International Journal of Multiphase Flow 000 (2018) 1–11

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmulflow

Investigations on two-phase flow resistances and its model modifications in a packed bed

Liangxing Li[a,*], Xumao Zou[a,b], Huasheng Wang[a], Shuangbao Zhang[a], Kailin Wang[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

ARTICLE INFO

Article history:
Received 10 April 2017
Revised 12 November 2017
Accepted 18 December 2017
Available online xxx

Keywords:
Debris bed
Two-phase flow
Pressure drops
Interfacial drag
Coarse particles

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. Motivated by reducing the uncertainties in debris coolability assessment, this paper reports an experimental study on two-phase flow resistance in porous packed beds, and a modified model is proposed to predict the pressure drops of two-phase flow through packed beds with coarse particles. The tests are performed on the DEBECO-LT facility which is constructed to investigate the friction laws of adiabatic single and two-phase flow in a particulate bed. The spherical particles of 1.5 mm, 2 mm, 3 mm, 4 mm, 6 mm and 8 mm in diameter are packed separately in the cylindrical test section with the inner diameter of 120 mm and the height of 600 mm. The quality of experimentation and instrumentation can be ensured by the good agreement between the measured pressure drops of single phase flow tests and the predictions of Ergun equation. Then air-water co-current two-phase flow tests are conducted to investigate the flow resistance characteristics, providing the basic data for verifying, analyzing and modifying the existing models. The results show that: 1) when two-phase fluids flow upward through the porous beds packed with the smaller particles (e.g. 1.5 mm and 2 mm), the flow resistance increases gradually with the fluid flowrate, and the predictions of Reed model are more comparable with the measured pressure drops. While for the beds with larger size parties (e.g. 4 mm, 6 mm, and 8 mm), the flow resistances of two phase flow show a down-up tendency and hardly be predicted well by previous models; 2) it is believed that the interfacial drag plays non-ignorable role to the flow resistances for the beds packed with larger size particles, and should be considered specifically in the analysis models; 3) A modified model is proposed to predict the two-phase flow resistance in the packed bed with coarse particles. Compared with the previous models, the predictions of modified model show a favorable agreement with the experimental data under different 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 when corium melt comes in contact with the coolant water under the severe accident scenario of light water reactor (LWR). This may occur in-vessel in the lower head when melt is discharged from the core to the lower head (e.g. TMI-2), and also probably occur in ex-vessel, when the melt is discharged from the vessel failure site to the containment. Therefore, coolability of 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).

Towards quantitative understanding of debris bed coolability, lots of experimental and analytical studies (Lipinski, 1981, 1984; Reed et al., 1982, 1984; Tutu et al., 1984; Hu and Theofanous, 1984, 1991; Tung et al., 1984, 1988; Schulenberg and Muller, 1987; Schmidt, 2004, 2007; Rashid et al., 2008, 2011, 2012; Ma and Dinh, 2010; Repetto et al., 2013; Thakre et al., 2014; Chikhi et al., 2016, 2017; Clavier et al., 2015, 2017; Li and Ma, 2011a, 2011b; Li et al. 2012, 2015a, 2015b, 2016, 2017) have been performed, and a great

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

https://doi.org/10.1016/j.ijmultiphaseflow.2017.12.012
0301-9322/

Nomenclature

A	interfacial area (m^{-1})
d_b	bubble diameter (m)
d_b'	modified bubble diameter (m)
d_p	particle diameter (m)
F_i	interfacial drag (Nm^{-3})
J	superficial velocity (ms^{-1})
K	permeability (m^2)
K_r	relative permeability
m	exponent
M	mass (kg)
n	exponent
P	pressure (Pa)
s	saturation
t	exponent
V	volume (m^3)
Greek letters	
α	void fraction
α'	modified void fraction
ε	porosity
η	passability (m)
η_r	relative passability
μ	dynamic viscosity (Pas)
ρ	density(kgm^{-3})
ξ	an interpolation function
ω	weighing function
Subscripts	
g	gas phase
l	liquid phase
p	particle
Superscripts	
af	annular flow
bf	bubble flow
sf	slug flow

number of empirical models or semi-empirical analytical models and correlations had been developed for assessing debris coolability. The models are related to the theoretical knowledge and treatment of two-phase flow and heat transfer in porous media. Summaries and reviews of the previous studies can be found in the works of Li et al (2012, 2016, 2017), Chikhi et al. (2016), Chikhi and Fichot (2017), Bürger et al. (2010), Schmidt (2007), Boyer et al. (2007), Bordas et al. (2006), Nemec and Levec (2005) and Lindholm (2002, 2006). It is generally accepted and widely used by engineers that satisfactory predictions for frictional pressure drops pressure losses of single phase flow in packed beds with spheres can be achieved by simple semi-empirical models like 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.

