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One Dimensional Approach to External Cooling of Reactor Vessel Lower Head

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Abstract

The Corium Attack Syndrome Immunization Structures (COASIS) are being developed as prospective in-vessel retention devices for an advanced light water reactor (ALWR) in concert with existing ex-vessel management measures. Both the engineered gap inner structure (COASISI) and outer structure (COASISO) are demonstrated to maintain effective heat transfer geometry during molten core debris attack when applied to the TMI-2 and the Korean Standard Nuclear Power Plant (KSNPP) reactors. To quantity the external cooling effect, we wrote a computer program using the one-dimensional transient heat conduction equation. Using the above program we investigated the effects of the mass and initial temperature of the fallen material, and the effect of the heat transfer coefficient value in convection with water or air. To verify the validity of the program, we applied the written program to predict the LAVA preliminary test. Of all the cases considered, the shortest melting time was calculated to be about 70 sec compared with 2~3 sec in the tests. As the impingement demonstrated a decisive impact on the failure of the vessel in the tests, our prediction of the temperature profile based on pure thermal behavior of the vessel tends to overestimate the time to failure. According to the results, the mass effect diminished if the mass exceeds an arbitrary critical quantity and the temperature profile of the vessel depended on the initial temperature of the fallen material.

1. Introduction

O'Brien and Hawkes [1] performed thermal analysis to assess the viability of the external water flooding as a cooling strategy to prevent reactor vessel thermal failure during a severe accident with partial core melting and core relocation to the reactor vessel lower head. They predicted the vessel wall temperature and heat flux using a one-dimensional heat conduction model and considering natural convection in the molten pool. Though their results were reasonable, they used only nucleate boiling heat transfer coefficient when they considered the external cooling.

Henry and Fauske [2] calculated the heat removal capability for external cooling of an insulated reactor pressure vessel. The heat removal capability was evaluated using the water inflow through the insulation, the two-phase heat removal in the gap between the insulation and the vessel and the flow of steam through the insulation. According to their result, methods suggested above had a good capability in removing decay heat generated in the debris.

Park et al.[3] studied the effect of external cooling on the thermal behavior of a boiling water reactor. They concluded as follows: (1) the effect of emissivities of the pool surface, the structure, the vessel wall and the baffle plate is predicted to be small, (2) the effect of variation in the molten corium decay heat on the vessel shell temperature is small, (3) the effect of variation in the thermal conductivity of the vessel shell is small.

2. Model Description

This study was performed to estimate the effect of the external cooling using a computer program based on a one-dimensional transient heat conduction equation.

2.1 Assumptions

Several assumptions were made as follows.

1. The thickness of the carbon steel is 15cm.
2. Consider only thermal aspect in both the vessel and the debris neglecting the effect of the impingement of the debris and the creep of the vessel.
3. For external cooling, the bulk temperature of the external water is 100°C and the film boiling heat transfer coefficient is applied.
4. The volumetric heat generation rate is 1MW/m^3 [1].

2.2 Computational model

The basic control volume is shown in Figure 1. In calculating the conduction including the effect of radiation, the flow of heat was not in the same direction in all the nodes. The energy balance was formulated by assuming that all the heat flow is into the node. If the rate equations are expressed in a manner consistent with this assumption, the correct form of the finite-difference equation is obtained. Energy conservation may be written as follows

$$\dot{E}_{in} + \dot{E}_{g} = \frac{dE_{st}}{dt} \equiv \dot{E}_{st} \tag{1}$$

where $\dot{E}_{in}$ = the rate of incoming energy $\dot{E}_{g}$ = the rate of outgoing energy $\dot{E}_{st}$ = the rate of storing energy.

The nodal finite-difference equations can be expressed as follows. Nodes 1 to 6 represent the vessel and nodes 7 to n represent the debris.

