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Development of High-Performance Reflective Metal Insulation Through Optimized Sheet Plate Design

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1. Introduction

The recent Fukushima accident in Japan has led to an increase in concerns about the safety of nuclear power plants. Existing types of insulation used to minimize thermal loss is difficult to apply to nuclear reactors, steam generators, pressurizers and recirculation pumps in nuclear power plants—facilities in which a high level of safety is required. Conservative insulation is especially difficult to apply to NPP facilities in consideration of operators' safety due to its characteristics of having unstable chemical and structural property, being easily degradable, and being able to produce harmful gases in the case of accidents and exposure to high temperature. Korean regulation organizations, together with the U.S., are considering the possibility of implementing a safety-enhanced technology of Reflective Metal Insulation (RMI) in order to solve safety problems such as sump clogging and ECC failure. RMI is made of stainless sheet plates with low emissivity and closed air spaces. The low emissivity in stainless steel blocks out thermal radiation, while the closed air spaces block out thermal conductivity and thermal convection. In this study, we made an analysis of the structure and shape of stainless sheet plates, the most important factor for the RMI design, by using Therm 7.3.

2. Methods and Results

2.1 Experiment of Reflective Metal Insulation

Thermal conductivity of RMI was measured and compared to the simulation results. Thermal conductivity measurements were conducted using the guarded hot plate (GHP) technique with steady-state method at 200 degrees Celsius in accordance to ASTM C177 [1,2], which is schematically shown in Fig. 1. Thermal conductivity based on GHP measurement can be calculated using the following equation, where, Q is the net heat flow supplied by the main heater and
$\Delta T = T_H - T_C$.

$$K = \frac{Q \cdot d}{A \cdot \Delta T} \quad (1)$$

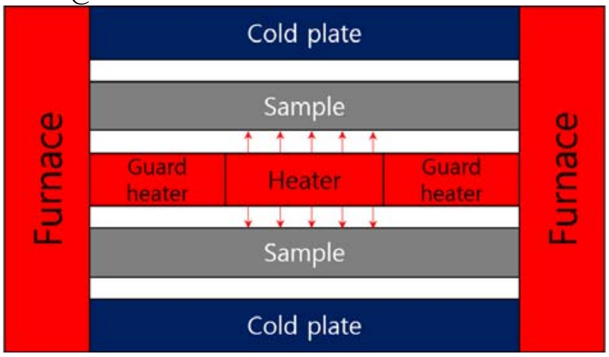

Fig.1: Schematic diagram of GHP apparatus

The guarded heater and ring play the role of thermal barriers to secure the one-dimensional heat flow from the main heater to the cold plate, making it possible to measure the exact value of Q. The expanded uncertainty of thermal conductivity measurements considering both random and systematic errors was evaluated to be 5.4% with a confidence level of 95% [3].

2.2 Model of Reflective Metal Insulation

Through Therm 7.3, RMI's conjugate heat transfer (radiation, conduction, convection) was analyzed through simulations of various designs of sheet plates. The temperature of hot plate (heater) is 210℃, and the temperature of the cold plates are 190℃. Then, the boundary conditions are: left and right adiabatic boundary, bottom and top isothermal boundary and no-slip condition in the walls (including the partitions). In this study, we will present an investigation of shape and configuration of the sheet plates. Table 1 shows sample information.

Sample dimension (mm)	300(w) X 95(h)
Material	Stainless steel
Thermal conductivity (W/mK)	15
Surface emissivity	0.24
Layer emissivity	0.18
Surface thickness (mm)	1
Layer thickness (mm)	0.06
Layer number (#)	4, 16

2.3 A comparison between simulation & experimental results

In the experiment from 2.1, thermal conductivity of RMI had a result of 0.046W/m·K. In the case of an air layer with 0.54cm thickness and 16 parallel partitions, thermal conductivity of RMI was calculated to be 0.055W/m·K. This difference is thought to be caused by the influx of heat from the surrounding areas due to the use of an inhomogeneous sample. The computational result is validated by the experimental result. The basic method for optimized sheet plate design is shown in Fig. 2, and Fig. 3 shows the analysis results using Therm 7.3. Heat transfer occurs through conduction, convection and radiation. In the case of an air layer with 10mm or less of thickness, heat transfer by convection is completely blocked regardless of the direction of heat flow[4]. Therefore, when designing a sheet plate, heat transfer by radiation and heat conduction is the most important factor.

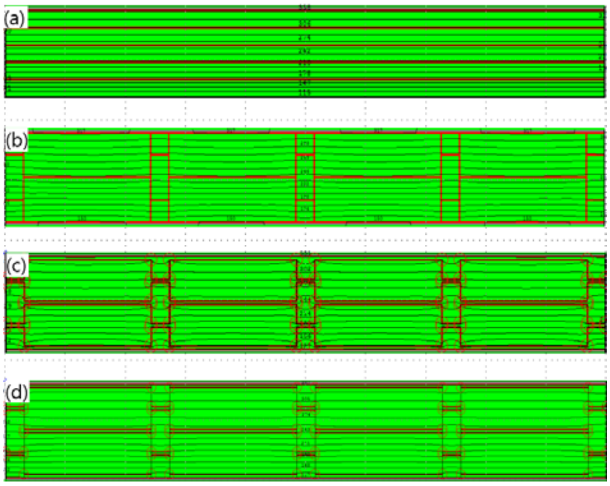

Fig. 2: Four types of thin plate stacks (a) Thin plate of the flat type (b) Contact between sheet plates (c) No contact between sheet plates (d) No contact between sheet plates and no sheet plates of horizontal direction

