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Modeling and Validation of Pressure Vessel Hole Ablation During Severe Accidents

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1. Introduction

In light water reactor core-melt accident in a nuclear power plant, the pressure vessel may fail by molten corium at the lower head. The released corium flow may cause fuel-coolant-interaction(FCI), or molten-corium-concrete-interaction(MCCI). The most crucial initial condition for interpreting these phenomena is the nozzle diameter at which the corium jet is emitted.

Several prediction models have been developed to estimate reactor vessel hole diameter due to ablation by molten corium flow. Pilch[1] developed hole ablation model with simple heat balance equations, and validated the model against the available database. Recently, Pilch's model is applied to MELCOR code[2]. Dinh and Sehgal[3] proposed a model considering the existence of an crust layer made by freezing of corium flow on the ablating molten wall interface. The existence of the crust layer evaluates the final ablating diameter to about half that of Pilch's model[4].

However, the criterion for the existence of the crust layer is not clear and depends on the user input expressed as an critical molten wall thickness (These will be explain on *2.3 Critical molten wall thickness*). In this study, the hole ablation model and a method that can determine the existence of a crust layer according to each condition will be suggested. Then, the experimental data will be verified and the ablation diameter calculation in reactor conditions will be shown.

2. Hole Ablation Prediction Model

2.1 Governing Equations

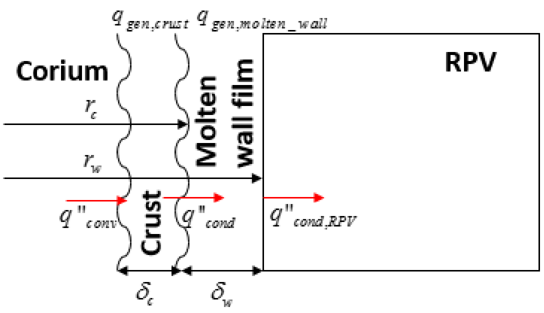

Fig.1. Ablation with floating crust

The heat balance in the corium flow channel was considered to obtain corium temperature along the axial direction. The calculation was performed with a 1-dimension transient, and the first upwind scheme was applied. After getting corium temperature, the crust layer and molten wall film were regarded.

When the crust exists, the heat balance equations for the crust layer and the molten wall are as follows in cylindrical geometry.

For crust layer:

$$q''_{conv}\,dt(2\pi r_c) - q''_{cond}\,dt(2\pi r_c) + q_{gen,crust}(2\pi r_c d\delta_c) = 0 \quad (1)$$

$$\rightarrow h\left(T_{cor} - T_{mp,c}\right)dt - \frac{k_c k_w\left(T_{mp,c} - T_{mp,w}\right)}{\left(k_c\delta_w + k_w\delta_c\right)}dt + \left(\rho h_{fs}\right)_c d\delta_c = 0 \quad (2)$$

$$\rightarrow \frac{d\delta_c}{dt} = \frac{-1}{\left(\rho h_{fs}\right)_c}\left(h\left(T_{cor} - T_{mp,c}\right) - \frac{k_c k_w\left(T_{mp,c} - T_{mp,w}\right)}{\left(k_c\delta_w + k_w\delta_c\right)}\right) \quad (3)$$

For molten wall film:

$$q''_{cond}\,dt(2\pi r_w) - q''_{cond,RPV}\,dt(2\pi r_w) + q_{gen,molten\_wall}(2\pi r_w d\delta_w) = 0 \quad (4)$$

$$\rightarrow \frac{k_c k_w\left(T_{mp,c} - T_{mp,w}\right)}{\left(k_c\delta_w + k_w\delta_c\right)}dt - \frac{k_{w,s}\left(T_{mp,w} - T_w\right)}{\sqrt{\pi\alpha t}}dt - \left(\rho h_{fs}\right)_w d\delta_w = 0 \quad (5)$$

$$\rightarrow \frac{d\delta_w}{dt} = \frac{1}{\left(\rho h_{fs}\right)_w}\left(\frac{k_c k_w\left(T_{mp,c} - T_{mp,w}\right)}{\left(k_c\delta_w + k_w\delta_c\right)} - \frac{k_{w,s}\left(T_{mp,w} - T_w\right)}{\sqrt{\pi\alpha t}}\right) \quad (6)$$

