Improvement of the GAMMA+ code for Turbulent Mixed Convection in the VHTR RCCS Riser

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1. Introduction

Very High Temperature gas-cooled Reactor (VHTR) is a GEN IV reactor that has been developed for hydrogen production and features enhanced inherent safety [1]. A key safety system of VHTR is a Reactor Cavity Cooling System (RCCS) that passively cools down the Reactor Pressure Vessel (RPV) in the case of Loss Of Flow Accident (LOFA) [2]. In RCCS, vertical rectangular ducts which are called risers surround the RPV and receive heat from it. The heat is transferred to air inside the riser and the heated air flows up, which is emitted to the outside atmosphere through the chimney. When the air is heated inside the riser, however, the heat transfer regime could be turbulent mixed convection regime where the heat transfer rate is lowered compared to the forced convection [3]. Therefore, the heat transfer phenomena inside the riser had been investigated in the previous study, and a new heat transfer coefficient correlation for the turbulent mixed convection inside the riser was suggested [4].

In this study, the newly suggested heat transfer coefficient correlation was implemented to GAMMA+ code [5] which is a thermal-fluid system code for VHTR. Except for the implementation of the correlation, the rectangular duct geometry model was also modified for the vertical rectangular riser in the GAMMA+ code. With the modified GAMMA+ code, the SNU RHEF experiments were calculated and the calculation results were discussed.

2. Modification of the GAMMA+ code

In the GAMMA+ code, the method of 'Engineering Approach (Eng.App.)' was adopted to calculate heat transfer coefficient (HTC) in turbulent mixed convection regime as follows.

$$Nu_{MT} = \left| Nu_{NT}^3 - Nu_{FT}^3 \right|^{1/3} \quad \text{(Eq. 1)}$$

where $Nu_{FT} = 0.021 \Pr_f^{0.4} \mathrm{Re}_f^{0.8} \left(\frac{T_b}{T_w} \right)^{0.5}$ and

$$Nu_{NT} = \left(0.825 + \frac{0.387 Ra_f^{1/6}}{\left(1.0 + \left(0.492 / \Pr_f\right)^{0.5625}\right)^{8/27}} \right)^2 .$$

In this method, the HTC for turbulent mixed convection is calculated simply by combination of HTCs in forced convection and natural convection. HTC of forced convection is obtained from modified Dittus-Boelter's correlation and HTC of natural convection is calculated by Churchill & Chu correlation [5].

Instead of this method, the newly developed HTC correlation for the turbulent mixed convection inside the riser was implemented to the GAMMA+ code. The new correlation is as follows.

$$\frac{Nu}{Nu_{F,ent}} = Max\left(f_1\left(Bo_{dt}, \frac{x}{D_h} \right), f_2\left(Bo_{dt}, \frac{x}{D_h} \right) \right) \quad \text{(Eq. 2)}$$

where

$$f_1\left(Bo_{dt}, \frac{x}{D_h} \right) = \exp\left(-\left(44.35\left(\frac{x}{D_h} \right) + 364.09 \right) Bo_{dt} \right)$$

and

$$f_2\left(Bo_{dt}, \frac{x}{D_h} \right) = \left(1.04\left(\frac{x}{D_h} \right)^{-0.215} \right) \exp\left(\left(6.72\frac{x}{D_h} + 92.83 \right) Bo_{dt} \right).$$

Bo_{dt} is a buoyancy parameter that was defined as follows.

$$Bo_{dt} = \frac{Gr_{dt}}{\mathrm{Re}_b^{2.60} \Pr_b^{0.55}} \quad \text{(Eq.3)}$$

And $Nu_{F,ent}$ is a Nusselt number for the forced convection considering the entrance effect. For the HTC correlation of forced convection, Gnielinski correlation was used and the Reynolds entrance effect correlation was adopted for the consideration of entrance effect [6].

