A New Form Loss Coefficient Model in CAP for Long Term Containment Vessel Air Cooling Analysis

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1. Introduction

In the innovative Small Modular Reactor (i-SMR), the chimney effect considered as a long-term cooling strategy. At the external containment vessel(CV) of i-SMR, air absorbs heat from the high-temperature containment vessel walls, and the natural convection is formed due to the chimney effect. When the pressure difference is low, the flow is driven by the chimney effect, and reverse flow occur at the outlet[1]. Jing[2] suggested a new pressure coefficient model considering the reverse flow.

In this study, a new model implanted in CAP was validated. Additionally, a preliminary analysis of the cooling capacity of the i-SMR chimney was conducted. A decay heat curve calculated with the ANS-5.1/N18.6[4] was compared to evaluate how many days after reactor shutdown the cooling chimney alone can effectively remove heat.

2. Effects of Reverse Flow in The Chimney

According to Cooper[1], when the pressure difference (ΔP) at the vent is lower than the critical pressure difference (ΔP_{Rev}), buoyancy forms the flow, which is a bidirectional flow that includes reverse flow. Therefore, the net flow is the value obtained by subtracting the reverse flow from the forward flow, and in such vents, a form loss coefficient that considers the effects of buoyancy should be used.

2.1 Model Description

Jing calculated the K value reflecting the reverse flow as follows. The Fr_{rev} is the critical value at which reverse flow occurs in the vent. When the Fr is lower than Fr_{rev}, reverse flow occurs in the vent. The modified form loss coefficient is calculated as follows[2].

(1) $Fr = \frac{Q}{A\sqrt{2gD_H\epsilon}}$

(2) $K_{out} = 1 + \left[0.61 * \left(0.1 + 0.19 * \frac{Fr}{Fr_{rev}}\right)\right]^{-2}$

Here, ϵ is $\frac{|\rho_2-\rho_1|}{(\rho_2+\rho_1)/2}$ [3].

Since Fr_{rev} is determined experimentally, a method to calculate Fr_{rev} is needed to implant it into the code. For this, Cooper's paper was referenced. Cooper proposed approximations for Q_{rev} and P_{rev}. The approximation is as follows:

(3) $\epsilon_{rev} = \frac{q}{Q_{rev}\rho_2 C_{p,2} T_2}$

(4) $Q_{rev} = e^{0.5536\epsilon_{rev}} 0.1754A\sqrt{2gD_H\epsilon_{rev}}$

(5) $\Delta P_{rev} = e^{1.1072\epsilon_{rev}} 0.2427 \cdot (1 + 0.5\epsilon_{rev}) 4gD_H\rho\epsilon_{rev}$

q is the heat supplied by heater, Q is the flow rate, ρ is the air density, C_p is isobaric specific heat, A is the outlet area, and D_H is the hydraulic diameter. Subscript 1 means to the thermodynamic state of the chimney outlet, and 2 means to the thermodynamic state outside(atmosphere).

With the Q_{rev} and P_{rev} calculated in this way, Fr_{rev} can be determined as follows.

(6) $Fr_{rev} = \frac{Q_{rev}}{A\sqrt{P_{rev}/\rho_2}}$

2.2 Validation of The Model

To validate the model, Chen's experiment was analyzed[3]. Chen's chimney has a height of 1.5 m and a width of 0.615 m. A heater is installed on single side of the chimney wall, as shown in Fig. 1. The gap between the chimney and the opposite wall is between 0.1 m and 0.6 m. The heat flux of the heater ranges from 200 to 600 W/m². The experiment was conducted in two cases: one where the heat flux was fixed at 400 W/m² and the gap was varied, and the other where the gap was fixed at 0.2 m and the heat flux was changed.

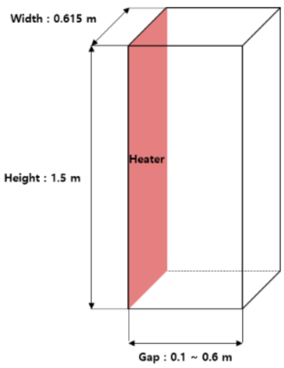

Fig. 1. Illustration of the chimney.

