Validation of New Friction Model for Dryout Heat Flux in Ex-Vessel Porous Debris Bed in the Multi-Dimensional Configurations

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1. Introduction

In the severe accident of a light water reactor (LWR) with water filled reactor cavity as a part of the accident management measures, the ex-vessel corium debris bed would be formed with the settled corium particles due to the breakup in water rather than a continuous molten phase. However, if the debris bed is not cooled effectively, the debris bed may re-melt and leads to the molten core-concrete interaction (MCCI). Considering such a situation, the coolability of the debris bed has to be reliably evaluated for the analysis of the accident scenario and consequences.

The cooling limitation of debris bed is often described as DHF (Dryout Heat Flux), which is defined as the maximum heat flux through the bed without dryout. In the modeling of DHF, one of the most important phenomenological factors is the flow resistance through the particle bed. Therefore, many researchers worked on two-phase friction model in porous media to predict DHF[1, 2]. We, recently[3] argued the necessity of friction model modifications especially at high void fraction conditions and suggested the modification of the previous drag force models by proposing channel and annular regime inside the porous media and for interfacial friction modeling in it. The modifications showed reasonable agreement with one dimensional pressure drop and dryout heat flux experimental database. Therefore, the purpose of this work is to examine the validity of the proposed model [3] in the multi-dimensional configurations.

2. Methods and Results

2.1 Governing equations

For the analysis of multi-dimensional effects on dryout phenomena in a porous bed, the ANSYS Fluent[4] 16.2 was used. In the Fluent 16.2, the mass conservation equation of two-phase flow in porous media with superficial velocity formulation for the phase 'i' is

$$\frac{\partial}{\partial t}\left(\alpha_i \rho_i\right) + \nabla(\alpha_i \rho_i \overrightarrow{j_{i,FL}}) = \Gamma_i \tag{1}$$

where $\overrightarrow{j_{i,FL}}$ is the superficial velocity which Fluent uses and is defined differently from conventional concepts such as

$$\overrightarrow{j_{i,FL}} = \frac{\vec{j_i}}{\alpha_i} \tag{2}$$

where $\vec{j_i}$ is the superficial velocity of 'i' phase.

In addition, Γ is the evaporation rate achieved from the volumetric heat generation divided by the latent heat.

$$\Gamma = \frac{Q_{vol}}{h_g - h_l} \tag{3}$$

The momentum equations with the superficial velocity formulations in Fluent 16.2 are

$$\begin{aligned} &\frac{\partial}{\partial t}\left(\alpha_i \rho_i \overrightarrow{j_{i,FL}}\right) + \nabla(\alpha_i \rho_i \overrightarrow{j_{i,FL}}\,\overrightarrow{j_{i,FL}}) \\ &= -\alpha_i \vec{\nabla} P_i + \alpha_i \rho_i \vec{g} + \frac{\overrightarrow{F_{s,i}}}{\varepsilon} + \frac{\vec{F_i}}{\varepsilon} \end{aligned} \tag{4}$$

As the Fluent does not include two phase friction force models by default, the $\overrightarrow{F_{s,i}}$ (drag force between solid and fluid) and $\vec{F_i}$ (drag force between fluid phases) terms have to be applied explicitly by a User Defined Function(UDF). The drag model proposed by our previous work [3] was applied in the present analysis and summarized in Table I.

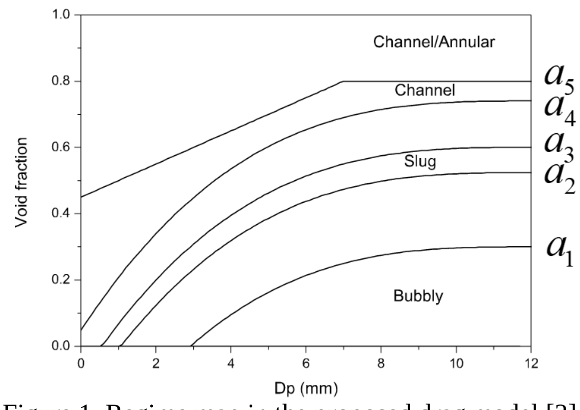


Figure 1. Regime map in the proposed drag model [3]

Table I. Two phase friction force model used in calculation [3]