Rectangular duct such as a riser was modelled as a circular pipe in the extant version of the GAMMA+ code as shown in Fig. 1. When a vertical rectangular riser is modeled as a circular pipe, the inside area and the outside area of the rectangular duct were preserved in a circular pipe. This is to preserve the effect of radiative heat transfer. With this method, however, the thickness of the circular pipe is different from the thickness of the actual riser duct, and the conduction effect through the solid region is distorted.

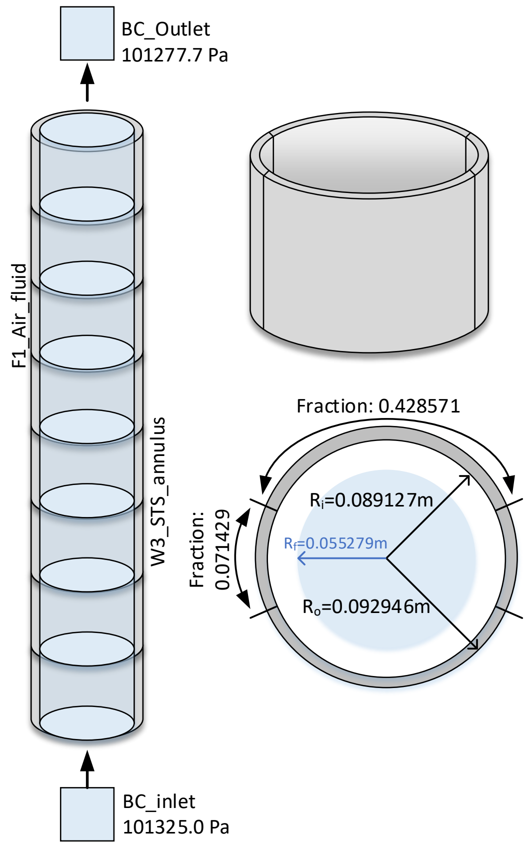

Fig 1. Riser modeling as a circular pipe in the extant version of the GAMMA+ code

Therefore, in this study, boundary condition options of the rectangular block were modified to simulate the rectangular duct by connecting the four rectangular blocks supported by GAMMA + code as shown in Fig. 2. Previously, 1-D fluid volumes could not be connected to the north and south sides of the 3D rectangular block with a convective heat transfer option, but the boundary conditions were modified to connect the interface of the 1-D fluid volume where the convective heat transfer occurs. Then the vertical rectangular duct can be modeled as shown in Fig 3.

