An Experimental Investigation of Corium Jet Impingement on Structural Material

Sang Mo An [a*], Kwang Soon Ha [a], Beong Tae Min [a], Seong Ho Hong [a], Hwan Yeol Kim [a]
[a] *Korea Atomic Energy Research Institute, 989-111 Daedeok-daero, Yuseong-gu, Daejeon, Korea*
[*] *Corresponding author: sangmoan@kaeri.re.kr*

1. Introduction

During a severe accident in a nuclear power plant, the erosion of external structures of a reactor vessel by corium jet impingement owing to the failure of the reactor lower head is an important issue because the containment integrity can be seriously threatened. KAERI has proposed an experimental methodology [1] and set up the VESTA (Verification of Ex-vessel corium STAbilization) facility to investigate the interaction of an oxidic jet with an oxidized steel (Fe_2O_3) structure containing a small amount of water and verify the existing ablation models.

2. Methods and Results

2.1 Ablation Models

There were two models introduced to estimate the ablation rate: convective and radiation heat transfer models [1]. The convective heat transfer model assumes that the convection during the jet impingement governs the ablation of the structural material, which gives the upper bound of the ablation rate:

$$v_{\max} = \frac{h_j\left(T_j - T_{mp,j}\right)}{\rho_{SM}\left[h_{fs,SM} + c_{SM}\left(T_{mp,SM} - T_o\right)\right]}, \qquad (1)$$

where h_j is the convective heat transfer coefficient; T_j, the jet temperature; $T_{mp,j}$, the jet melting temperature; ρ_{SM}, the density; $h_{fs,SM}$, the heat of the fusion; c_{SM}, the specific heat; $T_{mp,SM}$, the melting temperature; and T_o, the initial temperature of the structural material. Saito et al. [2] suggested the Stanton number for the corium jet using the Reynolds analogy, as follows:

$$\mathrm{St} = \frac{h_j}{\rho_j c_j u_j} = 0.0033, \qquad (2)$$

where ρ_j, c_j, and u_j are the jet density, specific heat, and velocity on the material surface. On the other hand, the radiation heat transfer model assumes that the radiation heat transfer governs the ablation for the water-contained structure because the steam layer can be generated suddenly on the material surface owing to a very high temperature, which provides the lower bound of the ablation rate:

$$v_{\min} = \frac{\varepsilon\sigma\left(T_j^4 - T_{mp,SM}^4\right)}{\rho_{SM}\left[h_{fs,SM} + c_{SM}\left(T_{mp,SM} - T_o\right)\right]}, \qquad (3)$$

where σ is Stefan-Boltzmann constant ($=5.67\times10^{-8}$ W/m^2K^4) and ε is the emissivity.

2.2 Experimental Facility

Figure 1 shows a test facility and the conditions for the jet impingement experiments. A cold crucible melting technique was employed to generate a ZrO_2 melt. After the melt generation, the plug at the bottom of the crucible is removed and the melt is transferred to a melt catcher through the hole made by the puncher system. The melt jet is then produced by passing through a nozzle underneath the melt catcher, and it falls onto the structural material.

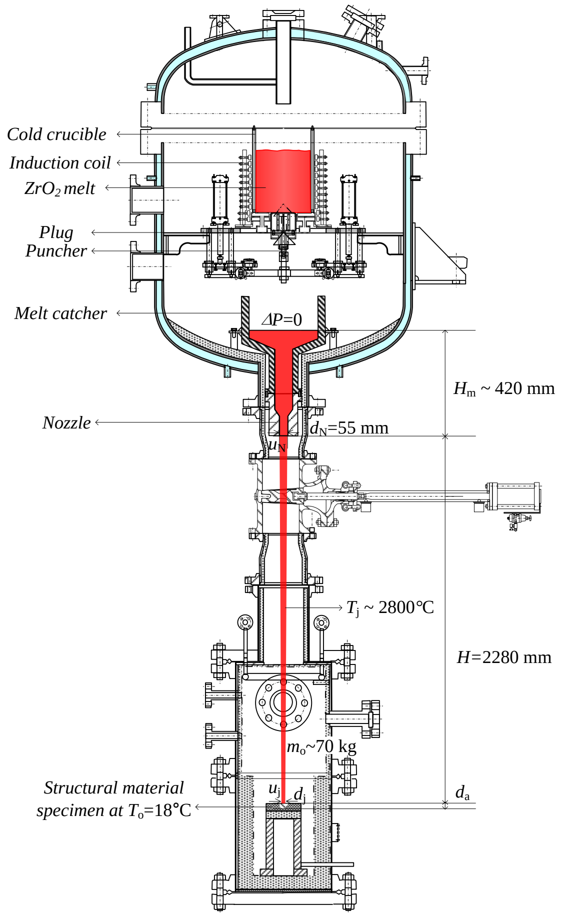

Fig. 1 Test facility

Figure 2 shows the specimen of structural material and locations of K-type thermocouples to measure the temperature of the specimen after the jet impingement. The specimen has a cylindrical shape of 216 mm in diameter and 50 mm in thickness, and it is supported by the MgO layer at the bottom. The thermocouple piles are installed at 5 locations (C, E, W, N and S); each pile consists of 7 thermocouples and has a different depth with a 2 mm interval.

