Transactions of the Korean Nuclear Society Spring Meeting
Gwangju, Korea, May 30-31, 2013

Experimental Methodology for Structural Material Ablation by Corium Jet Impingement

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1. Introduction

When a molten corium jet is discharged due to the reactor vessel failure during a severe accident, the external structures are eroded by a high thermal load with a chemical reaction, and consequently the containment integrity can be seriously threatened. The ablation of structural material by corium jet impingement is influenced by several factors such as the corium jet composition, degree of superheat, pouring time, impinging velocity, and thermophysical properties of the structural materials. Saito et al. [1] and Albrecht et al. (KAJET experiments) [2] performed a series of ablation tests for several structural materials and proposed the semi-empirical models based on the convective heat transfer analysis. They have demonstrated that the ablation rate is limited considerably by crust formation generated above the material surface and the ablation depth by metallic melt is larger than by the oxydic one. However, the ablation rate of material containing moisture like concrete can be lower than the model predictions because the thermal radiation heat transfer may be the dominant mechanism across the layer due to the suddenly generated steam layer above the surface [3]. KAERI set up an experimental facility and technique using a cold crucible melting method to investigate the ablation rate of the structural material containing moisture (i.e., special concrete) and verify the existing ablation models. In this paper, the effects of various parameters in jet impingement were investigated for the ablation tests.

2. Methods and Results

2.1 Ablation Rate Models

As mentioned previously, the ablation rate of a structural material can be bounded by thermal radiation and convective heat transfer assumptions between the impinging jet and structural material. Assuming the existence of steam layer on the material surface, the minimum ablation rate can be expressed as [3]

$$v_{\min} = \frac{\varepsilon\sigma\left(T_{\mathrm{j}}^4 - T_{\mathrm{mp,SM}}^4\right)}{\rho_{\mathrm{SM}}\left[h_{\mathrm{fs,SM}} + c_{\mathrm{SM}}\left(T_{\mathrm{mp,SM}} - T_{\mathrm{o}}\right)\right]} \qquad (1)$$

where σ is Stefan-Boltzmann constant (=5.67×10^{-8} W/m^{2}K^4); ε, emissivity; ρ_{SM}, density; $h_{\mathrm{fs,SM}}$, heat of fusion; c_{SM}, specific heat; $T_{\mathrm{mp,SM}}$, melting temperature; T_{o}, initial temperature of the structural material; and T_{j}, jet temperature.

On the other hand, the maximum ablation rate can be expressed by considering the convective heat transfer from the jet to the material as follows:

$$v_{\max} = \frac{h_{\mathrm{j}}\left(T_{\mathrm{j}} - T_{\mathrm{mp,j}}\right)}{\rho_{\mathrm{SM}}\left[h_{\mathrm{fs,SM}} + c_{\mathrm{SM}}\left(T_{\mathrm{mp,SM}} - T_{\mathrm{o}}\right)\right]} \qquad (2)$$

where h_{j} and $T_{\mathrm{mp,j}}$ are heat transfer coefficient and jet melting temperature, respectively. Saito et al. [1] suggested Stanton number for the corium jet using the Reynolds analogy as follows:

$$\mathrm{St} = \frac{h_{\mathrm{j}}}{\rho_{\mathrm{j}} c_{\mathrm{j}} u_{\mathrm{j}}} = 0.0033 \qquad (3)$$

where ρ_{j}, c_{j}, and u_{j} are the jet density, specific heat, and velocity on the material surface.

2.2 Parametric Study

Figure 1 shows a test facility and parameters to be determined for the ablation tests. The jet Reynolds number Re_{j} is defined as

$$\mathrm{Re}_{\mathrm{j}} = \frac{\rho_{\mathrm{j}} u_{\mathrm{j}} d_{\mathrm{j}}}{\mu_{\mathrm{j}}} \qquad (4)$$

where d_{j} and μ_{j} are the jet diameter on the material surface and viscosity, respectively. Re_{j} is known to have an order of 10^5 for the corium jet [1]. The jet velocity at the nozzle exit u_{N} can be determined by

$$u_{\mathrm{N}} = C_{\mathrm{D}}\sqrt{\frac{2\left(\rho_{\mathrm{j}} g H_{\mathrm{m}} + \Delta P\right)}{\rho_{\mathrm{j}}}} \qquad (5)$$

where C_{D} is the orifice coefficient; g, gravitational acceleration; H_{m}, melt height in a melt catcher; and ΔP, pressure difference at the nozzle exit. Assuming that a coherent jet core is maintained, the jet velocity u_{j} on the surface is determined by

$$\frac{1}{2}\rho_{\mathrm{j}} u_{\mathrm{N}}^2 + \rho_{\mathrm{j}} g H = \frac{1}{2}\rho_{\mathrm{j}} u_{\mathrm{j}}^2 \qquad (6)$$

