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Measurement of VIP Edge Conduction Using Vacuum Guarded Hot Plate

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***Abstract*—**Vacuum insulation panel (VIP) is a promising thermal insulator for buildings, refrigerator, LNG carrier and so on. In general, it has the thermal conductivity of 2~4 mW/m·K. However, this thermal conductivity is that measured at the center of VIP. The total effective thermal conductivity of VIP is larger than this value due to the edge conduction through the envelope. In this paper, the edge conduction of VIP is examined theoretically, numerically and experimentally. To confirm the existence of the edge conduction, numerical analysis is performed for simple two-dimensional VIP model and a theoretical model is proposed to calculate the edge conductivity. Also, the edge conductivity is measured using the vacuum guarded hot plate and the experiment is validated against numerical analysis. The results show that the edge conductivity is dependent on the width of panel and thickness of Al-foil. To reduce the edge conduction, it is recommended that the VIP should be made as big as possible or made of thin Al film envelope.

***Keywords*—**Envelope, Edge conduction, Thermal conductivity, Vacuum insulation panel.

I. Introduction

RECENTLY, energy shortage is a serious problem as the worldwide energy consumption is increased. Improvement of energy efficiency is a good remedy to overcome this energy crisis. Especially, it is important to reduce heat loss from buildings. This is because about 40% of worldwide energy is consumed by the building sector and the half of the building energy is used for space heating and cooling [1]. Vacuum insulation panel (VIP) is an outstanding thermal insulator to decrease the heat loss. It has very low thermal conductivity of about 2~4mW/m·K. This is approximately 1/10 compared with conventional insulators such as polyurethane foam and glass wool [2].

VIP is generally composed of an evacuated filler material, a getter and an envelope (Fig. 1). The filler material has to sustain the external atmospheric pressure. Glass wool and fumed silica are widely used as the filler material. The envelope maintains inner vacuum level by covering the filler material. It has multi-layered structure of polymers and aluminum. The aluminum layer blocks out gas permeation from the ambient thanks to its low gas permeability.

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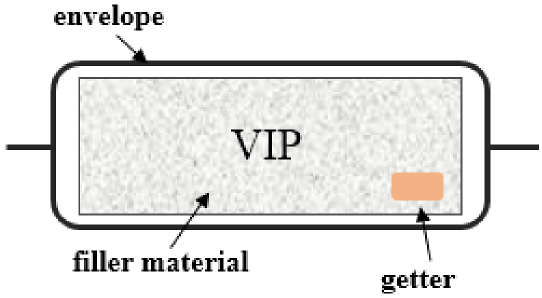

Fig. 1 Basic structure of the VIP

Heat transfer in the VIP mainly occurs in the filler material and the envelope. For the filler material, heat is transferred by solid conduction, residual gas conduction and radiation. These heat transfer modes are denoted by the conductivities k_s, k_g and k_r, respectively. There are theoretical models to investigate k_s [2], k_g [3] and k_r [4]. The residual gas conductivity k_g is negligible for perfectly evacuated filler material. For the glass wool and fumed silica in the vacuum state, the sum of k_s and k_r is about 2 and 4 mW/m·K, respectively. In the envelope, heat is transferred through the Al-foil layer with the thermal conductivity of about 200 W/m·K. Although the thickness of the Al-foil is small, the thermal conductivity is significantly higher than that of the filler material. As the net effect, the heat through the envelope is not negligible. It is called edge conduction [5]. The thermal conductivity commonly used to evaluate the insulation performance of VIP is only measured for the filler material but the edge conduction also has to be considered for practical applications. The total effective thermal conductivity of VIP can be expressed as

$$k_{eff} = k_{fm}(k_s + k_g + k_r) + k_{edge}, \quad (1)$$

where k_{edge} is edge conductivity and k_{fm} is conductivity of filler material.

In this study, the edge conduction is investigated by numerical and theoretical analyses. Also, it is measured using the vacuum guarded hot plate. By comparing with the numerical and the experimental results, the experiments are validated.

II. Analysis

A. Envelopes

There are two types of envelopes depending on whether it includes an Al-foil or an Al-metallized film [6]. Because the Al foil is thicker compared with the Al-metallized film, the Al-foil envelope is advantageous for the service life of VIP. On the other hand, it has the larger edge conduction compared with Al-metallized envelope.

The cross section of the Al-foil envelope is examined using a scanning electron microscope (SEM). To obtain the clean cross section, the envelope is cooled and cut in liquid nitrogen. As shown Fig. 2, the envelope is multilayered with linear low-density polyethylene (LLDPE), low-density polyethylene (LDPE), polyethylene terephthalate (PET) and Al-foil. The thickness of the Al-foil is about 6 μm.