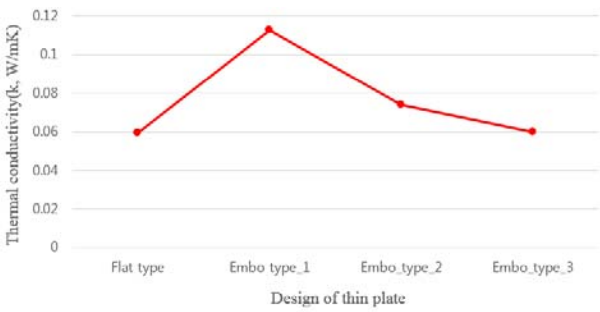

Fig. 3: Insulating capacity of RMI according to the design of sheet plate.

In the case of Fig. 2(b), thermal insulation capacity of RMI was measured to be very low. The causes can be analyzed in Fig. 3(c) and 3(d). If sheet plates are designed with an air-gap of 1mm in the contact area, such as in Fig 3(c), the insulation performance increases by about 48%. In comparison to Fig. 2(b), Fig. 3(c) shows an increase in insulation performance due to the air gap between the two sheet plates that allow low emission and high reflectivity, shielding radiation heat transfer; whereas Fig. 3(c)'s lack of air gap does not allow the benefits of radiation shielding to take place. Fig. 3(d) consist of only sheet plates of horizontal direction from Fig. 3(c). Thermal insulation capacity in case Fig. 3(d) has the same result as Fig. 3(a). From comparing the results of the simulations of 2(c) and 2(d), it can be seen that the presence of vertical sheets play a large role in the conductivity of heat. From this, it can be seen that an optimal design of sheet plates requires the least amount of variation to the flat plate—it should be produced as a flat-type with minimum modification for an optimal design.

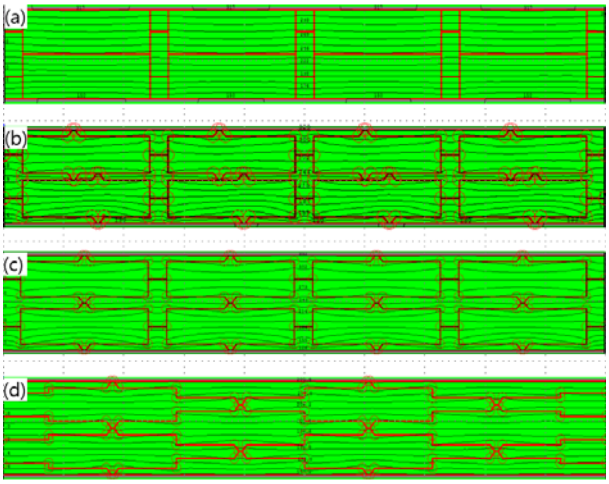

Fig. 4: RMI with or without protruding structure. (a) No protruding structure (b) Protruding shape_1 structure (c) Protruding shape_2 structure (d) Protruding & double-sided embossed structure.

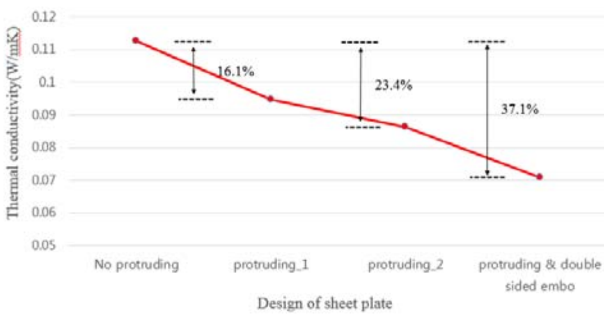

Fig.5: Effect of thermal insulation according to structure type.

Fig. 4 shows four types of sheet metal structure. As analyzed above, insulating capacity of RMI is improved by about 23.4% by adding a protruding structure, as shown in Fig. 4(c). Insulating capacity of RMI can be improved with a double-sided embossed structure by about 37.1%, as shown in Fig. 4(d). Therefore, it can be seen that the insulating capacity of RMI can be improved by design factors of the sheet plate, such as characteristics that include small protruding shape and double-sided embossed structure.

3. Conclusions

Sheet plate design for maximizing insulating capacity of RMI was analyzed by Therm 7.3. The results are as follows:

1. In the case of an air layer with a thickness of 10mm or less, heat transfer by convection is completely blocked regardless of the heat flow direction. Therefore, when designing a sheet plate, heat transfer by radiation and heat conduction are the most important factors.
2. By minimizing the contact area between the stainless steel sheets, it is possible to minimize heat loss through conduction and, at the same time, maximize the radiation shielding effect in all areas. An increase in contact area causes a decrease in air gap, disallowing radiation shielding effect to take place.
3. The ideal shape of sheet plate is the flat type, as shown in Fig. 2(a), but due to limitations in the production processes of manufacturing a thin plate (0.06mm) design, applicability is limited. Insulating capacity of RMI is improved by the sheet plate designs that include small protruding shapes and double-sided embossed structure (Fig. 4(a)).

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