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Modeling of pressure drop in two-phase flow of mono-sized spherical particle beds

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ABSTRACT

To reduce the uncertainty in predicting pressure drop for two-phase flow through spherical particle beds, especially composed of small-sized particles that adversely affect the cooling, an experimental study was performed. A series of experiments were performed to measure the pressure drop of upward two-phase flow through well-packed spherical particle beds with 2, 3.5, and 5 mm diameter particles under isothermal conditions varying the gas flow rates with no water inflow at the bottom. Based on the experimental results and the results of our previous study related to the modification of Ergun constants, a new improved model for prediction of the two-phase flow pressure drop through porous media was proposed. The adequacy of the proposed model was verified by comparison with various existing experimental data for particle diameters of 3.18–6.35 mm and the superficial air velocity of 0–0.8 m/s.

1. Introduction

Two-phase flow in porous media is a concern of various scientific, industrial, and engineering fields related to mechanical, chemical, petroleum, geologic, and environmental applications and so on. Among these applications, in a point of view of nuclear power plant safety particularly, a porous debris bed can be formed in the lower plenum of reactor pressure vessel (RPV) and the reactor cavity, when a severe accident occurs in nuclear power plants. A severe accident (SA) of a nuclear power plant is an accident condition more severe than a design basis accident (DBA). It is involving an initiating event by external factors such as seismic or flooding, or internal factors such as a loss of coolant accident (LOCA), transients with multiple equipment failures, resulting crippled engineered safety features (ESF), consequent problems in the reactor core cooling against the decay heat and significant core damages [1].

When the core damage occurs in a light water nuclear power plant, the molten core material (corium) can fall and relocate into the lower plenum of the reactor pressure vessel. In this case, a debris bed can be formed in the lower plenum of the reactor pressure vessel due to heat up and clad cracks which has been observed in the TMI-2 reactor. The molten core material can then be further released into the containment, e.g. the reactor cavity of a pressurized water reactor (PWR), when the reactor vessel fails. It is expected that the reactor cavity is filled with water supplied by the cavity flooding system (CFS), containment spray, or other systems as a part of severe accident management (SAM) strategies [2]. During the release of the molten core into the reactor cavity, the molten core material interacts with water, i.e. fuel coolant interactions (FCI), fragments into millimeter-sized particles and settles down as a debris heap on the reactor cavity floor [3–5].

In the late phases of a severe accident in nuclear power plants, to ultimately terminate the severe accident progression, it is crucial to cool and stabilize the molten core debris, which experiences internal heat generation by the decay heat of the fission products. Unless the decay heat in the core debris is not sufficiently removed, the once solidified particulate debris may heat up, re-melt and cause the molten core concrete interaction (MCCI). It threatens the integrity of the containment building, the final physical barrier preventing the release of radioactive materials into the environment. Therefore, it is of key importance to evaluate the long-term coolability of a debris bed on the reactor cavity floor.

The debris coolability can be accomplished by continuously supplying water to the heat generating debris bed, the effectiveness of which is determined based on the pressure drop through the bed. Thus, it is essential to adequately describe the friction in a debris bed and the resulting heat transfer performance for predicting the debris bed coolability. The important factors that affect the flow resistance and debris bed cooling are the geometry,

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Nomenclature

C_1, C_2	Ergun constants (–)
C_v, C_i	coefficients (–)
D_b	bubble diameter (m)
d_p	spherical particle diameter (m)
d_t	inner diameter of test section (m)
F^*	dimensionless volumetric drag force between phases, $F^* = F/(\varepsilon(\rho_l - \rho_g)g)$ (–)
F_i	volumetric liquid-gas drag force (Pa/m)
F_{pg}	volumetric particle-gas drag force (Pa/m)
F_{pl}	volumetric particle-liquid drag force (Pa/m)
f	geometric factor (–)
g	acceleration of gravity (m/s^2)
k_0	shape parameter of the cross-section of the channel (–)
K	permeability (m^2)
K_{ri}	relative permeability of i-phase fluid (–)
m_p	mass of particle (kg)
p	pressure (Pa)
s	liquid saturation (–), $s = 1 - \alpha$ (–)
V_r	relative velocity (m/s)
V_{si}	superficial velocity of i-phase fluid (m/s)
$V_{sl,0}$	superficial velocity of additional water inflow from the bottom of a bed (m/s)
V_t	volume of the test section (m^3)
$W(\xi)$	weighting function (–)