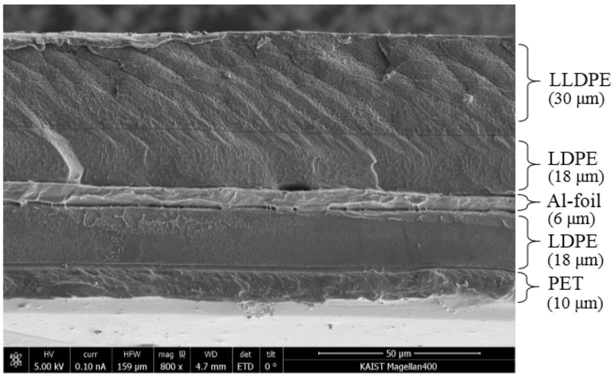

Fig. 2 SEM micrograph of the cross-section of Al-foil envelope

B. Numerical Analysis

Numerical analysis is performed by control volume method. The two dimensional steady state heat conduction equation is discretized for each control volume and the discretized equations are solved by the tri-diagonal matrix algorithm.

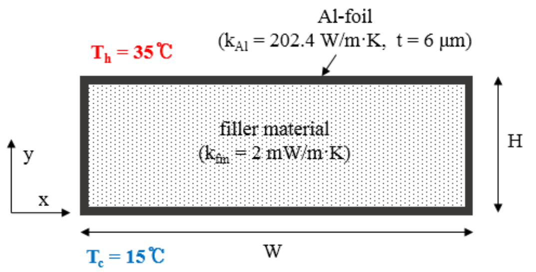

Fig. 3 Idealized two-dimensional geometry for numerical analysis

The numerical model of a VIP is shown in Fig. 3. Although the envelope is made of polymers and Al-foil, it is treated as a pure Al-foil with a thermal conductivity of 202.4 W/m·K. The filler material is taken as a glass wool with thermal conductivity of 2 mW/m·K. Heat-sealed flanges at sides of VIP and the getter in the filler material are not considered. Both sides of VIP are insulated and the upper and lower walls have constant temperatures.

C. Temperature and Heat Flux Distribution of VIP

Fig. 4 shows the temperature distribution at the left corner of VIP with size of 30 cm×1 cm (W×H). The overall temperature distribution is similar to that of one-dimensional heat conduction. Although the filer material is enclosed with the envelope, there is little heat conduction along the x-direction at the top and bottom envelopes.

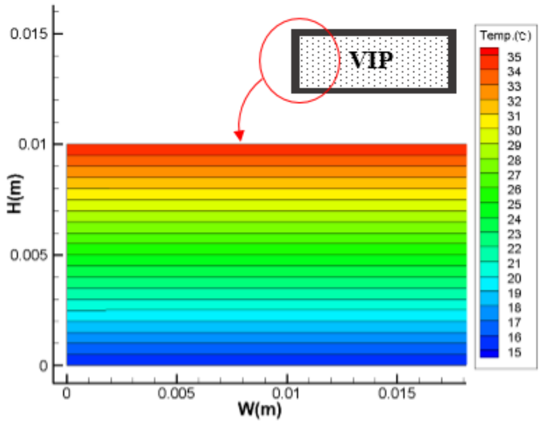

Fig. 4 Temperature distribution at the left corner of VIP

This is also confirmed by the heat flux distribution on the VIP. Heat flux distribution at the left corner of the VIP is shown in Fig. 5 (a). For the envelope with 6 μm Al-foil, the heat flux at the envelope is significantly larger than that at the center of panel. Also, the effect of the envelope and filler material on the heat flux is almost independent. In other words, the heat flux distribution of VIP indicates one-dimensional behavior as in the temperature distribution. If the Al-foils of top and bottom walls are thick enough to spread heat along the horizontal plane of VIP, a two-dimensional heat conduction appears as shown in Fig. 5 (b)

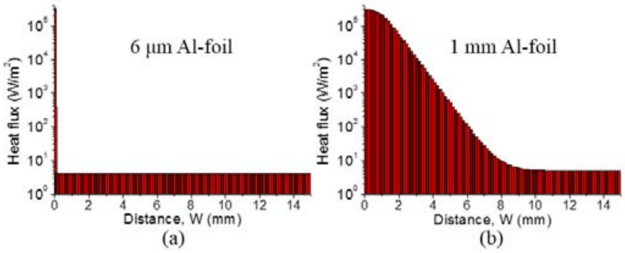

Fig. 5 Heat flux distribution at the left corner of VIP with (a) 6 μm Al-foil (b) 1 mm Al-foil

