

Study on Loss Coefficient Correlations for Bidirectional Flow Using CAP for the Improved Prediction of Chimney Effect

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***Keywords :** Chimney Effect, Reverse Flow, Bidirectional Flow, Form Loss Coefficient, CAP

1. Introduction

In the innovative Small Modular Reactor (i-SMR), the chimney effect outside the containment vessel (CV) can be considered as a long-term cooling means. Air absorbs heat from the high-temperature CV wall, and natural convection is established by buoyancy.

However, when the gap of the chimney flow path is wide or the driving pressure difference is not sufficiently large, cold ambient air is drawn in at the outlet, producing reverse flow and hence a bidirectional flow field [1]. Such reverse flow reduces the net flow rate and increases the flow resistance. Consequently, applying the conventional unidirectional form loss coefficient, such as 1.0, results in a large overestimation of the flow rate [1].

In this study, in order to improve the chimney flow prediction accuracy of CAP (Containment Analysis Package), the Cooper model [2] and the Jing model [1] were comparatively evaluated. In addition, a new Combined model integrating the two models was established and comparatively evaluated. The applicability of each model was assessed through comparison with experimental data for a large gap (Jing experiment)[1] and for narrow and intermediate gaps (Burek experiment)[3].

2. Review of Outlet Form Loss Coefficient Models and Proposal of the Combined Model

Following Jing and Cooper, the Fr number in this study is calculated as follows.

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

Here, Q, G and A denote the flow rate of the chimney, gravitational acceleration and the flow area of the chimney, respectively, and D is the shortest side length of the chimney cross-section. The temperatures T_1 and T_2 denote the air inside the chimney and the ambient air, respectively, and are used below to obtain the temperature difference ϵ across the outlet.

2.1 Discharge Coefficient Correlation of Cooper

Cooper [2] established the discharge coefficient for combined buoyancy- and pressure-driven flow through a horizontal opening as a function of the ratio of the actual

Fr number to the critical Fr number ($r = Fr/Fr_{rev}$). The dimensionless density-difference parameter ϵ based on the temperature difference, the critical Fr number Fr_{rev} , and the discharge coefficient C_D are calculated as follows.

$$\epsilon = \frac{T_1 - T_2}{(T_1 + T_2)/2} \quad (2)$$

$$Fr_{rev} = 0.1754 e^{-0.5536\epsilon} \quad (3)$$

$$C_D = \frac{0.6r}{\sqrt{(r-1+\sigma_2^2)^2 + \sigma_1^2 - \sigma_2^4}} \quad (4)$$

2.2 Pressure Loss Coefficient Correlation of Jing

Jing et al. [1] proposed a loss coefficient correlation based on chimney experiments with large gap-to-height ratios, using Fr_{rev} , the Fr number at which reverse flow begins.

To use the correlation of Jing, the minimum gap size at which reverse flow occurs, together with the corresponding flow rate and pressure difference, is required. Correlations for these quantities were found in the work of Cooper[2], and by applying those expressions Fr_{rev} could be obtained.

In the Jing model, the K value is obtained as follows.

$$Q_{rev} = 0.1754Ae^{0.5536\epsilon}\sqrt{2gD\epsilon} \quad (6)$$

$$\Delta P_{rev} = 0.2427e^{1.1072\epsilon}(1 + 0.5 \cdot \epsilon)4gD\rho_2\epsilon \quad (7)$$

$$Fr_{rev} = \frac{Q_{rev}}{A \cdot \sqrt{\Delta P_{rev}/\rho_2}} \quad (8)$$

$$K_{out} = 1 + \left[0.61 \cdot \left(0.1 + 0.19 \cdot \frac{Fr}{Fr_{rev}} \right) \right]^{-2} \quad (9)$$

Here, q , H , w , ρ_2 denote the heat flux of the heater, the chimney height, the chimney width, and the density of the ambient air, respectively. σ_1 , σ_2 take the values of 3.370, 1.045, respectively.

2.3 Combined Model

The combined model was developed based on the idea that the Jing model was a modification of the Cooper model. It combines the explicit Fr_{rev} expression of the

Cooper model (Eq. (3)) with the loss coefficient correlation of the Jing model (Eq. (9)).