Node 1

$$\rho_{v,1} c_{p_{v,1}} A \frac{\Delta x_{v}}{2} \frac{T_1^{n+1} - T_1^{n}}{\Delta t} = hA\left(T_{bulk} - T_1^{n+1}\right) + k_{v,1} A \frac{T_2^{n+1} - T_1^{n+1}}{\Delta x_{v}} \tag{2}$$

Nodes 2~5

$$\rho_{v,i} c_{p_{v,i}} A\Delta x_{v,i} \frac{T_i^{n+1} - T_i^n}{\Delta t} = k_{v,i} A \frac{T_{i-1}^{n+1} - T_i^{n+1}}{\Delta x_v} + k_{v,i} A \frac{T_{i+1}^{n+1} - T_i^{n+1}}{\Delta x_v} \quad (3)$$

Node 6

$$\begin{aligned} &\rho_{v,6} c_{p_{v,6}} A \frac{\Delta x_v}{2} \frac{T_6^{n+1} - T_6^n}{\Delta t} + \rho_{c,7} c_{p_{c,7}} A \frac{\Delta x_c}{2} \frac{T_6^{n+1} - T_6^n}{\Delta t} \\ &= k_{v,6} A \frac{T_5^{n+1} - T_6^{n+1}}{\Delta x_v} + k_{c,6} A \frac{T_7^{n+1} - T_6^{n+1}}{\Delta x_c} + q''' A \frac{\Delta x_c}{2} \end{aligned} \quad (4)$$

Nodes 7~ n-1

$$\rho_{c,i} c_{p_{c,i}} A\Delta x_{c,i} \frac{T_i^{n+1} - T_i^n}{\Delta t} = k_{c,i} A \frac{T_{i-1}^{n+1} - T_i^{n+1}}{\Delta x_c} + k_{c,i} A \frac{T_{i+1}^{n+1} - T_i^{n+1}}{\Delta x_c} + q''' A\Delta x_c \quad (5)$$

Node n

$$\rho_{c,n} c_{p_{c,n}} A \frac{\Delta x}{2} \frac{T_n^{n+1} - T_n^n}{\Delta t} = k_{c,n} A \frac{T_{n-1}^{n+1} - T_n^{n+1}}{\Delta x_c} + \varepsilon\sigma\left(T_{air}^4 - T_n^{n+1^4}\right) + q''' A \frac{\Delta x_c}{2} \quad (6)$$

In calculation, to set the initial temperature of the vessel, the steady-state conduction equation is solved. In normal operating condition of the pressurized water reactor, the inlet temperature of the water is about 280°C and the outlet temperature is about 320°C. So the temperature of the inner vessel was assumed to be 300°C. The heat transfer between the outer vessel and the air is assumed to be due only to convection to air with the heat transfer coefficient of 15 W/m^{2}K in the absence of water. The temperature profile of the vessel was solved by steady-state heat conduction equation as follows.

$$T = -130.23 \times (0.15 - x) + 300 \quad (7)$$

where the temperature T is in degrees C.

In estimating the external cooling effect, many investigators used the nucleate boiling heat transfer coefficient at the position where the vessel contacted with water. But if the debris falls into the inner vessel, the temperature of the vessel will escalate. Thus the initial boiling mechanism will obviously be film boiling. If the nucleate boiling heat transfer coefficient is used from the first stage, one may overestimate the heat removal capability of water initially. The film boiling correlation used in this study is the El-Genk and Glebov correlation [4]. The film boiling heat transfer coefficient value was varied arbitrary for verify the effect of the heat transfer coefficient value.

The vessel properties used in this calculation were taken from the NUREG/CR-5642 [5]. The debris properties were taken from the OECD RASPLAV Project [6]. In this project, experiments were performed for several material compositions. Among those cases, we used the data in Table 1.

2.3 Pre-test of the program

The program was applied to the LAVA preliminary experiment. LAVA preliminary experiments were performed to investigate the effect of the water in the lower plenum. In these experiments, thermite was used to simulate the molten debris. The 2.5cm carbon steel vessel represented for reactor vessel. The experiments were performed at 1atm.