Fig. 2 shows the nodalization used in CAP analysis. A constant heat flux is generated from heat structure, same as the experimental conditions. The flow area of the chimney changes depending on the gap size and is identical to the experimental conditions. The form loss coefficient at the inlet is 1.5.

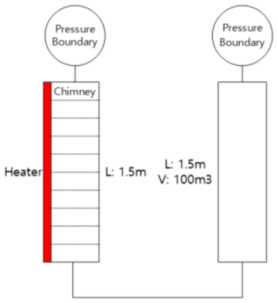

Fig. 2. Nodalizaiton of the chimney.

Fig. 3 and 4 show the analysis results. 'Default' applies the form loss coefficient 1.0, which is commonly used, while 'Modified' shows the results calculated using equation (2). As seen in Fig. 3 and 4, applying equation (2) shows higher accuracy.

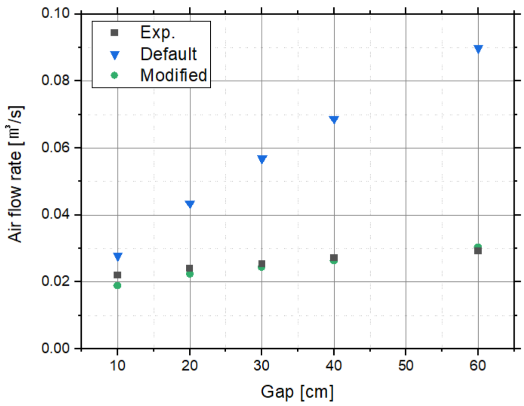

Fig. 3. Comparison of air flow rate with various gap.

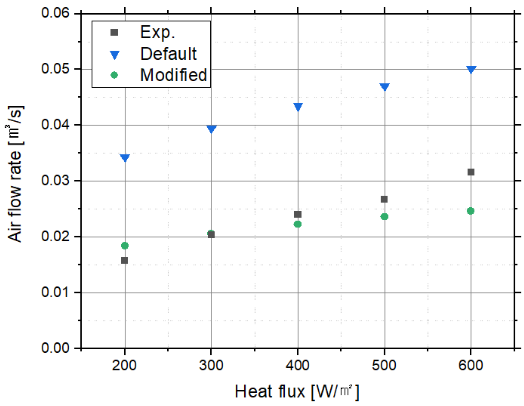

Fig. 3. 4omparison of air flow rate with various heat flux.

3. Cooling Chimney in i-SMR

3.1 Analysis Configuration

The nodalization of the cooling chimney for the i-SMR is shown in Fig. 5. The reactor side removes heat from the CV. The CV temperature starts at 100°C, as shown in Fig. 6, and increases by 50°C every 10,000 seconds to check the steady-state at each temperature. PB is the pressure boundary, with a temperature of 30°C and a pressure of 1 atm. The height of both the CV side and the building side is the same, at 34 m. The flow area of the C910 is 25% smaller than that of the C900. The Modified form loss coefficient is applied at junction between the pressure boundary and C902.

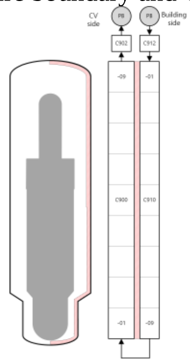

Fig. 5. Nodalization of the i-SMR chimney.

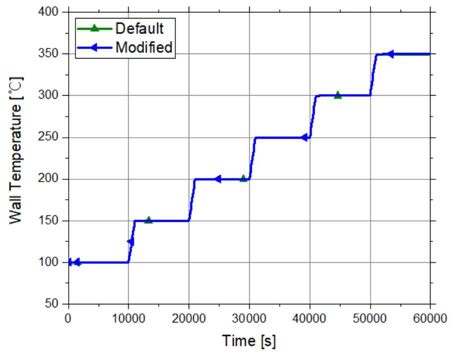

Fig. 6. Variation of wall temperature according to time.

