Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 18-19, 2017

The Assessment of the Accuracy of MARS-KS V1.4 & RELAP5/Mod3.3 for Natural Convection Heat Transfer in a Chimney System

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1. Introduction

The chimney system is used in the passive decay heat removal system such as Reactor Core Cooling System (RCCS) of the Very High Temperature Reactor (VHTR) and Passive Decay heat Removal Circuit (PDRC) of a Sodium-cooled Fast Reactor (SFR). The chimney systems improve the heat transfer by increasing the mass flow rate. In this study, to evaluate the accuracy of the MARS-KS V1.4 and RELAP5/Mod3.3 code, the calculation results using these codes were compared with both the results obtained by simulating the results of analogy experiment on natural convection heat transfer in a chimney system and the numerical analysis results of the FLUENT 6.3 software.

2. Theoretical background

2.1 Chimney Effects

A thermally insulated chimney attached to top of a vertical heated section induces an increase of the flow rate and leads to a higher heat transfer rate. This is called a chimney effect [1].

2.2 Passive Decay Heat Removal System

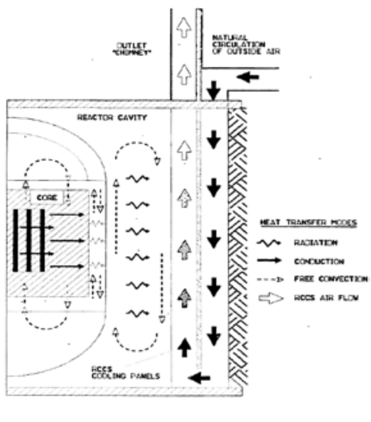

Fig. 1. RCCS – passive heat transfer mechanisms [2].

In the Very High Temperature Reactor (VHTR), a Reactor Cavity Cooling System (RCCS) is installed to protect the reactor vessel from overheating in the events such as loss of coolant accident or loss of heat sink, and to remove afterheat of the reactor. The function of this system is to remove the decay heat of the core by conduction, natural convection and radiative heat transfer through water or air riser tubes installed in the outer cavity of the reactor vessel (Fig. 1). In an accident, the heat from the core is discharged into the atmosphere through the chimney [2].

In the Sodium-cooled Fast Reactor (SFR), Decay Heat Removal System (DHRS) is adopted to remove the decay heat of the core in case of an accident. The DHRS of Prototype Gen-IV Sodium-cooled Fast Reactor (PGSFR) developed by KAERI is composed of two units of Passive DHRS and Active DHRS which have the natural-draft sodium-to-air heat exchanger (AHX) and the forced-draft sodium-to air heat exchanger (FXH), respectively (Fig. 2). Passive DHRS is activated by natural circulation without internal and external power supplies, and Active DHRS has also 50% of passive decay heat removal capability due to the chimney without power [3].

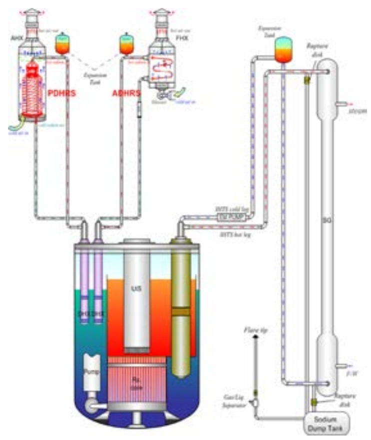

Fig. 2. Schematics of the DHRS of PGSFR [3]

2.3 The Correlation used in MARS-KS V1.4 and RELAP5 / Mod3.3 Computer Code

MARS-KSV1.4 and RELAP5/Mod3.3 use the Churchill-Chu (1975) correlation in natural convection heat transfer at a vertical geometry. The correlation is following [4]:

$$Nu_L = \left\{ 0.825 + \frac{0.387\left(Ra_L\right)^{1/6}}{\left[1+\left(\frac{0.492}{\mathrm{Pr}}\right)^{9/16}\right]^{8/27}} \right\}^2$$

Where, Nusselt number (Nu_L) is hL/k, Rayleigh number (Ra_L) is $Gr_L Pr$, Grashof number (Gr_L) is $g\beta\Delta TL^3/\nu^2$, Prantdl number is ν/α .