<table>
<tr><td colspan="3">F_i</td></tr>
<tr><td>Bubbly flow</td><td colspan="2">$F_{i,bubbly,proposed} = (18C_1\alpha f u_r + 0.34C_2(1-\alpha)^3\alpha f^2 \lvert u_r \rvert u_r)\cdot \min\left(1, \dfrac{D_P}{0.012}\right)$</td></tr>
<tr><td>Transition</td><td colspan="2">$F_{i,b-s,proposed} = (1-W_{b-s})F_{i,bubbly,proposed} + W_{b-s}F_{i,slug,proposed}$</td></tr>
<tr><td>Slug flow</td><td colspan="2">$F_{i,slug,proposed} = (5.21C_1\alpha u_r + 0.92C_2(1-\alpha)^3\alpha \lvert u_r \rvert u_r)\cdot \min\left(1, \dfrac{D_P}{0.012}\right)$</td></tr>
<tr><td>Transition</td><td colspan="2">$F_{i,s-c,proposed} = (1-W_{s-c})F_{i,slug,proposed} + W_{s-c}F_{i,channel,proposed}$</td></tr>
<tr><td>Channel flow</td><td colspan="2">$F_{i,channel,proposed} = \varepsilon(1-\alpha)^3\left(\dfrac{\mu_v}{KK_{rv}}u_{r,annular} + \dfrac{\rho_v}{\eta\eta_{rv}}\lvert u_{r,annular}\rvert u_{r,annular}\right)\cdot \min\left(1, \dfrac{D_P}{0.008}\right)$</td></tr>
<tr><td>Channel/Annular flow</td><td colspan="2">$F_{i,annular,proposed} = \varepsilon(1-\alpha)\left(\dfrac{\mu_v}{KK_{rv}}u_{r,annular} + \dfrac{\rho_v}{\eta\eta_{rv}}\lvert u_{r,annular}\rvert u_{r,annular}\right)\cdot \min\left(1, \dfrac{D_P}{0.008}\right)$
$F_{i,channel/annular,proposed} = (1-W_{c-c/a})F_{i,channel,proposed} + W_{c-c/a}F_{i,annular,proposed}$</td></tr>
<tr><td colspan="3">$F_{sv} = \varepsilon\alpha\left[\dfrac{\mu_v}{KK_{rv}}u_{s,v} + \dfrac{\rho_v}{\eta\eta_{rv}}\lvert u_{s,v}\rvert u_{s,v}\right]$</td></tr>
<tr><td></td><td>K_{rv}</td><td>η_{rv}</td></tr>
<tr><td>Bubbly/slug flow</td><td>α^4</td><td>α^4</td></tr>
<tr><td>Transition</td><td>$\dfrac{\alpha^4}{1-W_{s-a}(1-\alpha)}$</td><td>$\dfrac{\alpha^4}{1-W_{s-a}(1-\alpha)}$</td></tr>
<tr><td>Channel flow</td><td>α^3</td><td>α^3</td></tr>
<tr><td>Channel/Annular flow</td><td>$\dfrac{\left(\dfrac{1-\varepsilon}{1-\varepsilon\alpha}\right)^{4/3}\alpha^3}{\left(\dfrac{1-\varepsilon}{1-\varepsilon\alpha}\right)^{4/3} + W_{c-c/a}\left(1-\left(\dfrac{1-\varepsilon}{1-\varepsilon\alpha}\right)^{4/3}\right)}$</td><td>$\dfrac{\left(\dfrac{1-\varepsilon}{1-\varepsilon\alpha}\right)^{2/3}\alpha^3}{\left(\dfrac{1-\varepsilon}{1-\varepsilon\alpha}\right)^{2/3} + W_{c-c/a}\left(1-\left(\dfrac{1-\varepsilon}{1-\varepsilon\alpha}\right)^{2/3}\right)}$</td></tr>
<tr><td colspan="3">$F_{sl} = \varepsilon(1-\alpha)\left[\dfrac{\mu_l}{KK_{rl}}u_{s,l} + \dfrac{\rho_l}{\eta\eta_{rl}}\lvert u_{s,l}\rvert u_{s,l}\right]$</td></tr>
<tr><td></td><td>K_{rv}</td><td>η_{rv}</td></tr>
<tr><td>-</td><td>$(1-\alpha)^4$</td><td>$(1-\alpha)^4$</td></tr>
<tr><td colspan="3">$C_1 = \dfrac{\mu_l}{D_b^{\ 2}}$, $C_2 = \dfrac{\rho_l(1-\alpha)+\rho_v\alpha}{\varepsilon D_b}$, $f = 0.5\left(1+\dfrac{D_b}{D_{P,regime}}\right)\ln\left(1+\dfrac{2D_{P,regime}}{D_b}\right)$
$D_b = \min\left(1.35\sqrt{\dfrac{\sigma}{g(\rho_l-\rho_v)}}, 0.41D_{P,regime}\right)$, $u_r = \dfrac{(1-\alpha)}{\alpha}u_{s,v} - u_{s,l}$, $u_{r,annular} = u_{s,v} - \dfrac{\alpha}{(1-\alpha)}u_{s,l}$
$\zeta_{b-s} = \dfrac{\alpha-\alpha_1}{\alpha_2-\alpha_1}$, $W_{b-s} = \zeta_{b-s}^{\ 2}(3-2\zeta_{b-s})$, $\zeta_{s-c} = \dfrac{\alpha-\alpha_3}{\alpha_4-\alpha_3}$, $W_{s-c} = \zeta_{s-c}^{\ 2}(3-2\zeta_{s-c})$
$\zeta_{c-c/a} = \dfrac{\alpha-\alpha_5}{1-\alpha_5}$, $W_{c-c/a} = \zeta_{c-c/a}^{\ 2}(3-2\zeta_{c-c/a})$, $K = \dfrac{\varepsilon^3 D_p^{\ 2}}{150(1-\varepsilon)^2}$, $\eta = \dfrac{\varepsilon^3 D_p}{1.75(1-\varepsilon)}$</td></tr>
</table>