Greek symbol

α	void fraction (–)
β	ratio of pore diameter to throat diameter (–)
β_r	ratio of the average distance between two adjacent particles and the particle diameter (–)
γ	ratio of the bubble diameter and the particle diameter (–)
ε	porosity (–)
η	passability (m)
η_{ri}	relative passability of i-phase fluid (–)
μ	dynamic viscosity (Pa·s)
ρ	density (kg/m^3)
σ	surface tension (N·m)
τ	tortuosity (–)

Subscript

i	fluid phase; l = liquid, g = gas
p	particle

namely, the bed thickness [6], morphology [7], porosity [8], debris size distribution [9,10], and debris shape [8,11–14]. Other factors affecting a flow resistance are concerned with the characteristics of the fluid, such as the flow pattern and the properties based on the operating conditions.

Insights on the characteristics of a debris bed under accident conditions can be found in the results of previous investigations on FCI experiments [15,16]. A debris bed is composed of irregular shaped particles with a particle size distribution ranging from a few micrometers to approximately 10 mm, and has macro inhomogeneity, such as in axially and radially stratification, e.g. a layer of smaller particles covers the main part of the bed [3,16,17]. In a debris bed with internal heat generation by the decay heat, both co- and counter-current two-phase flow can occur by water inflow from the side and the top of the bed, combined with steam outflow at the top of the bed. In the case of the co-current flow of steam and water by water coming in the side of the debris bed, the debris bed cooling can be enhanced because water is dragged by the upward steam flow. In contrast, for the counter-current flow, a limitation of the coolability can be led by the interference of upward steam flow with water supply from the top of the debris bed, with which the evaporated water in the bed is no longer compensated by the downward inflow.

To resolve the safety issue of long-term coolability of an ex-vessel debris bed, intensive studies [18–24] have been conducted to describe not only the friction but also the heat transfer. Based on numerous results of the dryout heat flux and isothermal air/water experiments, many models of two-phase flow through porous media have been suggested by including the relative permeabilities and passabilities with/without consideration of the interfacial drag between liquid and gas based on the Ergun equation [25]. The Ergun equation is a semi-empirical equation for predicting the pressure drop of single-phase flow in homogeneous beds consisting of mono-sized spherical particles.

Nevertheless, there are still uncertainties in the evaluation of the resulting cooling potential of an ex-vessel debris bed due to the complexity of the bed structure, the interactions among the phases, and the influence of flow patterns on pressure drop and dryout heat flux, especially in the debris bed composed of small-sized particles. Specifically, the models by Hu and Theofanous [20], Lipinski [19], and Reed [18] developed from the results of the dryout heat flux did not consider the interfacial drag between liquid and gas. On the other hand, the models by Schmidt [23], Schulenberg and Müller [21], and Tung and Dhir [22] considered the interfacial drag in different ways each other, and they also bring uncertainties in predicting the pressure drop in particle beds composed of small-sized particles with a diameter less than or equal to 5 mm. Moreover, Clavier et al. [24] developed a model for multi-phase flows in porous media, however, there exists empirical function for their proposed model k_{lg} and exponent n by fitting. The range of values are 4–70 and 2.2–9 according to the particle diameter of 3.18–12.7 mm, respectively.

Considering the influence of two-phase flow pressure drop on the assessment of the debris bed coolability, it is significantly meaningful to clarify the reasons of existing disagreement among two-phase flow pressure drop models for particle beds. Besides, it is important to seek for adequate formulations considering the influence of debris bed characteristics on the hydrodynamic resistance with various flow conditions. Furthermore, the pressure drop modeling could help either dry-out or quenching situation [26,27]. Therefore, the objective of the present study is to develop a pressure drop model for two-phase flow in particle beds, especially, which is composed of small-sized particles with diameters less than or equal to 5 mm.

For this objective, a series of experiments were performed to measure the pressure drop of two-phase flow through packed particle beds with spherical particles (2, 3.5, and 5 mm in diameter) under isothermal conditions. An isothermal water/air experiment is a useful way to investigate the pressure drop of two-phase flow in particle beds without considering the influence of the phase change occurring under circumstances as such boiling. In addition, based on our previous study [28] on modifying the Ergun constants, $C_1 = 36k_0\tau^2$ and $C_2 = 3\tau(3/2 + 1/\beta^4 - 5/2\beta^2)/4$, the present study proposes a new improved model for two-phase flow through porous media based on the Schmidt [23] model. Moreover, various existing experimental data, especially composed of