2.4 Prandtl Number Influence

The influence of the interaction of boundary layers on the chimney effect is dependent on the value of the Prandtl number. As shown in Fig. 3, Prandtl number of larger than one causes a thicker layer of unheated fluid being driven upward by the heated layer. However, when the Prandtl number is less than one, the thermal boundary layer is thicker than the momentum boundary layer, and the fluid flows upward through buoyancy [5].

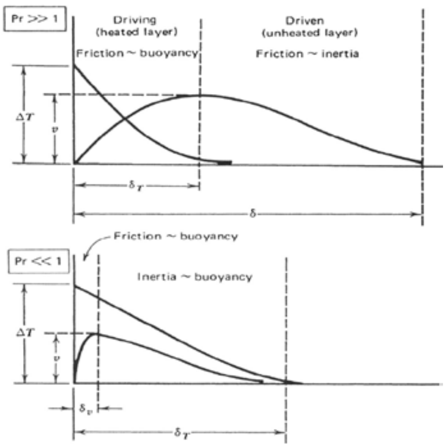

Fig. 3. Two length scales of the boundary layer flow along a heated vertical wall [5]

3. Experiment, numerical analysis and safety analysis computer code

3.1 Experiments [6]

The experiments cited in this study used the analogy concept for heat and mass transfer and were performed for high Rayleigh numbers. The natural convection heat transfer phenomena in a chimney-system were simulated by mass transfer experiments. Fig. 4 shows the test facility.

Fig. 4. Test facility [6]

3.2 Numerical Analysis

Numerical analysis was carried out using FLUENT 6.2 software [7]. GAMBIT software was used to generate the two-dimensional (2D) mesh of the chimney system. The edge assigned along the adiabatic and heated walls had 15-30 rows; it began with a row of a thickness of 10^{-5} m, and used a growth factor of 1.05. The temperature of the heated wall was maintained at a constant temperature of 400 K, and the bulk temperature of fluid remained constant at 300 K.

3.3 MARS-KS V1.4 and RELAP5/Mod3.3 Input Model

The schematic diagram of the MARS-KS V1.4 and RELAP5/Mod3.3 models for simulating the chimney effect experiment is shown in Fig. 5. The hydraulic volume of the heated section is modeled as a pipe component having 7 sub-volume and the height of each part is uniformly divided.

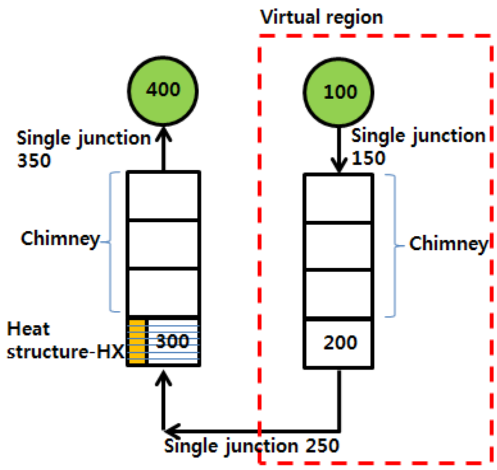

Fig. 5. MARS-KS V1.4 & RELAP5/Mod3.3 Nodalization

3.4 Test Matrix

Table I presents the test matrix and geometrical arrangements. The diameter and length of heated pipe are 0.035 m and 0.07 m, respectively. The diameter of the chimney is 0.035 m, but the heights of chimney are varied from 0 m to 2.0 m.

Table I: Test matrix.

Case	D (m)	L (m)	Ra_L	*Pr*	Chimney heights (m)
Experiments	0.035	0.07	5.78×10^{10}	2,094	0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0
Numerical analysis	0.035	0.07	1.93×10^{7}	0.7	0.0, 0.4, 0.8, 1.0, 1.5, 2.0
			5.78×10^{10}	2,094	
MARS-KS V1.4 & RELAP5/Mod3.3	0.035	0.07	1.93×10^{7}	0.7	0.0, 0.4, 0.8, 1.0, 1.5, 2.0

4. Results and discussion

4.1 Experimental Results at Pr = 2,094

Fig. 6 presents the measured Nu_L values for the heated cylinder with respect to the chimney height. The Nu_L value in the absence of a chimney agreed well with the following heat transfer correlation for a vertical plate [8].