D. Analytical Model

The actual thickness of the Al-foil is too small to spread the heat along the top and bottom surfaces. Therefore, the heat transfer mode of VIP can be regarded as one-dimensional heat conduction (Figs. 4, 5). For this reason, the effective thermal conductivity of the VIP can be obtained using the electrical resistance analogy. The thermal resistances of Al-foil at the two sides and at the filler material act in parallel whereas those of Al-foils at top and bottom surfaces are negligible. Consequently, the effective thermal resistance R_{eff} can be expressed as

$$\frac{1}{R_{eff}} = \frac{1}{R_{fm}} + \frac{1}{R_{Al}}, \tag{2}$$

where R_{fm} and R_{Al} are the thermal resistances of filler material and Al-foil, respectively. They are;

$$R_{eff} = \frac{k_{eff} W^2}{H},\ R_{fm} = \frac{k_{fm} W^2}{H},\ R_{Al} = \frac{2k_{Al} t_{Al} W}{H}, \tag{3}$$

where k_{eff}, k_{fm} and k_{Al} are the effective thermal conductivity, thermal conductivities of filler material and Al-foil, respectively. Thickness t_{Al} is that of Al-foil, W is the width of VIP and H is the height of VIP.
Substituting (3) into (2) yields

$$k_{eff} = k_{fm} + \frac{2k_{Al} t_{Al}}{W}. \tag{4}$$

Therefore, the edge conductivity k_{edge} is given as

$$k_{edge} = k_{eff} - k_{fm} = \frac{2k_{Al} t_{Al}}{W}. \tag{5}$$

III. Experiments

A. Vacuum Guarded Hot Plate

A vacuum guarded hot plate (VGHP) is developed from guarded hot plate (GHP). It consists of the GHP part [7] to measure the thermal conductivity, pressing load exerting components and vacuum components to control the inner pressure. Therefore, VGHP can measure the thermal conductivity in various ambient pressure and external compression load [8].

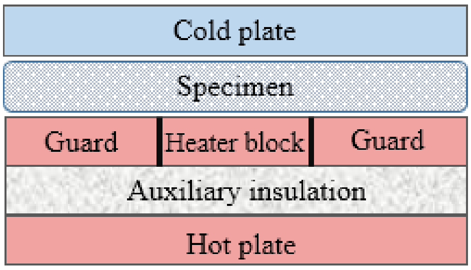

Fig. 6 Schematic diagram of GHP mounted in VGHP

The GHP part is composed of a cold plate, a hot plate, a heater block, a guard and an auxiliary insulator (Fig. 6). The heater block made of pure copper with size of 150×150×50 mm^3 is placed at the center. In this block, an electric heater is inserted and controlled by a power supply. The guard, cold plate and hot plate are maintained at constant temperatures by two water circulators. When the specimen is sandwiched between cold plate and heater block, the electric power of the heater is adjusted until the temperature of the heater is equal to the guard and hot plate temperatures. If these temperatures are exactly same with each other, the generated heat from the heater block flows vertically to the cold plate via the specimen. Then, the thermal conductivity of the specimen k_s can be obtained as

$$k_s = \frac{q_{heater} H}{A_{meas} \Delta T}, \tag{6}$$

where q_{heater} is the generated heat, H is the height of the specimen, A_{meas} is the measuring area and ΔT is the temperature difference between the upper and the lower surfaces of the specimen. A standard reference material (SRM) is used to validate the apparatus. The maximum relative error between measurements and references is estimated to be 2.6% and the average is 1.5%.

B. Specimen

VIP is generally placed at the center of the measuring part during the measurement. Therefore, the measured value is very close to the thermal conductivity at the center of panel.

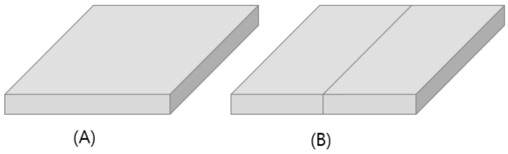

Fig. 7 VIP specimens to measure the edge conductivity
(a) 300×300×10mm^3, (b) 300×150×10mm^3, 2EA

Two types of samples are fabricated to measure the edge conductivity. Fig. 7 (a) shows the general VIP specimen which has a dimension 300×300×10 mm^3. In that case, the measured thermal conductivity is equal to the k_{fm} of (5). Fig. 7 (b) shows the shape of a new specimen. It is composed of two VIPs which have half size of the former. These VIPs are located side by side. Thus, the two edges of VIPs are placed on the center of measuring area. The measured thermal conductivity of it is equal to the k_{eff} of (5). Thus, the difference between the k_{eff} and k_{fm} is equal to k_{edge}.

