Modified Two-Phase Friction Model for Porous Media to Better Predict Dryout Heat Flux

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1. Introduction

In the severe accident of light water reactor (LWR) with water filled containment cavity, the ex-vessel debris bed would be formed with settled corium particles rather than molten phase due to FCI (Fuel Coolant Interaction). In this case, the coolability of debris bed has to be reliably evaluated for the analysis of the possibility of MCCI occurrence.

The cooling limitation of debris bed is often described as DHF (Dryout Heat Flux), which is the maximum heat flux through the bed without dryout. In the modeling of DHF, the most important phenomenological factor is the flow resistance through the particle bed. Therefore, many researches worked on two-phase friction modeling in porous media to predict DHF[1, 2]. It has been known that the model suggested by Reed[2] shows good agreement with 1D top flooding DHF experimental results[3]. On the other hand, in the case of co-current flow condition, such as bottom fed condition, the Reed model often strongly underestimates DHF[4].

The ex-vessel debris bed is expected to form in a mound shape[5], which allows lateral flow of water into the bed resulting co-current flow inside the bed. In order to capture the amount of water ingression into the ex-vessel debris bed, the interfacial friction between gas and liquid phases, which is not considered in the Reed's model, is important. Therefore, in this research, an improvement of two-phase friction model in porous media including the interfacial drag is proposed. This modified model is also compared with experimental data of two-phase pressure drop in both isothermal air/water and boiling conditions and DHF experiments.

2. Method

2.1 Models of two-phase flow in porous media

The drag forces between solid and fluid phases are generally modelled based on Ergun's single phase flow model:

$$F_{pg} = \varepsilon\alpha\left(\frac{\mu_g}{KK_{rg}}j_g + \frac{\rho_g}{\eta\eta_{rg}}|j_g|j_g\right) \tag{1}$$

$$F_{pl} = \varepsilon(1-\alpha)\left(\frac{\mu_l}{KK_{rl}}j_l + \frac{\rho_l}{\eta\eta_{rl}}|j_l|j_l\right) \tag{2}$$

$$K = \frac{\varepsilon^3 d^2}{150(1-\varepsilon)^2} \tag{3}$$

$$\eta = \frac{\varepsilon^3 d}{1.75(1-\varepsilon)} \tag{4}$$

where ε is the porosity, α the void fraction, μ the viscosity, ρ the density, j the superficial velocity, K and η the permeability and the passability, respectively, and d the particle diameter, K_r and η_r the relative permeability and the relative passability, respectively. The relative permeability and passability in previous models are summarized in Table I.

Table I: Relative permeability & passability

	K_{rl}	η_{rl}	K_{rg}	η_{rg}
Tung & Dhir[6]	$(1-\alpha)^4$	$(1-\alpha)^4$	Table II	
Schulenberg & Müller [7]	$(1-\alpha)^3$	$(1-\alpha)^5$	α^3	α^6 $(\alpha > 0.3)$ $0.1\alpha^4$ $(else)$

The interfacial friction force suggested by Schulenberg & Müller [7] is written below.

$$F_i = C_1(1-\alpha)^7\alpha\left(\frac{j_g}{\alpha} - \frac{j_l}{1-\alpha}\right)^2 \tag{5}$$

$$C_1 = 350\frac{\rho_l K}{\eta\sigma}(\rho_l - \rho_g)g \tag{6}$$

Unlike Schulenberg & Müller's model, which is an experimental correlation, Tung & Dhir model used completely different approaches. They suggested two-phase flow regime inside porous media depending on the void fraction based on observation of relatively larger (>6 mm) particle bed. In their model, the interfacial drag correlation for single bubble/slug has been modified by considering number density of bubbles/slugs in porous media. In the annular flow regime, they assume gas flows through the gap among solid particles covered by water layer. They simply model as gas-solid friction force by adopting effective particle diameter enlarged by the thickness of the liquid film on the particles. The details of Tung & Dhir's model are summarized in Table II and III.

2.2 Modifications of Tung & Dhir model

As the validity range of Tung & Dhir model is for relatively large particles compared to the prototypic debris bed particle size (2~5 mm), the model has to be somehow modified for smaller particles. Due to smaller pore size, the flow pattern would change at a lower void fraction, as bubble can grow as big as pore size even in very low void fraction. Based on the point, Rahman[8] suggested modified flow regime map. In addition to this, Schmidt[9] reported that Tung & Dhir's model over estimates the interfacial friction drag compared to the Tutu's experiment[10], which was conducted at up to 0.6 of void fraction. Therefore, Schmidt proposed a correction factor $(1-\alpha)^2$ for the annular regime.