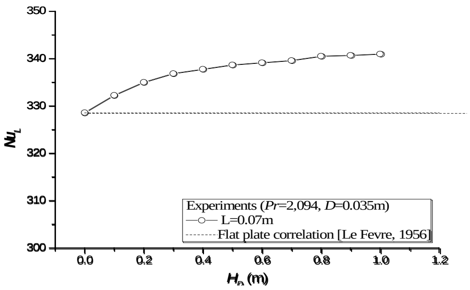

Fig. 6. Comparison of the test results with the Le Fevre correlation for a vertical flat plate

The increase of the chimney height up to the effective length enhanced the heat transfer. Further extension in more than the effective length does not cause the enhancement of the heat transfer due to the balance of acceleration driven by buoyancy and deceleration caused by friction between the fluid and the wall of the chimney.

4.2 Comparisons of Experimental and Numerical Results at Pr = 2,094

Fig. 7 presents the average Nu_L values in the heated cylinder for each chimney height. The experiments and the numerical analysis were in good agreement with each other. The relative differences between the experimental and numerical results were a maximum of 5.44% and a minimum of 1.35%.

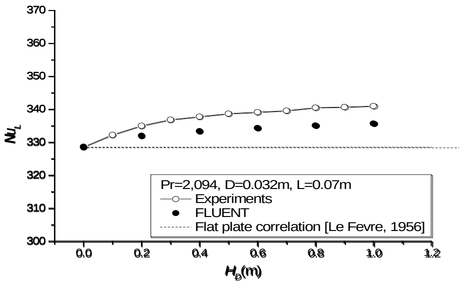

Fig. 7. Comparison between experimental and numerical average Nu_L values in the heated cylinder

4.3 Comparisons of Experimental and MARS-KS & RELAP5 Code Results

Fig. 8 shows the Nu_L/Nu_0 values with respect to the chimney height for each Prandtl number of 0.7 and 2,094 with a heated wall length of 0.07 m, where Nu_L is the value for a certain chimney height and Nu_0 is the value without the chimney. For the results of the MARS-KS V1.4 and RELAP5/Mod3.3 codes for the Prandtl number of 0.7, the chimney effect was noticeable up to the 0.2 m of the chimney height due to the influence of the Prandtl number. But further extensions were less effective with similarity to the trend of the experiments.

Fig. 9 presents the velocity and temperature fields for Prandtl number 0.7 and 2,094. As the Prandtl number decreased, the thickness of the thermal boundary layer increased and the chimney effect was enhanced.

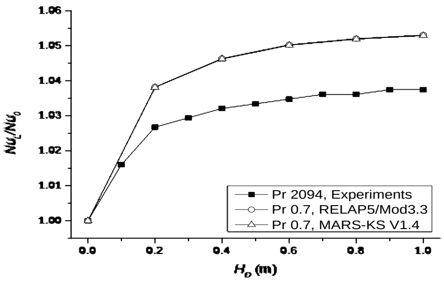

Fig. 8. Comparison among experiment, MARS-KS V1.4 and REALP5/Mod3.3 code Nu_L/Nu_0 ratio at each chimney height

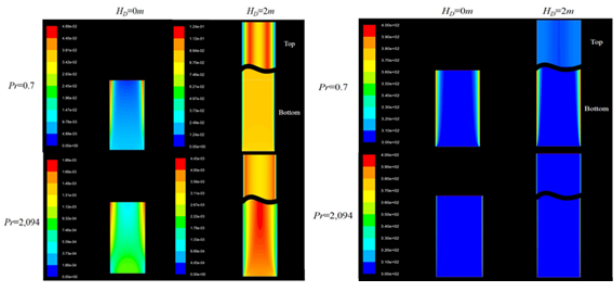

Fig. 9. Velocity & Temperature fields for different Prandtl numbers.