3. Results and Discussion

3.1 LAVA preliminary test

LAVA preliminary experiments were performed at the Korea Atomic Energy Research Institute (KAERI) to investigate the melt-vessel interaction without water inside or outside the vessel. A total of 20kg thermite was poured to the carbon steel vessel. The diameter of the vessel is 50cm and its thickness is 2.5cm. Experiments were performed at 1atm. Two types of experiments were performed. One was the case where Fe composition was drained first and the other was the case where the uniformly mixed thermite was drained. For the first case, the carbon steel vessel was penetrated as soon as the molten material got into contact in 2~3 sec. For the other case, the penetration time was later than the first case. KAERI concluded that these phenomena were due to jet impingement. We calculated the temperature behavior of the carbon steel as summarized in Table 2. When we applied the program to LAVA preliminary experiments, natural convection effect in the molten thermite was considered. To consider natural convection in the molten pool, the experimental correlation for circular segments suggested by Mayinger et al. [7] was used.

$$Nu_{dn} = 0.54 Ra'^{0.18} \left(\frac{H}{R}\right)^{0.26} \tag{8}$$

In the above correlation, Ra' is the modified Rayleigh number with volumetric heat generation component. But thermite had no heat generation source. So the volumetric heat generation term was changed as

$$\frac{q''' \times \frac{2}{3}\pi r^3}{2\pi r^2} = q'' = h(T_{bulk} - T_w) \tag{9}$$

T_{bulk} = the bulk temperature T_w = the wall temperature

The finite-difference equation for node 6 was accordingly rewritten as

$$\begin{aligned} &\rho_6 c_{p,6} A \frac{\Delta x_v}{2} \frac{T_6^{n+1} - T_6^n}{\Delta t} + \rho_7 c_{p,7} A \frac{\Delta x_c}{2} \frac{T_6^{n+1} - T_6^n}{\Delta t} \\ &= k_6 A \frac{T_5^{n+1} - T_6^{n+1}}{\Delta x_v} + h\left(T_{pool} - T_6^{n+1}\right) \end{aligned} \tag{10}$$

If the temperature of the lowest position of the thermite was below the melting point (i.e., solidified), the convection effect was not considered.

The calculated results are shown in Figures 2 through Figure 9. In the results, T1 was the outer vessel node that contacts with the air and T6 was the inner vessel node that contacts with the molten thermite. As mentioned previously, we did not consider structural mechanics and jet impingement effects in this purely thermal calculation. When we compared the results, the penetration time was later than in the tests. Nonetheless the results showed correct trend for the effect of the initial temperature, natural convection and falling material components. In LAVA preliminary experiments, the case where the Fe having larger density relatively fell first resulted in the shorter penetration time than the other case. The computed results showed the same trend. According to the calculation, the penetration time depended on the initial temperature, material and the natural convection in the molten pool.

3.2 Application to the external cooling

Based on the previous results, we investigated the external cooling effect on the nuclear reactor scale. In this calculation, we focused on the effect of the amount of the fallen material, the external cooling and heat transfer coefficient value.

To find the effect of the amount of the fallen debris, we changed the total amount of the fallen debris from 1ton to 60 ton. The results are shown in Figure 10 for the initial temperature of 2700°C. In the result, T1 indicates the outer vessel node and T51 indicates the inner vessel node. According to the results, if the amount of the debris exceeds 10 tons, the mass effect of the fallen debris diminished. This result indicates that there are critical amounts of heat that can be removed by the external cooling. If the mass of the fallen debris is larger than the critical value, the temperature profile of the vessel demonstrates a similar trend but the amount of the total energy to be removed is different. Thus if the vessel will fail for any reason at the initial stage, there is no effect of the mass of fallen debris.

Figures 11 show the effect of the initial temperature of the fallen debris. The initial temperature affected the peak temperature of the vessel. Namely, if the fallen debris is very superheated and the proper cooling is not established, the penetration time of the vessel will be shortened. Figure 12 shows the consideration of the fusion heat of the vessel. As there is only increase in the enthalpy at the melting point with no change in temperature, the temperature remains constant until the total enthalpy exceeds the fusion heat. Finally according to Figure 13, the temperature of the vessel was steady state for the long run when we applied the film boiling correlation. The applied heat transfer coefficient is about 250W/m^2K and if we use the other correlation, the temperature increases for the long run. But the entire temperature decreased for the long run given h=500W/m^2K. That is, even if the external cooling system is operational, the vessel will melt if the heat transfer coefficient is not large enough. So when we consider the external cooling system, the heat transfer coefficient must be larger than the value deduced from the analytical film boiling correlation.

