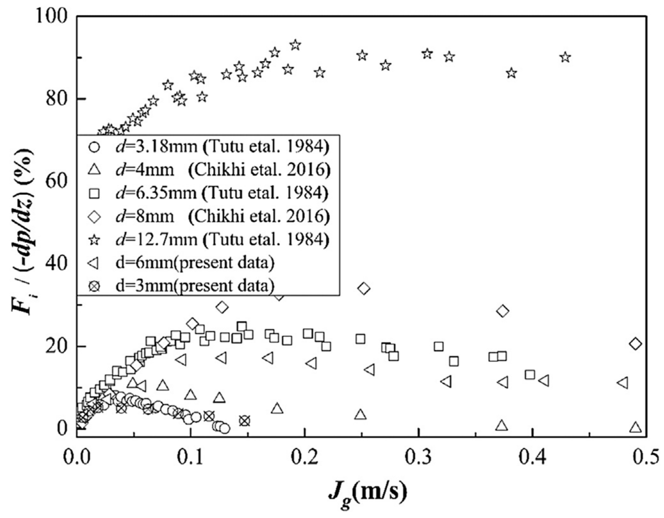

Fig. 10. The rates of interfacial drag to pressure losses.

bed vary under about 10% while those of packed bed with 12.7 mm particle rise dramatically near 90%. In other words, the influence of the interfacial drag on two-phase pressure losses is more and more significant with greater particle sizes of packed beds and the importance of the interfacial drag is once again verified, indicating the necessity of considering the interfacial drag in two-phase flow resistance analysis models.

4. Conclusions

Motivated by the reducing uncertainties in quantification of debris bed coolability and investigating the effects of interfacial drag on debris coolaiblity analysis, this paper reports an experimental study on the pressure drops and interfacial drag for two phase flow through packed porous beds. The pressure drops are measured when air-water two phase flow through the porous beds packed with different size particles, and the effects of interfacial drag are studied especially. The results show that, for the beds packed with small size particles such as 1.5 mm and 2 mm spheres, the contribution of interfacial drag to the pressure drops is weak and ignorable, while the significant effects are found on the pressure drops of two phase flow through the beds with bigger size particles like 3 mm and 6 mm spheres, where the interfacial drag will result in a descent-ascent tangency in the pressure drop curves along with the Reynolds number, and the effect of interfacial drag should be considered in the debris coolability analysis models for beds with big particles. This is a clear indication that the phenomenology of friction between phases is not enough and requires further investigations. New correlations have to be proposed in order to cover the whole range of flow parameters and particle diameters which are expected in reactor situations.

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Nomenclature

d	particle diameter *(m)*
D_b	bubble diameter *(m)*
F_i	Interfacial drag (Nm^{-3})
F_i^*	dimensionless interfacial drag
J	superficial velocity (ms^{-1})
K	permeability (m^2)
K_r	relative permeability
M	mass *(kg)*
P	pressure *(Pa)*
P^*	dimensionless pressure drop
s	Saturation
V	volume (m^3)

Greek letters

α	void fraction
ε	Porosity
η	passability *(m)*
η_r	relative passability
μ	dynamic viscosity *(Pa.s)*
ρ	density(kgm^{-3})
σ	surface tension(Nm^{-1})

Subscripts

g	Gas
l	Liquid

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