where H is a melt falling height. The jet diameter d_{j} and

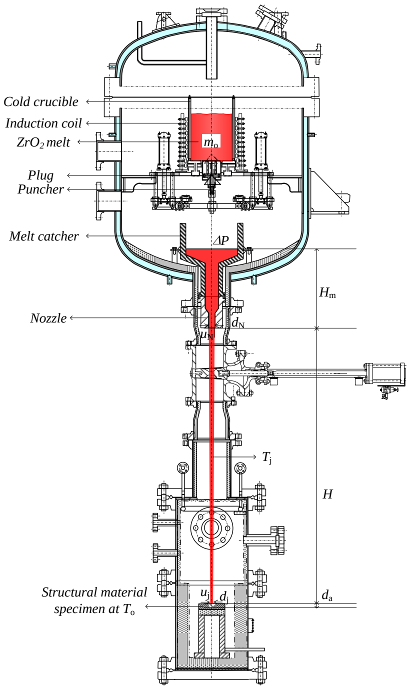

Fig. 1 Test facility

nozzle diameter d_N can be calculated by Eq. (4) with the following equation.

$$d_N^2 u_N = d_j^2 u_j \tag{7}$$

The jet mass flow rate $\dot{m}$ and pouring time t_{pour} are determined by

$$\dot{m} = \rho_j u_N \left(\pi d_N^2 / 4 \right) \tag{8}$$

$$t_{pour} = m_o / \dot{m} \tag{9}$$

where m_o is the melt mass. Finally, the ablation depth d_a is given as

$$d_a = v \times t_{pour} \tag{10}$$

The jet superheat (T_j-$T_{mp,j}$), m_o, H and ΔP were selected as the controllable parameters, and m_o and ΔT_j were found to be effective parameters for changing the ablation rate and depth, as shown in Figs. 2 and 3. The jet Reynolds number has an order 10^5 for ZrO_2 melt, which implies that the corium jet impingement phenomenon can be simulated appropriately by the present test facility with ZrO_2 melt. Moreover, the ZrO_2 jet breakup length L was predicted to be between 3.1 and 7.6 m by the following correlation [4]:

$$L / d_j = 8.51 \left(\mathrm{We}_j^{0.5} \right)^{0.64} \tag{11}$$

where jet Weber number We_j is defined as $\rho_j u_j^2 d_j / \gamma_j$ (γ_j is jet surface tension). That is, the jet breakup length is larger than the melt falling height H (~ 2.3 m), which shows that the coherent jet is a reasonable assumption.

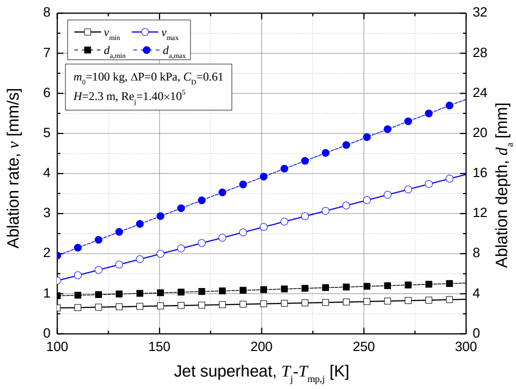

Fig. 2 Jet superheat effect

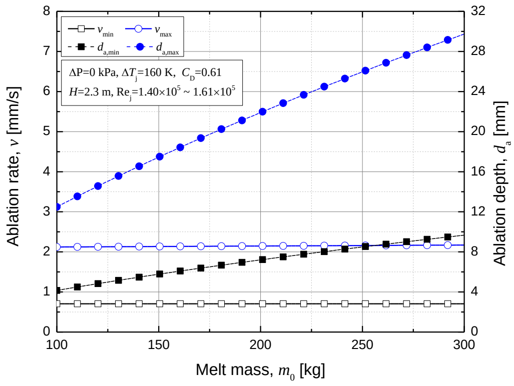

Fig. 3 Melt mass effect

3. Conclusions

The effect of jet impinging experimental parameters on the ablation of the structural material has been investigated. It was found that the corium jet impingement phenomenon can be reasonably simulated by the present experimental conditions. The verification of the ablation models using the experimental results is left as a future work.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST) (No. 2012M2A8A4025885).

REFERENCES

[1] M. Saito, K. Saito, A. Furutani, M. Isozaki, S. Imahori, Y. Hattori, Melting Attack of Solid Plates by a High Temperature Liquid Jet-Effect of Crust Formation, Nuclear Engineering and Design, Vol. 121, pp. 11-23, 1990.

[2] G. Albrecht, F. Huber, E. Jenes, A. Kaiser, W. Schütz, KAJET Experiments on Pressure-Driven Melt Jets and Their Interaction with Concrete, FZKA7002, Forschungszentrum Karlsruhe in der Helmholtz-Gemeinschaft, 2005.

[3] H. K. Fauske, Consulting Report – Independent Review of the Core Catcher Design, Fauske & Associates, LLC, 2011.

[4] R. P. Grant, S. Middleman, Newtonian Jet Stability, AIChE Journal, Vol. 12, No. 4, pp. 669-678, 1966.