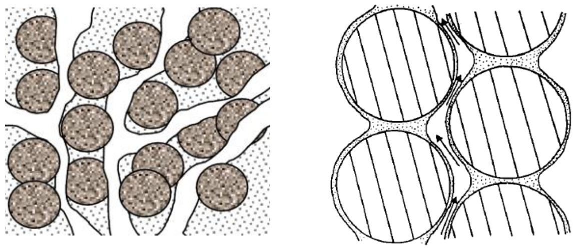
Table II: Gas relative permeability & passability in Tung & Dhir model

<table>
<tr><th rowspan="2">Flow regime</th><th colspan="2">Tung & Dhir</th></tr>
<tr><th>K_{rg}</th><th>η_{rg}</th></tr>
<tr><td>Bubbly</td><td rowspan="3">$(\frac{1-\varepsilon}{1-\varepsilon\alpha})^{4/3}\alpha^4$</td><td rowspan="3">$(\frac{1-\varepsilon}{1-\varepsilon\alpha})^{2/3}\alpha^4$</td></tr>
<tr><td>Transition</td></tr>
<tr><td>Slug</td></tr>
<tr><td>Transition</td><td>$\frac{[(\frac{1-\varepsilon}{1-\varepsilon\alpha})^{4/3}\alpha^2]}{(W+\frac{1-W}{\alpha})}$</td><td>$\frac{[(\frac{1-\varepsilon}{1-\varepsilon\alpha})^{2/3}\alpha^2]}{(W+\frac{1-W}{\alpha})}$</td></tr>
<tr><td>Annular</td><td>$(\frac{1-\varepsilon}{1-\varepsilon\alpha})^{4/3}\alpha^3$</td><td>$(\frac{1-\varepsilon}{1-\varepsilon\alpha})^{2/3}\alpha^3$</td></tr>
</table>

Table III: Interfacial friction in Tung & Dhir model

<table>
<tr><th rowspan="2">Flow regime</th><th colspan="2">Tung & Dhir</th></tr>
<tr><th>C_1</th><th>C_2</th></tr>
<tr><td>Low void bubbly flow</td><td>$18\alpha f$</td><td>$0.34(1-\alpha)^3\alpha f^2$</td></tr>
<tr><td>High void bubbly flow</td><td>$18(\alpha_0 f+\alpha-\alpha_0)$</td><td>$0.34(1-\alpha)^3\cdot(\alpha_0 f^2+\alpha-\alpha_0)$</td></tr>
<tr><td>Transition</td><td colspan="2">Interpolation with weighting function: $W=\zeta^2(3-2\zeta)$</td></tr>
<tr><td>Slug flow</td><td>5.21α</td><td>$0.92\alpha(1-\alpha)^3$</td></tr>
<tr><td>Transition</td><td colspan="2">Interpolation with weighting function: $W=\zeta^2(3-2\zeta)$</td></tr>
<tr><td>Annular</td><td colspan="2">$F_i=\varepsilon(1-\alpha)(\frac{\mu_g}{KK_{rg}}j_{r,a}+\frac{\rho_g}{\eta\eta_{rg}}{j_{r,a}}^2)$</td></tr>
<tr><td colspan="3">$F_i=\left(C_1\frac{\mu_l}{{D_b}^2}j_r+C_2\frac{\rho_l(1-\alpha)+\rho_g\alpha}{\varepsilon D_b}{j_r}^2\right)$
$j_r=\frac{(1-\alpha)j_g}{\alpha}-j_l,\ j_{r,a}=j_g-\frac{\alpha}{1-\alpha}j_l,$
$\zeta=\frac{\alpha-\alpha_{i-1}}{\alpha_{i+1}-\alpha_{i-1}}$
$D_b=1.35\sqrt{\frac{\sigma}{g(\rho_l-\rho_v)}}$
$f=0.5(1+\gamma)\ln(1+\frac{2}{\gamma}),\ \gamma=D_b/d$</td></tr>
</table>

However, this descripency seems to come from the characteristics of annular flow in porous media. As there are uncountably many flow paths inside porous media, some of flow paths are remained water-filled when the void fraction is not high enough as shown in Fig. 1. (a), which means the application of Tung & Dhir's annular regime (Fig. 1 (b)) into such condition can be inappropriate. The Tung & Dhir's annular regime would be only valid and occur when most of flow paths are allowed for gas, that occur at very high void fraction. Therefore we propose to divide annular regime in Tung & Dhir's model into channel and annular regime (Fig2.).