TABLE I
Edge Conductivities from Numerical/Theoretical Analysis and Experiments

	k_{fm} (mW/mK)	k_{eff} (mW/mK)	k_{edge} (mW/mK)
VGHP	1.82	18.26	16.44
Numerical analysis	2.0	18.194	16.194
Theoretical model	2.0	18.192	16.192

IV. Results and Discussion

The edge conductivity of VIP with Al-foil envelope is obtained in various ways: numerical analysis, theoretical model and experiments (Table I). Note that the measuring area is not the surface area of VIP but the surface area of the heater block. Therefore, the widths of VIP in numerical analysis and theoretical model of (5) have to be that of the heater block to compare with results from experiments. The thermal conductivity of filler material measured for Fig. 7 (a) is 1.82 mW/mK and that for Fig. 7 (b) is 18.26 mW/mK. So, the edge conductivity is equal to 16.44 mW/mK. The error between the experiments and numerical analysis is 1.5%. Therefore, the measurement method using VGHP for edge conductivity is found to be valid. Also, the results from theoretical and numerical analyses agree well with each other.

An actual VIP has four sides. Thus, the theoretical model of edge conductivity has to be modified as

$$k_{edge} = \frac{4k_{Al}t_{Al}}{W}. \tag{7}$$

The edge conductivity obtained by (7) is 16.19 mW/m·K for the VIP of 300×300×10 mm^3. This is much larger than that of the filler material. For this reason, even if we replace the conventional insulators with VIP in the buildings, improvement of insulation performance is marginal. This shows the importance of the edge conduction for practical VIP application.

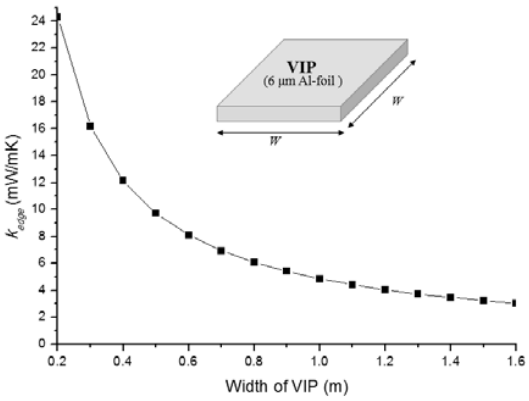

Fig. 8 Edge conductivity depending on the width of VIP

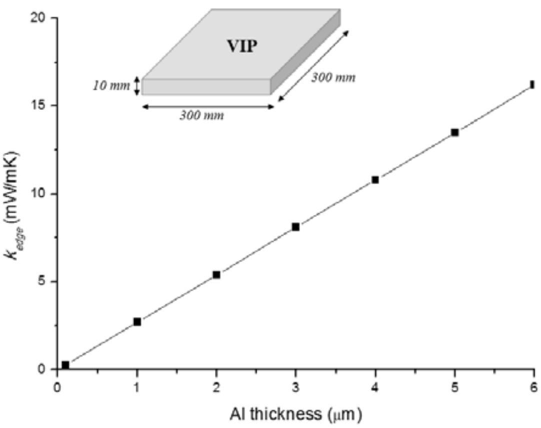

Fig. 9 Edge conductivity depending on the thickness of Al layer

If the width of VIP is extended, the edge conductivity can be reduced as shown in Fig. 8. For example, the edge conductivity of VIP with size of 1x1x0.01 m^3 is as small as 4.85 mW/m·K.

Also, it is desirable to use the envelope with thin Al film because the edge conduction is proportional to the thickness of the Al film (Fig. 9). For example, an Al-metallized envelope can have three aluminum laminated layers with 300 nm thickness each. On the other hand, however, the lifetime of VIP can be worse due to the increase of permeability of the envelope through the pin-hole.

V. Conclusion

Edge conduction of VIP is investigated numerically, theoretically and experimentally. From the numerical results, it is found that the heat transfer mode of VIP can be regarded as one-dimensional heat conduction. Therefore, the theoretical model using the electrical resistance analogy is proposed for the edge conductivity. The results from numerical analysis and theoretical model agree well with each other. Also, the experiment method to measure the edge conductivity is validated. The error between the experiments and numerical analysis is within 1.5%.

From the results, it is confirm that the amount of the edge conductivity to the total effective thermal conductivity is significant. To enhance the insulation performance, therefore, the edge conductivity has to be reduced. To do this, the VIP should be made as big as possible. Also, it is better to use envelopes with thin Al-foil such as Al metallized film.

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