3. Experimental Validation

3.1. Target Benchmark Experiments

In this study, two sets of experimental data were used to verify the applicability of the models in the large-gap region tested by Jing et al. [1] and in the narrow and intermediate gap regions tested by Burek et al. [3]. The experimental apparatus is shown in Fig. 1, in which the key dimensions are the height, the width and the gap. The width is the width of the heater, and the gap is the distance between the heater and the wall opposite the heater. As listed in Table I below, Jing and Burek carried out experiments at various gaps and heater outputs. This study presents the analysis results for the maximum and minimum heater output cases of each experiment.

Table I: Conditions and geometric specifications of the target benchmark experiments

Experiment	Height [m]	Width [m]	Gap [m]	Heater output [W/m ²]
Jing et al. (2015)	2.0	1.0	40 ~ 120	200 ~ 400
Burek et al. (2007)	1.0	0.925	2 ~ 15	210 ~ 1050

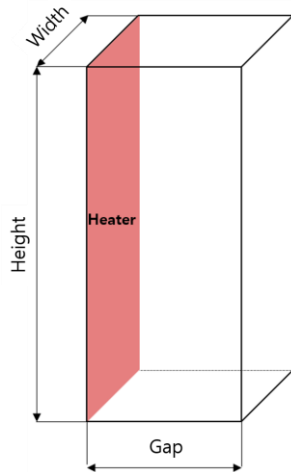


Fig. 1. Schematic of the experimental apparatus

3.2 Nodalization for CAP Assessment

As shown in Fig. 2, for the CAP code modeling the vertical chimney flow path was divided axially into ten uniform lumped volumes. A uniform heat flux condition identical to that of the experiments was imposed on the heated wall, and both ambient-side boundaries were set as pressure boundaries at 1 atm and 30 °C. A conventional K value of 1.5 is applied at the chimney inlet [1]. In this study, the three models introduced above

and the outlet loss coefficient of 1.0 conventionally used were applied to the junction between the uppermost node and the outlet pressure boundary, and steady-state analyses were performed.

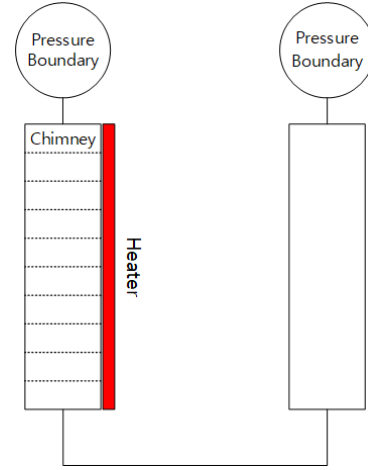


Fig. 2. Nodalization of CAP

To prevent a flow from being established by the elevation difference between the boundary conditions, a downward flow path was added as shown on the right-hand side of Fig. 2. If the boundary conditions are connected directly to the inlet and the outlet of the chimney as in the actual apparatus, a flow is established by the chimney height itself; the downward flow path must therefore be added to prevent this.

4. Analysis Results

4.1 Analysis Results for the Jing Experiment

The volumetric flow rate (m³/s) results for the heat flux conditions of 200 W/m² and 400 W/m² are as follows.