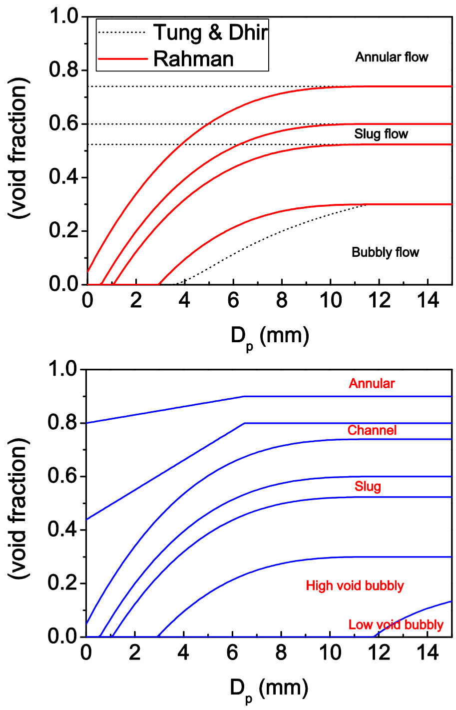


(a) (b)

(a) Schematics of channel flow concept[11]
(b) Annular flow concept in Tung & Dhir's model[6]
Fig. 1. Annular/Channel flow concepts in porous media

(a)

(b)



(a) Regime map suggested by Tung & Dhir, Rahman
(b) Proposed modified regime map
Fig. 2. Two-phase flow regime map in porous media

In the channel flow regime (Fig. 1. (a)), the actual flow path size for gas should be larger than the one in the annular flow concept when we assume the same void fraction. Also, the actual gas-liquid interfacial area should be much smaller than in the annular regime. In this research, we adopted the Schmidt's modification factor $(1-\alpha)^2$ to account the differences of interfacial area.

In addition to this, the correction term $(\frac{1-\varepsilon}{1-\varepsilon\alpha})$, for the effective gas flow path by assuming particles covered by liquid, in particle-gas drag and interfacial drag is only adopted in the annular regime.

For extending the Tung & Dhir's model into smaller particle bed, three modifications have been proposed. First, the bubble diameter is changed into $\min(D_{b,TD}, 0.41d)$, which is suggested by Schmidt[9], to prohibit bubble size exceeding pore size. Second, the interfacial drag is decreased as particle size becomes smaller. Recent researches reported the decrease of interfacial friction fraction in the total pressure drop with smaller particle sizes[12]. The proposed modification factors are $\min(1, \frac{\mathrm{d(mm)}}{10})$ for bubbly and slug flow and $\min(1, \frac{\mathrm{d(mm)}}{8})$ for channel and annular flow. Third, due to the drastic decrease of the interfacial friction for beds of very small particles, less than 1 mm, relative permeability and passability are modified to the cubic of volume fractions of each phase just like the classical two-phase flow models.

For accounting the actual pore size effect, the criterion for the application of the modified model is defined by the permeability rather than the particle diameter. Thus, the modification is applied for cases the permeability is less than 1.3e-9 (corresponding to 1 mm particle size with 0.4 porosity). For keeping continuity of pressure drop with changing particle sizes, an interpolation is used to obtain relative permeability up to 5e-9 (~ 2 mm of particle size). The interpolation factor is proposed as below.

$$W_2 = \tau^2(3-2\tau), \tag{7}$$

$$\tau = \frac{\mathrm{K} - 1.3\times10^{-9}}{5\times10^{-9} - 1.3\times10^{-9}} \tag{8}$$

3. Results

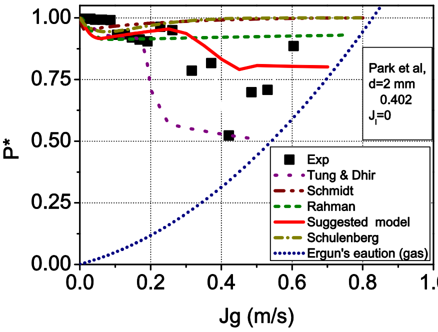
3.1 Air-water pressure

The modified model is compared to the isothermal air-water pressure drop experimental data by Park et al. [18] and by Chikhi et al. [19] in Fig. 3.