If there is not crust layer, the heat balance equation associated with molten wall changes as follows:

$$q''_{conv}\,dt(2\pi r_w) - q''_{cond,RPV}\,dt(2\pi r_w) + q_{gen,molten\_wall}(2\pi r_w d\delta_w) = 0 \quad (7)$$

$$\rightarrow h\left(T_{cor} - T_{mp,w}\right)dt - \frac{k_{w,s}\left(T_{mp,w} - T_w\right)}{\sqrt{\pi\alpha t}}dt - \left(\rho h_{fs}\right)_w d\delta_w = 0 \quad (8)$$

$$\rightarrow \frac{d\delta_w}{dt} = \frac{1}{\left(\rho h_{fs}\right)_w}\left(h\left(T_{cor} - T_{mp,w}\right) - \frac{k_{w,s}\left(T_{mp,w} - T_w\right)}{\sqrt{\pi\alpha_w t}}\right) \quad (9)$$

Finally the vessel hole diameter becomes:

$$\frac{dD}{dt} = 2\frac{d\delta_w}{dt} \quad (10)$$

In these model, the temperature profile was assumed to be linear, and conduction heat transfer to the RPV wall was treated as semi-infinite conduction case. And advection effect of the crust and molten wall was neglected. Eq(3), (6) or (9) were computed semi-implicitly with each other.

2.2 Constitutive Relations

To obtain solutions through the above equations, some constitutive relations are needed. These are the corium flow heat transfer coefficient h, and corium flow discharge coefficient C_d. As for the discharge coefficient, Pilch[1] suggested a value of 0.6, and Sehgal[3] suggested a value of 0.9-1.1 those were obtained by their experiments. In this paper, since Sehgal's experimental data were verified, C_d was selected as 1.0.

Because L/D is less than 8 for all experiment and reactor conditions, the skin friction coefficient was chosen as an external turbulent flow case. Then the skin friction coefficient was applied to the Reynold analogy as shown in the following equations.

$$c_f = 0.0287\,\mathrm{Re}_L^{-0.2} \tag{11}$$

$$h = \frac{k_{cor}}{L}\left(\frac{c_f}{2}\mathrm{Re}_L\,\mathrm{Pr}_{cor}\right) \tag{12}$$

Sehgal[4] experimentally obtained the skin friction coefficient and used it as 0.005 value, also applied the Reynold analogy. Since the heat transfer coefficient in vessel ablation phenomenon is not general, the detailed CFD analysis is required.

2.3 Critical molten wall thickness

In some experiments in Sehgal[4], crust layer was present on the melt surface. In this situation, the ablation diameter was predicted to be about half that of the absence of crust layer. Therefore, it is important to determine whether a crust layer exists or not.

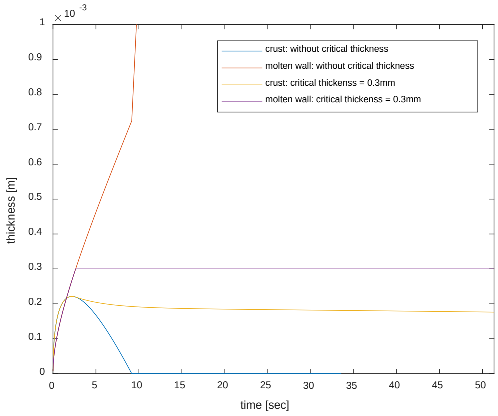

Fig. 2. Time histories of crust thickness and molten wall thickness with and without critical molten wall thickness concept – water-ice salt case

Fig. 2 shows the results of calculating the governing equations and relations of the previous sections. These are consistent with the solutions of Epstein[5] who performed more detailed calculations. As shown in the figure 2, the crust layer disappears after a few seconds. To overcome this, Sehgal proposed a critical molten wall thickness concept, and applied to the above Equations (3), (6). The concept is to use the critical molten wall thickness, $\delta_{w,critical}$, instead of δ_w on the right hand side of Eq (3), (6) or (9), if δ_w exceeds the critical molten wall thickness, $\delta_{w,critical}$. Then the crust layer can exist over time as shown in Fig. 2.

This idea can be explained by the dynamics of corium melt flow with molten wall film. Sehgal[3] applied the critical molten wall thickness value of 1mm for all cases, however there was no theoretical reason for that.