4. Conclusion

This study showed that one must consider the jet impingement for the period that the material is falling and the thermal ablation of the vessel for the period that the pool of the high temperature material is formed.

From this study, when we focused on the long term cooling, as the temperature of the vessel increases gradually though we applied the film boiling correlation to the convection, we conclude that one must devise a methodology that can provide with higher heat transfer coefficient. One such methodology can be combination of the forced convection effect and the subcooling effect.

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Table 1. The debris composition (Taken from Reference 6)

	Debris composition
Mass %	78 UO_2 – 22 ZrO_2
Molar %	62 UO_2 – 38 ZrO_2
Volume %	65 UO_2 – 35 ZrO_2

Table 2. Computational cases for the temperature profile

Case #	Note
1	Temp. of the thermite = 2500°C, uniformly mixed
2	Temp. of the thermite = 3000°C, uniformly mixed
3	Temp. of the thermite = 2500°C, <Al_2O_3, Fe> stratified
4	Temp. of the thermite = 3000°C, <Al_2O_3, Fe> stratified
5	Temp. of the thermite = 2500°C, uniformly mixed, convection.
6	Temp. of the thermite = 3000°C, uniformly mixed, convection.
7	Temp. of the thermite = 2500°C, <Al_2O_3, Fe> stratified, convection
8	Temp. of the thermite = 3000°C, <Al_2O_3, Fe> stratified, convection