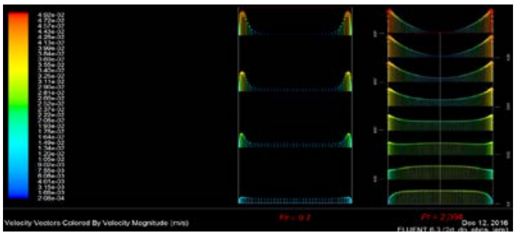

Fig. 10. Velocity vector fields for different Prandtl numbers - without the chimney

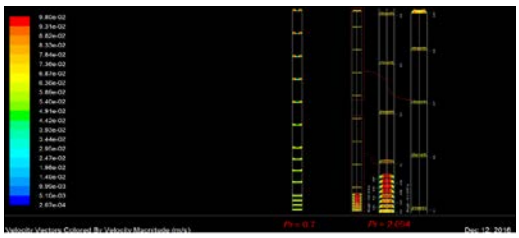

Fig. 11. Velocity vector fields for different Prandtl numbers - with the chimney (height= 0.80 m)

Fig. 10 and Fig. 11 present the velocity vector fields for different Prandtl numbers without and with the chimney, respectively. In the absence of a chimney, the velocity peaked near the wall, indicating dominance of natural convection. However, in the presence of a chimney, the velocity peak shifted to the centerline of the domain, indicating dominance of forced convection. Also, up to the height of the chimney of 0.20 m, the difference between the Prandtl number 0.7 and 2,094 was clearly noticeable as shown in Fig. 11.

4.4 Comparisons of Numerical Analysis (FLUENT) with MARS-KS & RELAP5 Code Results at Pr = 0.7

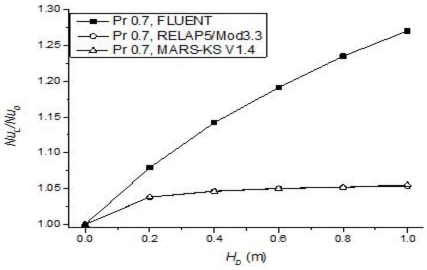

Fig. 12. Comparison of FLUENT with MARS-KS and REALP5 code Nu_L/Nu_0 ratio at each chimney height

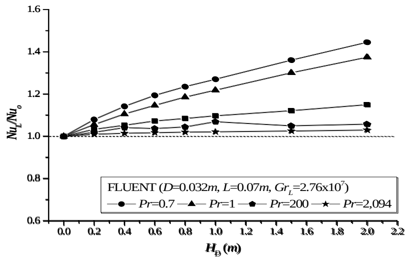

Fig. 13. Nu_L number ratios for different Prandtl numbers [9]

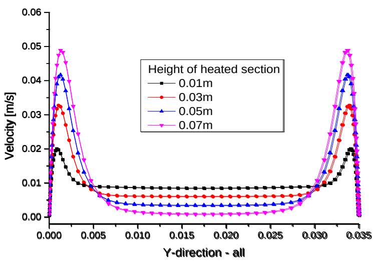

Fig. 14. Velocity profiles in the heated wall without the chimney calculated by FLUENT

Fig. 12 shows the Nu_L/Nu_0 ratios calculated by the FLUENT, MARS-KS V1.4 and RELAP5/Mod3.3 codes for Pr = 0.7. The chimney effect was the largest in the FLUENT simulation. As shown in Fig. 13 [9], when the Prandtl number is decreased, the chimney effect is expected to be large due to the increase of the thermal boundary layer. However, in case of the MARS-KS V1.4 and RELAP5/Mod3.3 code, the chimney effects were not large even though the Prandtl number was 0.7. This seems to result from the fact that in the numerical analysis using FLUENT program with the 2-D model, the velocity peak near the heated wall has a great influence on the heat transfer as shown in Fig. 14, whereas the average velocity is used in the calculation of heat transfer in the MARS-KS V1.4 and RELAP5/Mod3.3 codes with the 1-D model.

5. Conclusions

This study evaluated the accuracy of the MARS-KS V1.4 and RELAP5/Mod3.3 code through the comparison with the results obtained by experiments and numerical analysis (FLUENT). In the MARS-KS V1.4 and RELAP5/Mod3.3 code, an increase in the chimney height enhanced the heat transfer up to a certain height (effective length) and that further extensions did not affect the heat transfer in similarity with the experiments and numerical simulations.

However, the results of the MARS-KS V1.4 and RELAP5/Mod3.3 code were somewhat different with the results of the numerical analysis at same Prandtl number, 0.7. The chimney effects were not noticeable in the results of MARS-KS V1.4 and RELAP5/Mod3.3 even though the Prandtl number was small. This seems to result from the fact that in the numerical analysis using FLUENT program with the 2-D model, the velocity peak near the heated wall had a great influence on the heat transfer, whereas the average velocity was used in the calculation of heat transfer in the MARS-KS V1.4 and RELAP5/Mod3.3 codes with the 1-D model.

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