3.2 Analysis Results

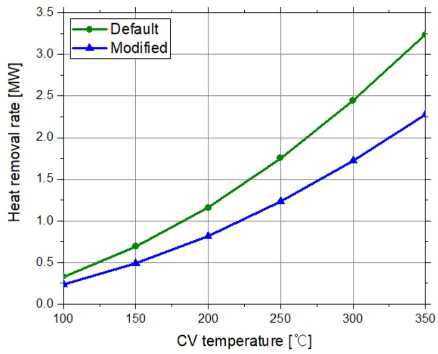

Fig. 7. Comparison of heat removal rate with various CV temperature.

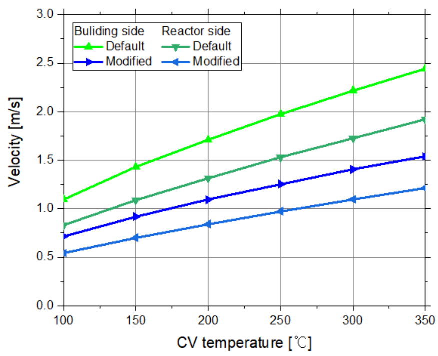

Fig. 8. Comparison of velocity with various CV temperature.

Fig. 7 and 8 show the analysis results. 'Default' refers to the simulation results with a loss coefficient of 0.1 applied to the C902 outlet, while 'Model' refers to the results with a modified loss coefficient applied to the same outlet. It can be seen that applying the model results in a higher form loss coefficient, which reduces the flow rate and heat removal.

3.3 Long-term Cooling Capability

The cooling chimney is a system designed to remove residual heat in long-term accident scenarios where the emergency cooling tank of the i-SMR is depleted. To evaluate the cooling capacity of the cooling chimney, it was compared with the decay heat curve of the i-SMR. The decay heat curve was calculated using ANS-5.1/N18.6[4].

Before comparing, the CV pressure is an important factor in terms of the structural integrity of the CV. Therefore, the heat removal is evaluated considering the CV pressure. In the previous analysis, assuming the CV temperature is the saturation temperature of water, Figure 9 was drawn based on the pressure corresponding to the saturation temperature. In case of the 'Modified' results, when the cooling chimney operates alone, the pressure of i-SMR is expected to remain within 3 MPa after approximately 30 days and within 1 MPa after 100 days.

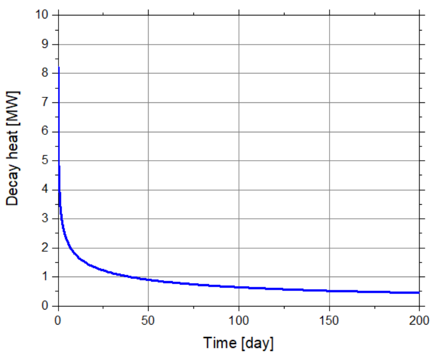

Fig. 9. Decay heat curve of i-SMR.

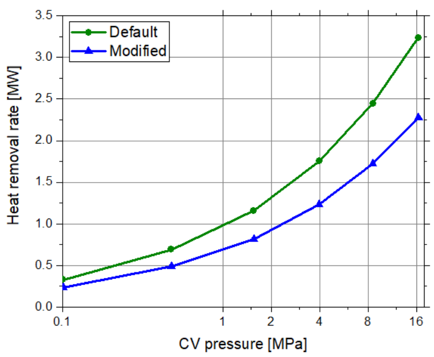

Fig. 10. Comparison of heat removal rate with various CV pressure.

4. Conclusions

The pipeline utilizing the chimney effect may experience a decrease in flow rate due to reverse flow. Taking this into account, it is necessary to apply a higher K value than usual. In this study, a new K value was calculated by referencing Jing and Cooper, and it was implemented into the CAP. As a result of the implementation, higher accuracy was observed in comparison with Chen's experiments.

The cooling chimney of the i-SMR was evaluated to determine how much heat it can remove on its own. The CV temperature was increased by 50°C from 100°C to 350°C, and the heat transfer rate was calculated when steady-state conditions were reached. Using the decay heat curve of the i-SMR, it was possible to determine how much time after reactor shutdown is required for the cooling chimney to remove heat on its own. The result showed that when the cooling chimney operates alone, the pressure of i-SMR is expected to remain within 3 MPa after approximately 30 days and within 1 MPa after 100 days.

ACKNOWLEGDEMENT

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