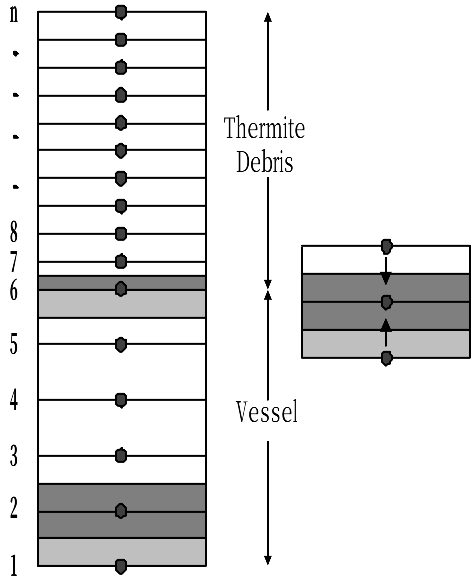

Fig 1. Control volume for the one-dimensional heat conduction equation

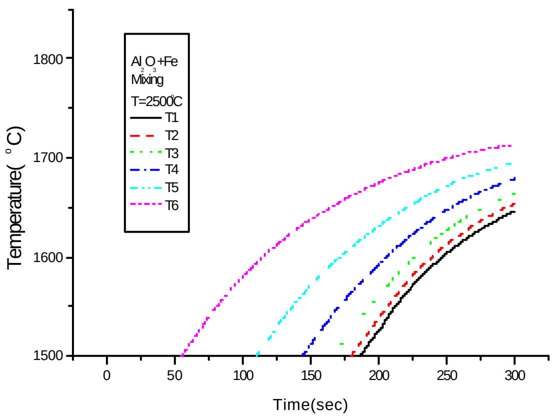

Fig 2 Temperature of the thermite = 2500°C, uniformly mixed

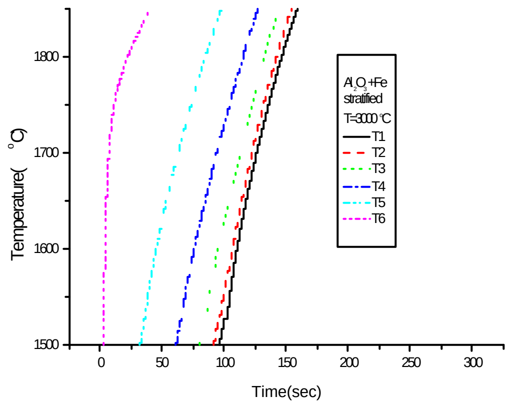

Fig 5 Temperature of the thermite = 3000°C, <Al_2O_3, Fe> stratified

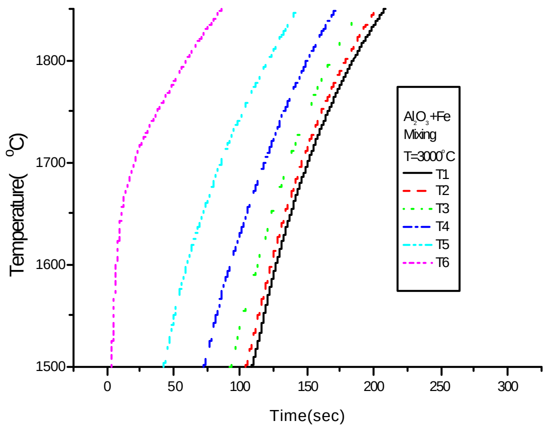

Fig 3 Temperature of the thermite = 3000°C, uniformly mixed

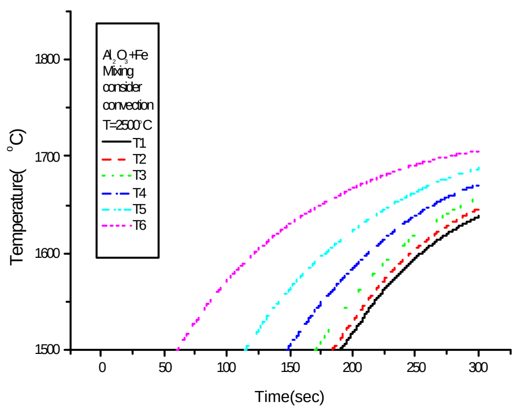

Fig 6 Temperature of the thermite = 2500°C, uniformly mixed, convection.