2.2 Validation of the COOLOCE experiments
2.2.1. Description of the COOLOCE experiments

The COOLOCE experiments were conducted in VTT[5], Finland to evaluate the effectiveness of debris bed geometry and multi-dimensional effects on its coolability. The experiments were conducted with various debris bed formation configurations with the shapes of cone, cylinder and truncated cone. The dimension of each shape is listed in Table II.

Table II. Dimension of porous bed in the COOLOCE experiments[5]

Shape	Cone	Cylinder	Truncated Cone
Diameter (mm)	500	310	500
Height (mm)	270	270	160
Volume (dm^3)	17.6	20.4	15.1

The test bed in the COOLOCE experiments are consisted of spherical zirconia/silica beads whose sizes are 0.97 mm and the metal mesh is used to form the shape of porous bed. The porosity of the test beds are about 0.4 and ϕ 6.3mm cartridge heaters are used to simulate decay power with careful configuration for uniform power distribution in the bed.

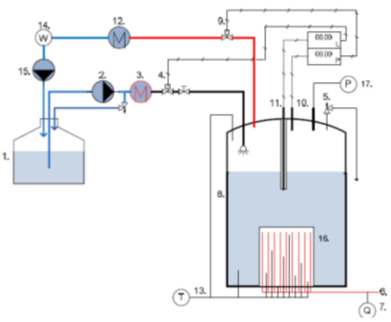


Figure 2. Schematic of the COOLOCE experimental facility[6]

2.2.2. CFD calculation for the COOLOCE experiments

The Fluent calculation was conducted with 10 mm of unit cell size on the axisymmetric coordinates. The time step in the calculation was 100ms. The detailed numerical scheme and methodology, boundary condition setting of the Fluent calculation is the same as the previous work[7].

Table III. Conditions for each shape of porous bed.

Quantity (unit)	Cone	Cylinder	Truncated Cone
Pressure (bar)	0.11	0.13	0.125
Particle diameter (mm)	0.97		
Porosity (-)	0.38	0.392	0.38

The calculated dryout power density matches with experimental data in the cases of cylinder and truncated cone shapes. On the other hand, the result underestimates dryout power density in the cone shaped bed.

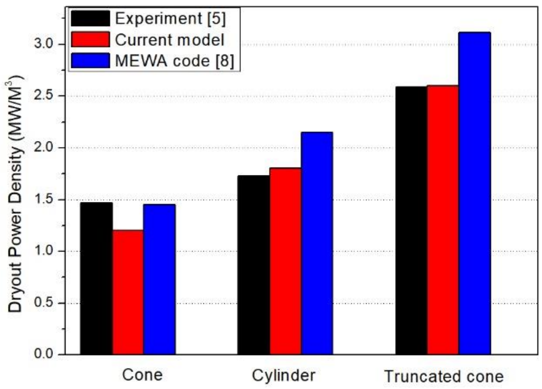
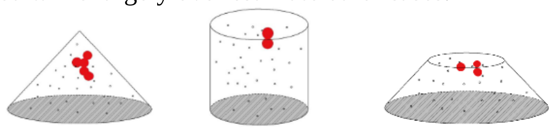


Figure 3. Comparison dryout power density between experiments and CFD results.

