Study on the Thermal Resistance of Wet Thermal Insulator

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1. Introduction

SMART developed in KAERI is an integral type nuclear cogeneration reactor. Since SMART has a nitrogen-filled gas pressurizer, the steam partial pressure should be minimized and the pressurizer should be under low temperature. In order to maintain low temperature condition, the wet thermal insulator is installed on the boundaries between the pressurizer and reactor coolant system, and the pressurizer cooler is used to remove the heat from the primary system. Since the performance of the wet thermal insulator is a dominant parameter to determine the capacity of the pressurizer cooler, it is important to evaluate the insulation. In the design of SMART, the empirical correlation by Adamovich [1] was used to estimate the thermal resistance of the wet thermal insulator. However, the experimental condition and results are not clear so that this correlation should be verified. In this study, the thermal resistance of wet thermal insulator is evaluated and the correlation by Adamovich is verified by numerical analyses and experiments.

2. Analysis and Experiment

The wet thermal insulator in the pressurizer of SMART consists of 20 layers and there is a 0.8 mm gap between 0.2 mm thick stainless steel plates in each layer. Generally, when the enclosure is sufficiently long and wide in the horizontal direction and is heated from below, the natural convection occurs. The natural convection is related to the Rayleigh number and there is a critical Rayleigh number from which the natural convection will be initiated. Above the critical Rayleigh number ($= g\beta\Delta T\delta^3/\alpha\nu \equiv 1708$), the flows consist of the two-dimensional square rolls, which is recognized as Bénard convection [2].

In order to estimate performance of wet thermal insulator, the thermal resistance is evaluated and the verification for the Adamovich correlation is performed by numerical calculation, heat balance calculation and experiment.

2.1 Adamovich Correlation (Multilayer)

Adamovich suggested the empirical correlation on the thermal resistance of a single layer which does not have terms for width of layer as Eq.(1).

$$r = \frac{\delta}{\lambda_e} = \left(\frac{7.5}{\lambda_f}\left(\frac{\nu^2}{3\cdot \mathrm{Pr}\cdot \beta \cdot \Delta t}\right)^{1/3}\right)_{water} \tag{1}$$

where λ_f and λ_e are actual and effective coefficients of thermal conductivity in a liquid. From this correlation, the thermal resistance of multilayer is calculated considering the overall temperature difference and the number of layers as Eq.(2).

$$R_{total} = n \cdot r = \frac{7.5}{\lambda_f}\left(\left(\frac{\nu^2}{3\cdot \mathrm{Pr}\cdot \beta \cdot \Delta T}\right)^{1/3}\right)_{water} n^{4/3} \tag{2}$$

In multilayer correlation, the thermal properties should be obtained at an average temperature between hot and cold part temperatures.

2.2 Single Layer Correlation

Raithby and Hollands [3-4] recommended the following correlation on horizontal single layer condition.

$$Nu = 1 + \left[1-\frac{Ra_c}{Ra}\right]^{\bullet}\left[k_1 + 2\left(\frac{Ra^{1/3}}{k_2}\right)^{1-\ln(Ra^{1/3}/k_2)}\right] + \left[\left(\frac{Ra}{5380}\right)^{1/3}-1\right]^{\bullet}\left(1-\exp\left\{-0.95\left[\left(\frac{Ra}{Ra_c}\right)-1\right]^{\bullet}\right\}\right) \tag{3}$$

where $k_1 = 1.44/\left[1+0.0018/\mathrm{Pr}+0.00136/\mathrm{Pr}^2\right]$, $k_2 = 75\exp(1.5/\mathrm{Pr}^{1/2})$, $[x]^{\bullet} = (|x|+x)/2$.

The calculation is initiated assuming that the linear temperature distribution comes out. The thermal resistance is determined by above correlation through heat balance calculation using iterative method. Thus, the total thermal resistance is obtained with a sum of thermal resistance of each layer. Moreover, Adamovich single layer correlation, Eq.(1) is applied at the same way.

2.3 Numerical Calculation

The numerical calculation for the thermal resistance was carried out. ENCLREC code for a single layer by Naylor [5] was used to evaluate thermal resistance, flow pattern and temperature distribution. To analyze the multilayer characteristic, the number of layer is extended. When the pressure, temperatures of hot and cold part and the number of layers are determined, the overall thermal resistance is obtained.