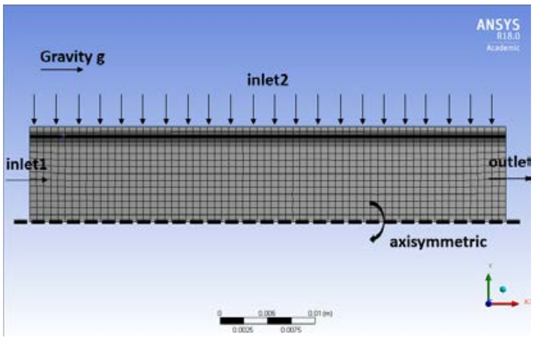

Fig. 3. Flow domain and meshing for obtaining critical molten wall thickness

In this study, the $\delta_{w,critical}$ value was determined by CFD calculation for two streams with different fluid case as shown in Fig. 3. Inlet1 represents corium melt flow, and Inlet2 represents molten wall film. ANSYS FLUENT 18.0 was used as solver. VOF model for multiphase and SST model for turbulence were applied as physical model. The application of these models on ANSYS FLUENT is well validated in two different stream cases[6].

Fig. 2 shows that $\delta_{w,critical}$ is a factor which determines whether crust is formed or not. However, the exact $\delta_{w,critical}$ is not required. Because once the crust is formed, the calculation results do not change. The reason is that after the crust is generated, only convective heat affects wall melting. More specifically, $\frac{d\delta_c}{dt}$ becomes 0 after crust has been generated as represented in Fig. 2, then convective heat becomes the same with conduction heat which transferred to the wall as can be seen through Eq (3).

Combining all the governing equations and models described above, logical flow chart for calculating vessel hole ablation is shown in Fig. 4.

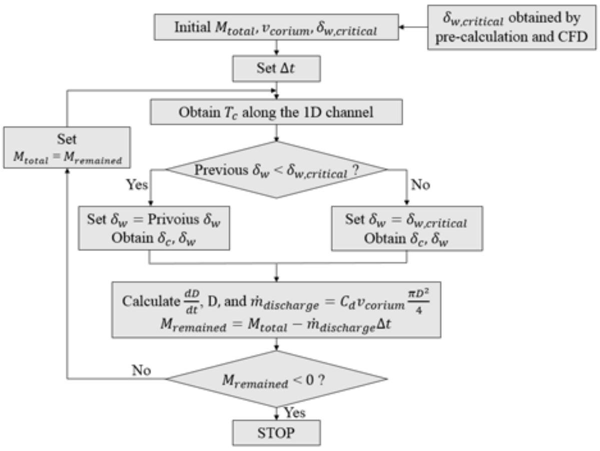

Fig. 4. Logical scheme of vessel ablation calculation model

3. Data Validation

Table I shows the experimental data in order to verify the model developed in this study. Case 1~9 are the experiments in which water was applied as a corium melt, and salt-ice was applied as a vessel wall. Case 10 used 20-80 w/o (Na,K)NO3 molten flow and cerrobend plate, case 11 used 20-80 w/o (Na,K)NO3 with Tin plate, and case 12 used 50-50 w/o (Na,K)NO3 with Tin plate.

As can be seen in Table II, the model predicts well the final hole size and crust existence. But there are some limitations to this results. First the melt discharge velocity was predicted to satisfy the experimental condition and discharge time adequately because there was no discharge information for case 1-9. However, since the melt discharge velocity has little effect on the final hole size in a similar range. Second, there was no results of crust formation in case 10-12, the comparison was not possible about crust formation. But the model well predicted the final hole size, and it determined that the crust exist for those cases.

Table I: Experimental Data[4][7]

	$D_{initial}$ (mm)	L (mm)	T_{cor} (℃)	T_w (℃)	V_{melt} (liters)	Discharge Time (s)	D_{final} (mm)	Crust
1	20	50	23	-30	78	16	72	-
2	20	50	41	-28	78	12	68.5	-
3	10	60	48	-20	78	14	90.5	-
4	10	60	46	-33	78	15	88	-
5	10	60	80	-40	76	12	93	-
6	20	60	3	-30	76	77	26.5	○
7	10	38	11	-41	78	27	62	-
8	10	80	44	-24	78	14	97	-
9	20	79	91	-31	78	10	104	-
10	10	50	450	25	25	11	66.5	no info
11	10	50	420	25	25	12	55	
12	10	50	440	50	23	12	64	