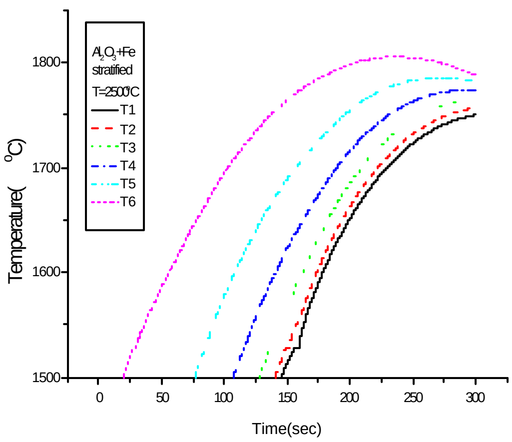

Fig 4 Temperature of the thermite = 2500°C, <Al_2O_3, Fe> stratified

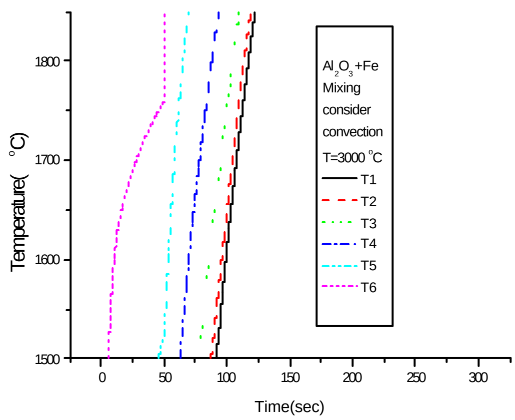

Fig 7 Temperature of the thermite = 3000°C, uniformly mixed, convection

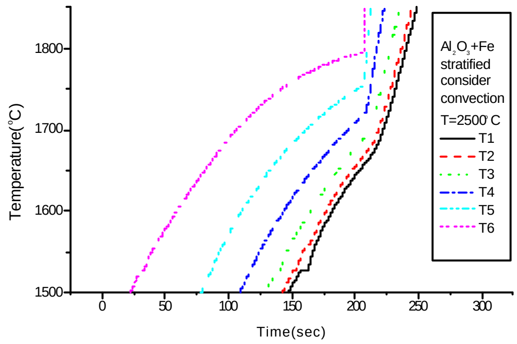

Fig 8 Temperature of the thermite = 2500°C, <Al_2O_3, Fe> stratified, convection

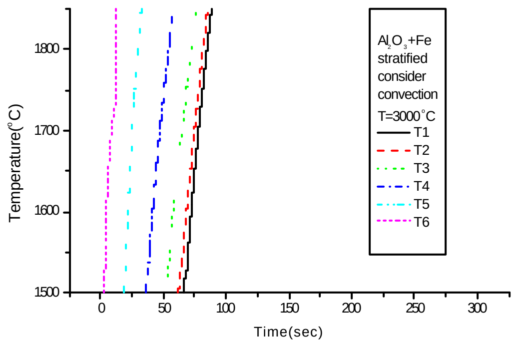

Fig 9 Temperature of the thermite = 3000°C, <Al_2O_3, Fe> stratified, convection

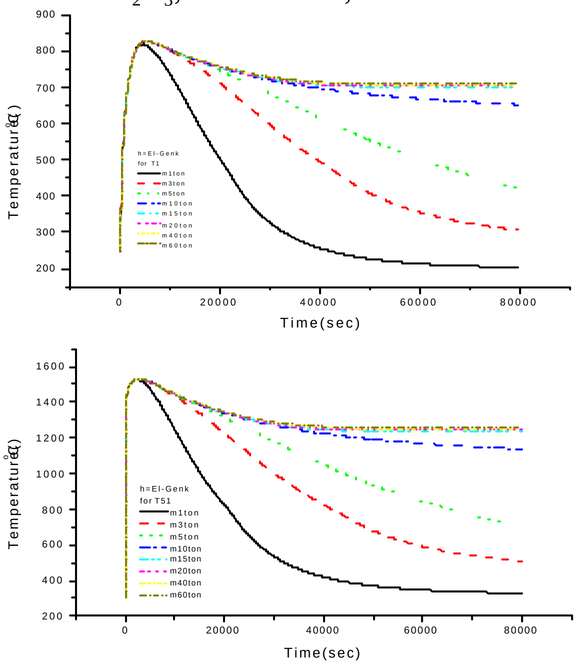

Fig 10 The mass effect of the accumulated material for external cooling using theEl-Genk and Glebov correlation [4]

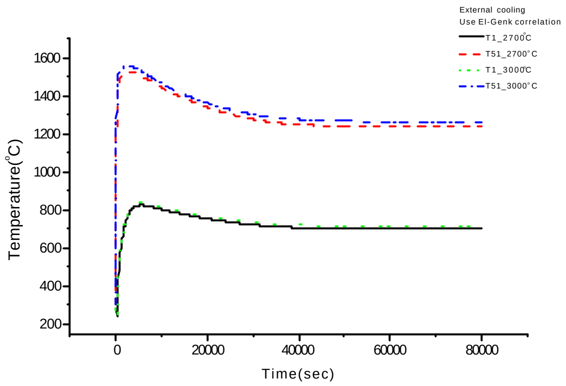

Fig 11 The effect of the initial temperature of the debris for external cooling using the El-Genk and Glebov correlation[4]

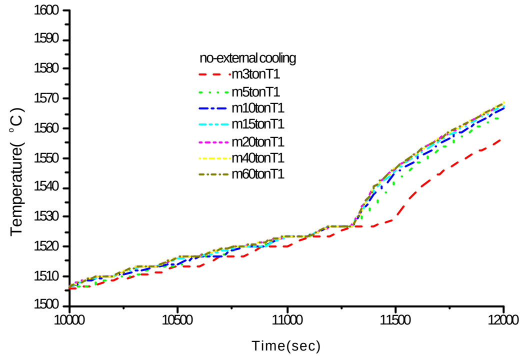

Fig 12 Thermal behavior near the melting point of the vessel

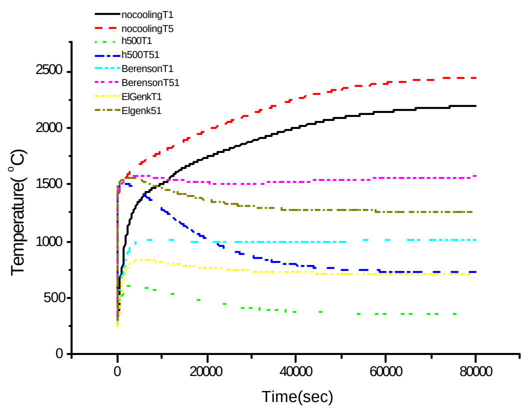

Fig 13 The effect of external cooling