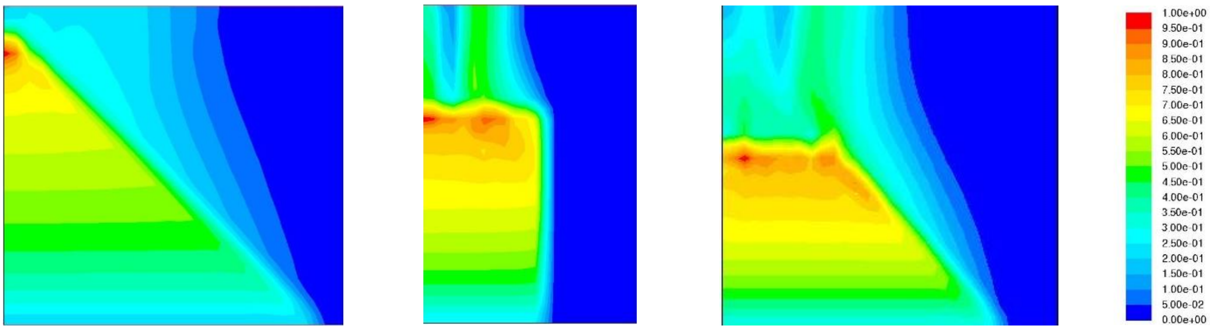
The MEWA code results[8], another CFD analysis model developed in IKE, Germany with the Rahman's friction model shows good agreement to the cone shaped bed while largely over estimate other cases.



(a) Cone (b) Cylinder (c) Truncated cone

Figure 4. Measured dryout location in the COOLOCE experiment[5].

The reason of different trend in the cone shape case can be found from the comparison of dryout positions between experiments and simulation results as shown in the Figure 4 and 5. The measured dryout position in the experiment is slightly lower than the simulation result due to the lack of temperature measurement at the top region of the cone. Therefore, it would be likely that the detection of dryout in the experiment was slightly higher power than the actual dryout power density while a dryout zone develops downward to the thermocouple position. However, unfortunately, the development of dryout zone was unable to be calculated by the current method due to the lack of energy models.



(a) Cone (b) Cylinder (c) Truncated cone

Figure 5. Void fraction profile at the onset of dryout

3. Conclusions

The multi-dimensional CFD simulation of dryout in porous beds has been conducted to test applicability of proposed two phase friction drag models in porous media in our previous work[3].

In overall, the proposed model shows reasonable agreement to the COOLOCE experimental results. The cone shape porous bed case showed more deviation from the experimental data compared with other shapes. The comparison of dryout location with the experimental result indicated that it would be caused by the limitation of measurement point in the experiment. Therefore, for the accurate comparison for the cone shape, the calculation of post dryout condition to capture development of dry zone will be attempted in the future by addition of energy models.

Acknowledgements

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REFERENCES

[1] R. J. Lipinski, "Model for boiling and dryout in particle beds.[LMFBR]," Sandia National Labs., Albuquerque, NM (USA)1982.

[2] A. W. Reed, "The effect of channeling on the dryout of heated particulate beds immersed in a liquid pool," Massachusetts Institute of Technology, 1982.

[3] Mooneon Lee, Jin Ho Park, Hyun Sun Park, Kiyofumi Moriyama, and Moo Hwan Kim, "Comparison of Dryout Heat Flux Models in One Dimensional Porous Bed Configuration," to be presented at the NURETH-17, Xian, China, 2017.

[4] A. Fluent, "Fluent User's Guide," Avaliable at: http://148.204.81.206/Ansys/readme.html, 2015.

[5] E. Takasuo, "An experimental study of the coolability of debris beds with geometry variations," Annals of Nuclear Energy, vol. 92, pp. 251-261, 2016.

[6] E. Takasuo, T. Kinnunen, S. Holmstroem, and T. Lehtikuusi, "COOLOCE debris bed experiments and simulations investigating the coolability of cylindrical beds with different materials and flow modes," Nordisk Kernesikkerhedsforskning, Roskilde (Denmark)2013.

[7] M. Lee, J. H. Park, and H. S. Park, "Validation of CFD Modeling for Multi-dimensional Effects in Ex-vessel Debris Bed Coolability," in Korean Nucelar Society Autumm Meeting, ed. Gyeongju, Korea, 2015.

[8] V. T. Eveliina Takasuo, Ville Hovi, "A study on the coolability of debris bed geometry variations using 2D and 3D models.," Denmark, Report. June 2014.