Table II: Data Validation

	Experiments			Model in this study			Relative Error (%)
	Discharge Time (s)	D_{final} (mm)	Crust	Discharge Time (s)	D_{final} (mm)	Crust	
1	16	72	-	15.95	72.3	-	0.42
2	12	68.5	-	12.09	83.6	-	22.04
3	14	90.5	-	13.36	86.1	-	-4.86
4	15	88	-	15.00	85.5	-	-2.84
5	12	93	-	11.67	99.7	-	7.20
6	77	26.5	○	70.16	34.3	○	29.43
7	27	62	-	26.02	62.5	-	0.81
8	14	97	-	14.67	82.4	-	-15.05
9	10	104	-	8.90	102.1	-	-1.83
10	11	66.5	no info	10.5	71.9	○	8.12
11	12	55		12.15	57.6	○	4.72
12	12	64		10.66	59.0	○	-7.81

4. Applications

In this section, the vessel ablation model was also applied to the actual reactor condition. Also results of Pilch's model used in the MELCOR code[2] was compared. The pressure difference between the vessel and cavity was fixed at 1MPa, and the vessel steel wall temperature was set to 800K. The initial temperature and mass of the molten corium, and initial diameter of the vessel were controlled to compare the models.

From the tables below, it can be seen that the predicted final diameter from the model developed in this study was lower than Pilch's value. Because the crust was not considered in the Pilch's model, and crust was formed in this model.

Table III: Model Comparison - Initial Diameter

T_{cor} = 3000K $M_{initial}$ = 200 ton	Pilch's model D_{final}, and t_d	Model in this study D_{final}, and t_d
$D_{initial}$ = 3cm	62.71cm, 80.68sec	46.18cm, 109.97sec
$D_{initial}$ = 7.62cm	62.74cm, 74.48sec	46.06cm, 97.73sec
$D_{initial}$ = 15cm	62.99cm, 64.85sec	46.12cm, 49.60sec

Table VI: Model Comparison - Initial Corium Temperature

$M_{initial}$ = 200 ton $D_{initial}$ = 7.62cm	Pilch's model D_{final}, and t_d	Model in this study D_{final}, and t_d
T_{cor} = 3100K	63.49cm, 72.87sec	53.01cm, 77.65sec
T_{cor} = 3000K	62.74cm, 74.48sec	46.06cm, 97.73sec
T_{cor} = 2800K	60.88cm, 78.79sec	24.94cm, 310.33sec

Table V: Model Comparison - Initial Corium Temperature

$D_{initial}$ = 7.62cm T_{cor} = 3000K	Pilch's model D_{final}, and t_d	Model in this study D_{final}, and t_d
$M_{initial}$ = 200 ton	62.74cm, 74.48sec	46.06cm, 97.73sec
$M_{initial}$ = 100 ton	49.83cm, 57.03sec	36.36cm, 74.80sec
$M_{initial}$ = 20 ton	29.27cm, 29.26sec	20.99cm, 37.48sec

The parameter that makes the most difference between the models were the initial corium temperature as shown in Table VI. The reason is that the Pilch's model used the temperature difference term which driven the convective heat transfer as the difference between melt flow and molten wall film. These results indicates that crust formation plays an important role in evaluating the vessel hole diameter.

5. Conclusion

The evaluation of vessel ablation hole diameter is important for analyzing the reactor severe accident, such as FCI or MCCI. In this paper the vessel ablation model was developed with simple heat balance equations and some relations. Also unlike the existing models, a method have been developed to determine crust formation with the concept of critical molten wall thickness. The vessel ablation model was well validated with a mean error of 8.76%. Finally a comparisons of calculation results with the Pilch's model used in MELCOR was presented, and pointed out important differences.

6. Future Works

- Find the Heat transfer coefficient for vessel wall ablation situation. The existing heat transfer coefficient correlation could be limited to the application of vessel wall ablation process. Therefore, CFD approach will be conducted about these issue.
- Critical molten wall thickness determines the formation of crust layer. However, once it is determined that the crust is formed or not, the heat transfer calculations are not affected by the critical molten wall thickness, as described in section *2.3*. A quantitative interpretation of this will be added at the time of the presentation.

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