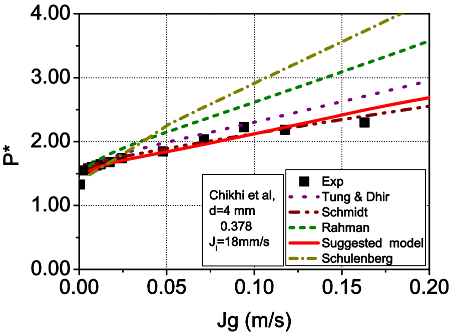
In the case of 2 mm experiment, the present model can predict sudden decrease of the pressure drop in the transition region to single phase gas flow reasonably. The Tung & Dhir's model also predicts it, but with a strong exaggeration. Others cannot capture such a behavior. For the 4 mm particle bed with liquid inflow, all model can capture trend of pressure behavior. The Schulenberg & Muller's and Rahman's model seem to over-predict the pressure drop.

3.2 Dryout Heat Flux

The present model was implemented in an 1D DHF code. The modeling and calculation procedure are described in Lee et al.[3]. The top flooding experiments in Fig. 4. (a) includes conditions with 1-7 bar of system pressure, 0.804-15.88 mm of particle diameter, 2-64 cm of bed height and 0.363-0.473 of porosity from 6 different literatures[4, 13-17]. As shown in Fig 4. (a), the present model seems to well predict the top flooding DHF value. The model predicted DHF value within $0.7 \pm 16.7\%$



(a) Experiment by J. H. Park et al. [18]



(b) Experiment by N. Chikhi et al. [19]

Fig. 3. Comparison with isothermal air-water experiments

Fig 4. (b) shows model comparison with DHF experiments[4, 20, 21] with coolant ingression by hydrostatic head. The conditions are 1-5 bar of system pressure, 0.37-0.405 of porosity, 48.5-64 cm of bed height and the particle diameter 2.5-3 mm.

In the case of bottom injection, the Tung & Dhir's, Rahman's and the present model well predicts the experimental results, while others under-estimate for all case of experiments.

4. Conclusion

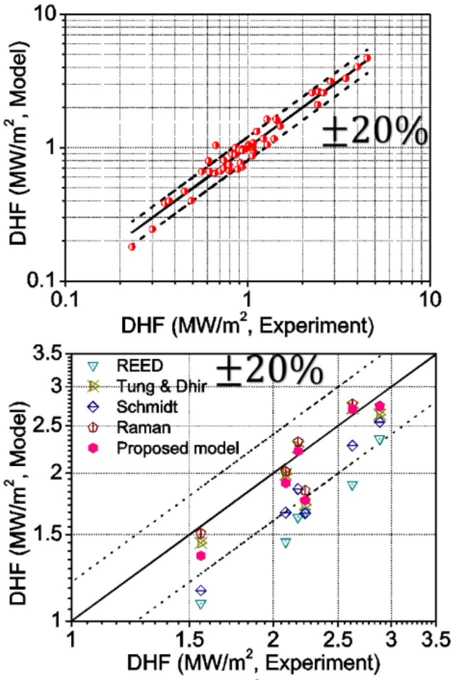
A two-phase friction model for porous media was proposed by modification of Tung & Dhir's model. The model well agreed with experimental data for isothermal air-water system not only in the overall trend but also quantitatively.

The model was also compared to the DHF experimental results including both top flooding and bottom ingression cases. In the top flooding case, as there are many experiments conducted, statistical analysis was proceeded. As a result, the model can predict 1D top flooding DHF experimental data with about $0.7 \pm 16.7\%$ of error. In addition, the model showed relatively good agreement also with experimental data under bottom water ingression condition. Therefore, it would be applicable to both in- & ex-vessel debris bed coolability assessment, which have feature of either co-current or counter-current flow between liquid and vapor.

In addition, in order to check the model capability of evaluation of ex-vessel debris bed coolability, which would be expected to be mound-like shape, the multi-dimensional analysis will be conducted in the future.

(a)

(b)



(a) Comparison with 1D top flooding experiments

(b) Comparison with 1D bottom ingression

Fig. 4. Comparison with DHF experiments (with 20% of error lines)

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