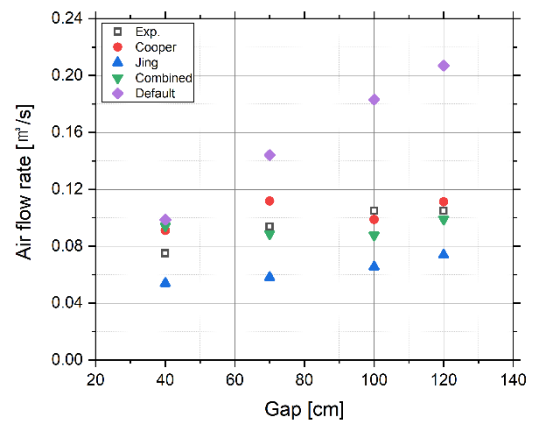


Fig. 3. Jing's experiment, 200 W/m²

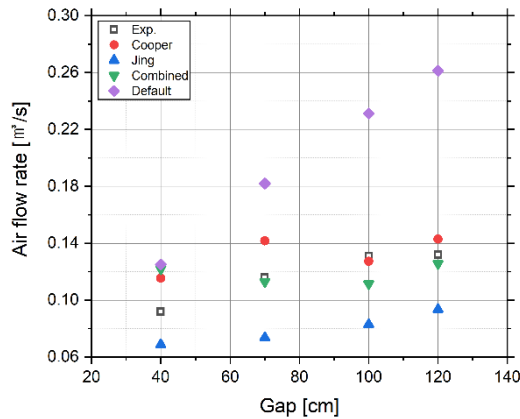


Fig. 4. Jing's experiment, 400 W/m²

The analysis results showed that the Cooper and Combined models agreed best with the experimental data.

4.2 Analysis Results for the Burek Experiment

The mass flow rate (kg/s) results for the narrow and intermediate gap region (2 ~ 15 cm) are as follows, and the Combined model and the Default model were confirmed to show the highest accuracy.

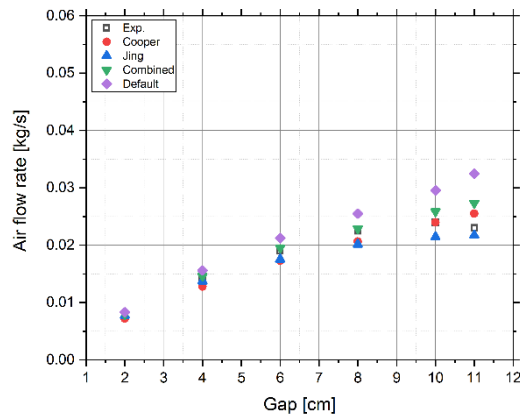


Fig. 5. Burek's experiment, 210 W/m²

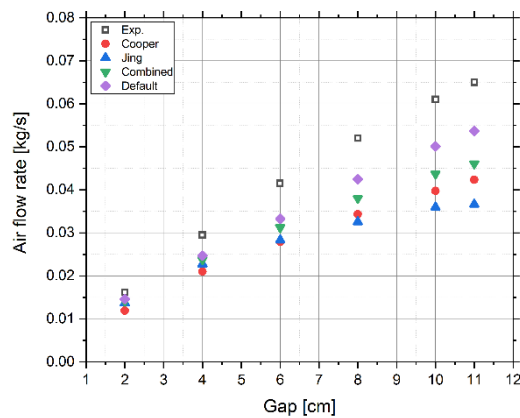


Fig. 6. Burek's experiment, 1050 W/m²

5. Conclusion

In order to predict the natural convection flow rate of a chimney, bidirectional flow loss coefficient models were applied to the CAP code and validation was performed. The Default model ($K = 1.0$) was found to have the limitation of largely overestimating the flow rate under large-gap conditions where reverse flow is dominant. The Jing model tended to overpredict the outlet loss coefficient and thus to underestimate the flow rate. The Combined model, which combines the critical Fr number expression of Cooper with the loss correlation of Jing, showed the best flow rate prediction performance in most of the results for both the large gap (Jing experiment) and the narrow and intermediate gaps (Burek experiment).

In the Burek experiment, the flow rate is underpredicted. This indicates that the input model needs to be optimized. Optimization of the input model will be carried out in a future study.

Acknowledgement

This work was supported by the Innovative Small Modular Reactor Development Agency grant funded by the Korea Government(MSIT) (No. RS-2024-00403548).

REFERENCES

- [1] H. Jing, Z. D. Chen, and A. Li, Experimental study of the prediction of the ventilation flow rate through solar chimney with large gap-to-height ratios, *Building and Environment*, Vol. 89, pp. 150-159, 2015.
- [2] L. Y. Cooper, Combined Buoyancy and Pressure-Driven Flow Through a Shallow, Horizontal, Circular Vent, *Journal of Heat Transfer*, Vol. 117, pp. 659-667, 1995.
- [3] S. A. M. Burek and A. Habeb, Air flow and thermal efficiency characteristics in solar chimneys and Trombe Walls, *Energy and Buildings*, Vol. 39, pp. 128-135, 2007.