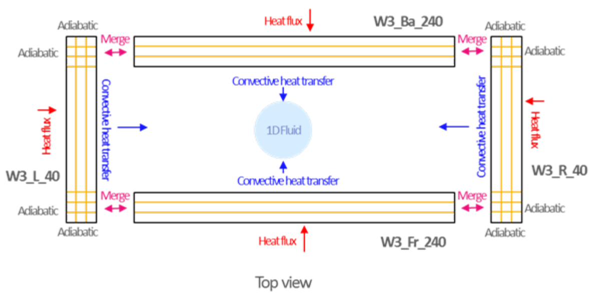

Fig 2. Modification of the boundary condition option of the GAMMA+ code

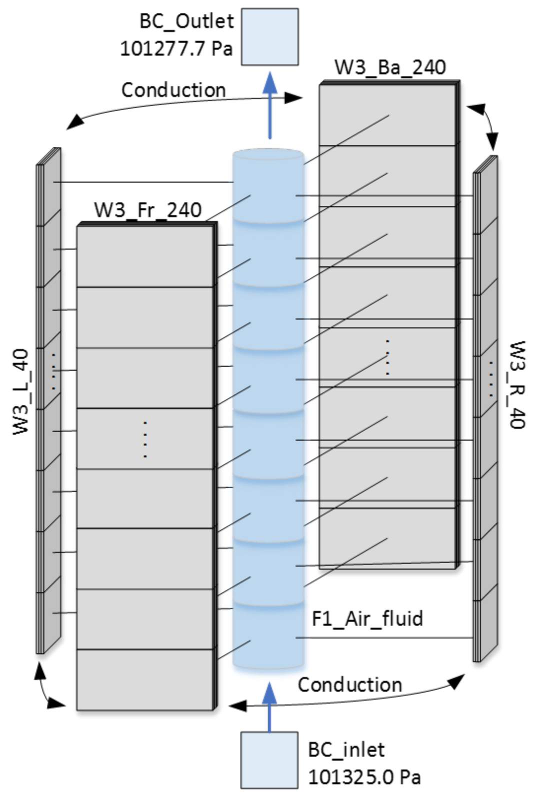

Fig 3. Riser modeling as a rectangular duct in the modified GAMMA+ code

3. Calculation results with the modified GAMMA+ code

After the modification of the GAMMA+ code for the turbulent mixed convection inside the vertical rectangular riser, validation calculations were performed. Firstly, the twelve cases of SNU RHEF experiments were calculated as validation problems. SNU RHEF experiment is the heat transfer experiment in the turbulent mixed convection regime with the 4.0 m-height vertical rectangular duct [7]. Calculation conditions are described in Table 1.

Fig. 4 shows the comparison between the wall temperature obtained from the calculation and the wall temperature in the experiment. The calculation results with the Eng.App. that was the extant method to obtain HTCs in the turbulent mixed convection showed the 24.65% average discrepancy. The calculation results with modified GAMMA+ code shows the 2.45% difference from the experiment results, which is ten times more accurate result compared to extant method.

Table 1. Test matrix of SNU RHEF experiment

Case	Mass flow rate (kg/s)	Inlet temperature (°C)	Heat flux (W/m^2)
Re4293HF344	0.01108	24.75	343.56
Re4290HF487	0.01076	14.09	487.17
Re4342HF900	0.01127	26.97	900

Re8985HF402	0.02351	29.96	402.87
Re8950HF721	0.02317	25.96	721.25
Re8921HF1070	0.02303	24.92	1070.23
Re15625HF610	0.04061	25.55	610.45
Re11999HF764	0.02985	11.05	763.99
Re7685HF378	0.01955	19.35	378.27
Re6916HF701	0.01818	26.33	701.31
Re4457HF420	0.01133	19.09	420.01
Re3113HF318	0.00804	24.79	318.42

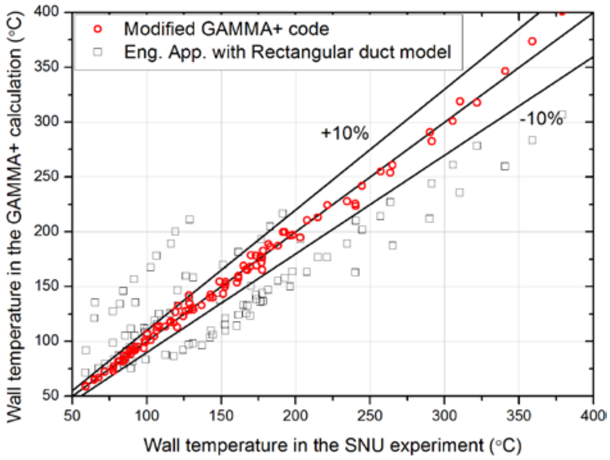

Fig 4. Calculation and comparison results for the SNU RHEF experiment

4. Conclusion

In this study, modification of the GAMMA + code for turbulent mixed convection inside a vertical rectangular riser was performed. Rectangular block geometry model was modified to allow the modeling of rectangular duct by adding convective heat transfer options to north and south boundary condition. In addition, the heat transfer correlation developed for vertical rectangular duct in turbulent mixed convection was implemented to the GAMMA + code. The validation calculation was performed for the SNU RHEF experiment using the modified GAMMA + code as described above. And the calculation result was consistent with the experiment with an accuracy of 2.45%. This study will contribute to the safety analysis of VHTR and accurate modeling of the RCCS system in VHTR.

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