2.4 Experiment

The pressure and the core exit temperature in SMART operation are 14.7 MPa and 310 ^{o}C, respectively. In order to describe the heat transfer characteristics of wet thermal insulator of SMART, the experimental pressure condition is determined to be 2.0 MPa and 2.5 MPa considering the Rayleigh number scaling. In addition, the test section consists of 5 water layers as shown Fig. 1. The constant temperatures are sustained as boundary conditions at hot part and cold part. The temperature of each plate was measured by 0.254 mm thermocouples (K-type) and the copper plate was used to make heat transfer uniform in the hot part.

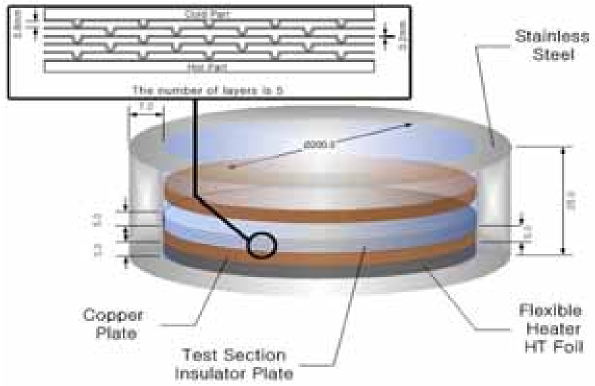

Figure 1. Schematic diagram of test section.

The experiment is performed by Table 1.

Case	Pressure (MPa)	Hot part (°C)	Cold part (°C)
1	0.1	100	50
2	2.0	200	80
3	2.0	200	100
4	2.5	200	80
5	2.5	200	100

Table 1. Experimental conditions.

3. Results

The total thermal resistance is shown in Table 2.

Case	Adamovich Single layer	Adamovich Multilayer	Raithby and Hollands	Numerical Calculation	Experiment
1	0.008645	0.008492	0.006044	0.006044	0.006320
2	0.004472	0.004426	0.003682	0.003548	0.003589
3	0.004560	0.004524	0.003754	0.003638	0.003757
4	0.004474	0.004426	0.003685	0.003551	0.003727
5	0.004563	0.004527	0.003759	0.003645	0.003356

Table 2. Thermal resistance of all cases (m^2 K/W)

As shown in Table 2, it is found that Adamovich correlation overestimates the thermal resistance compared with other methods. However, the results from numerical calculation and Raithby and Hollands correlation show a good agreement compared with those of experiments.

In addition, Figure 2 shows the temperature distribution according to the thermal resistance of each layer using heat balance calculation in case 3. In case 1, the conduction is a dominant heat transfer mechanism over all of layers because the Rayleigh numbers in all layers are under the critical Rayleigh number. In others, the thermal resistance and the tendency of temperature distribution are similar each other. Moreover, it is also found that the pressure effect on the thermal resistance can be negligible.

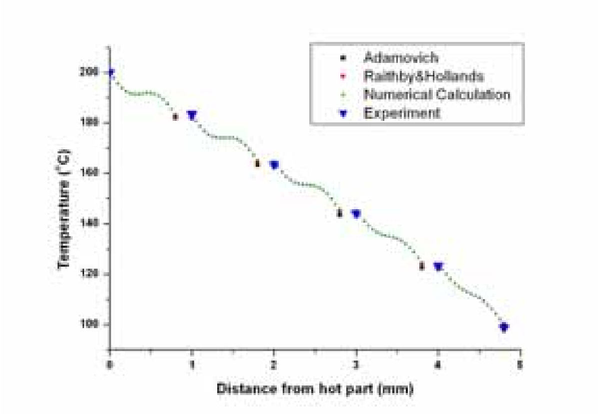

Figure 2. Temperature distribution in case 3.

From the Figure 2, it is found that the temperature difference near the hot part is smaller than that in cold part due to natural convection or thermal mixing. In addition, the results from numerical calculation are in a good agreement with those of experiment.

4. Conclusion

The numerical and experimental study on the thermal resistance of the wet thermal insulator was carried out. From the results, it was found that Adamovich correlation overpredicts the total thermal resistance. In the viewpoint of nuclear reactor design, it is not conservative because the pressurizer cooler can be designed with smaller heat removal capacity than actually required. Thus, an additional study should be performed to obtain new correlation to consider multilayer insulator.

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