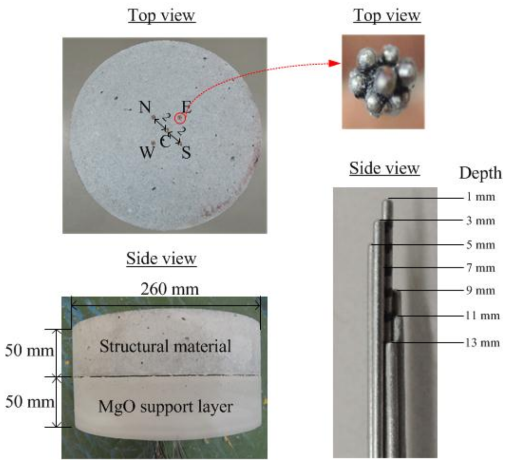

Fig. 2 Specimen of structural material and installation locations of thermocouples

2.3 Results and Discussion

Typical thermocouple readings at the center ('C' in Fig. 2) of the specimen after the jet impingement are shown in Fig. 3. Around 70 kg of melt at 2800℃ was impinged on the specimen. The propagating speed of the interaction front (i.e., ablation rate) was measured as 1.59 m/s, where the ablation rate was determined by a sudden increase in the thermocouple readings. That is, it was assumed the ablation front reaches the thermocouple at the instant time when its temperature increases suddenly at up to 1000℃. Using Eqs. (1) and (3), the lower and upper bounds of the ablation rate were estimated to be 0.63 m/s and 1.47 m/s, respectively, and the measured value was found to be very close to the upper bound. Therefore, it was verified that the ablation was governed by jet convective heat transfer rather than radiation heat transfer.

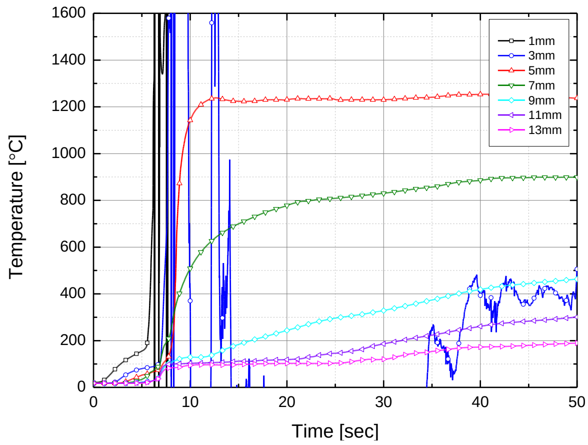

Fig. 3 Thermocouple readings at the center of the specimen

Figure 4 shows the specimen after the experiments. The specimen is covered with a ZrO_2 crust layer with a 10 ~ 17 mm thickness (Fig. 4(a)), and the surface was ablated uniformly over the whole area (Fig. 4(b)). The ablation depths were measured to be between 3.28 mm and 4.33 mm.

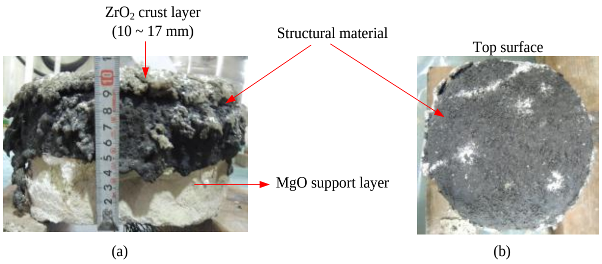

Fig. 4 Specimen of structural material after the jet impingement experiment

The ablation depth d_a can be estimated by the following equations:

$$d_a = v \times t_{pour} , \quad (4)$$

where v is the ablation rate and t_{pour} is the melt pouring time. Equations (1) and (3) are used to calculate the lower and upper bounds of the ablation depth, and the melt pouring time t_{pour} is determined by the melt mass and melt pouring rate $\dot{m}$, as follows:

$$t_{pour} = m_o / \dot{m} \quad (5)$$

The ablation depth was estimated to be between 2.84 mm and 6.39 mm; therefore, the measured values were included within the prediction boundaries.

3. Conclusions

The oxidic jet impingement experiments on the oxidized steel structure containing a small amount of water content in crystalline hydrates were performed, and the ablation depth and rate were compared with the predictions by the existing models. The ablation of the structural material turned out to be governed by the jet convection, and the experimental results were predicted properly by the models. However, the models need to be improved by considering the transient effect of the heat transfer for better predictions, which 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] S. M. An, K. W. Ha, B. T. Min, S. H. Hong, H. Y. Kim, Experimental Methodology for Structural Material Ablation by Corium Jet Impingement, Proceedings of Korean Nuclear Society Spring Meeting, Gwangju, Korea, May 30-31, pp. 679-680, 2013.

[2] 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.