Different from single-phase flow in porous media, the mutual influence between the fluid phases on the pressure drops of two-phase flow in porous media should be considered additionally. Lots of models and correlations (Lipinski, 1981, 1984; Reed, 1982; Tutu et al., 1984; Schulenberg and Muller, 1987; Tung and Dhir, 1988; Hu and Theofanous, 1991; Schmidt, 2007; Taherzadeh and Saidi, 2015; Clavier et al., 2017) had been proposed to assess the pressure drops of two-phase flow in porous media, however their prediction results are inconsistent with each other (Li et al., 2012; Chikhi et al., 2016). 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.

$$-\frac{dp_l}{dz} = \rho_l g + \frac{\mu_l}{KK_{r,l}}J_l + \frac{\rho_l}{\eta\eta_{r,l}}J_l|J_l| - \frac{F_i}{1-\alpha} \quad (2a)$$

$$-\frac{dp_g}{dz} = \rho_g g + \frac{\mu_g}{KK_{r,g}}J_g + \frac{\rho_g}{\eta\eta_{r,g}}J_g|J_g| + \frac{F_i}{\alpha} \quad (2b)$$

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, it can be seen from Eq. (2) that the total pressure drops consist of three terms: gravity force term, fluid-particles drag term and interfacial drag term.

Tables 1 and 2 summarize the models and their corresponding parameters which are employed especially for debris coolability analysis in nuclear engineering, where s means the liquid saturation, and the value equals to 1-α. Generally, these models can be categorized into two types. One kind of models such as Lipinski model (Lipinski, 1981), Reed model (Reed, 1982) and Hu & Theofanous model (Hu and Theofanous, 1991) did not take account of interfacial drag. Correspondingly, the interfacial drag in Eq. (2) is zero in these models. On the other hand, the influence of interfacial drag is specifically considered by other researchers, such as Tutu et al (1984), Schulenberg and Muller (1987), Tung and Dhir (1988); Schmidt (2007) and Taherzadeh and Saidi (2015). A latest model has been proposed by Clavier et al. (2017) on the basis of recent developments of theoretical averaging of momentum equations in porous media. The pressure drops can be determined by eight terms related to the viscous, inertial and interfacial friction between the phases based on an original experimental database containing measurements of pressure drops, average velocities and void fractions from the IRSN CALIDE experiment. However, the model involved in some empirical parameters deduced from ideal assumption, and the applicability of the correlation still need further verification.

As listed in Tables 1 and 2, one can note that the key point in modeling two-phase flow in porous beds is to provide the formulation of the friction laws for momentum equations, since it is believed that the debris coolability is mainly restricted by hydrodynamic limitations of two-phase flow through the debris bed (Ma and Dinh, 2010). However, some of the key parameters (e.g. K_r, η_r) in above equations are given different expressions by different researchers. Especially for interfacial drag F_i, there is no common cognition yet. Therefore, even for the same conditions, the predicting results by different models may be discrepant due to different choices for the parameters. Recent work from Chikhi et al. (2016) also stated that there was no definitive conclusion on this subject.

Motivated by reducing the uncertainties in analyzing debris coolability, the frictional pressure drops of two-phase flow through the packed beds with different-size particles are investigated, and the experimental data are used to verify and analyze the models for two-phase flow friction in porous media. The objective is to qualify or proposed an appropriate calculation model for

Please cite this article as: L. Li et al., Investigations on two-phase flow resistances and its model modifications in a packed bed, International Journal of Multiphase Flow (2018), https://doi.org/10.1016/j.ijmultiphaseflow.2017.12.012