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Investigation of Long-Term Thermal Insulation Performance of Vacuum Insulation Panels with Various Enveloping Methods

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Abstract**—**To practically apply vacuum insulation panels (VIPs) to buildings or home appliances, VIPs have demanded long-term lifespan with outstanding insulation performance. Service lives of VIPs enveloped with Al-foil and three-layer Al-metallized envelope are calculated. For Al-foil envelope, the service life is longer but edge conduction is too large compared with the Al-metallized envelope. To increase service life even more, the proposed double enveloping method and metal-barrier-added enveloping method are further analyzed. The service lives of the VIP to employ two enveloping methods are calculated. Also, pressure increase and thermal insulation performance characteristics are investigated. For the metal-barrier-added enveloping method, effective thermal conductivity increase with time is close to that of Al-foil envelope, especially, for getter-inserted VIPs. For double enveloping method, if water vapor is perfectly adsorbed, the effect of service life enhancement becomes much greater. From these methods, the VIP can be guaranteed for service life of more than 20 years.

Keywords**—**Vacuum insulation panels, Service life, Double enveloping, Metal-barrier-added enveloping, Edge conduction.

I. Introduction

GLOBAL energy consumption is growing every year with the increase of CO_2 emission. However, the amount of available energy is not sufficient. Thus, to resolve the two issues at once, energy conservation is an indispensable solution. Heating, ventilating and air conditioning of buildings (HVAC) are the largest part of worldwide energy consumption. It accounts for more than 40% of the total consumption and correspondingly CO_2 emission [1]. If thermal insulation in buildings is improved two times better, it contributes more than anything else. Accordingly, application of super insulations is the critical factor. Most insulation materials were developed using air-containing pore structures in the early 20th century. Their thermal conductivities are stagnant almost for a century at the level of 30 mW/m·K, i.e., that of air. The vacuum insulation panel (VIP) to eliminate air inside pore is an ideal insulation tool. Thermal resistance of a VIP is about 5 to 10 times greater than that of conventional insulation material such as EPS (expanded polystyrene), PU (polyurethane), and glass wool [2]. Also, the VIP is extensively applied to not only buildings but also refrigerators, LNG ships and low temperature storage tanks to improve energy efficiency [3].

The VIP consists of core structure, envelope and a getter or desiccant as shown Fig. 1. Core structure is needed to withstand the atmospheric pressure. Envelope is a gas-tight barrier to maintain the inside vacuum level. Getters or desiccants are added to chemically adsorb residual gases and water vapor in the VIP. Inner pressure of the VIP is maintained at the initial vacuum level until the sorption capacity of getters and desiccants is exhausted.

The heat transport in the VIP is classified into three mechanisms as the following [4], [5]: solid conduction, gas conduction, radiative conduction. The total transport q_{eff} can be indicated as,

$$q_{eff} = q_s + q_g + q_r , \quad (1)$$

where q_s , q_g and q_r are heat transfer rates by solid conduction, gas conduction and radiative conduction, respectively. Thus, the effective thermal conductivity k_{eff} is determined by linear superposition of the solid, gas and radiative conductivities, i.e., k_s , k_g and k_r , respectively [6]. Among these, Gas conduction is made by the permeated gas inside a VIP. To have long service life, gas permeation should be minimized.

Typically, the service life of the VIP must be guaranteed for 10 to 15 years for home appliances or more than 50 years for buildings. In this paper, service life of the several types of VIP is estimated and characteristics of two enveloping methods to extend service life of the VIP are further investigated.

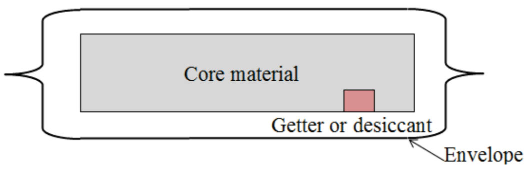

Fig. 1 General structure of the VIP

II. Long-Term Thermal Insulation Performance of a VIP

A. Theoretical Background

Gas conduction in rarefied regime is derived by Kwon et al.

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as follows [7]

$$k_g = \frac{k_{g0}}{1 + \frac{0.032}{P\phi}} \tag{2}$$

where k_{g0} is the thermal conductivity of the gas in the continuum state, P is the inner pressure in Pa (N/m^2) and ϕ is the pore size (m) of the core material. Equation (2) means that gas conduction is a function of pore size and inner pressure. When the core material has larger pore size, a slight increase in the pressure causes large increase in k_g. The most commonly used core materials are fumed silica in Europe and glass wool in Asia. Because fumed silica has pore size of about 10 to 100 nm and glass wool has relatively large pore size which ranges from a few micrometers to a few tens of micrometers, glass wool-based VIP must be protected from pressure increase.

Vacuum in a VIP is deteriorated with time mainly due to gas permeation through the envelope. This permeation can be classified into two: the normal direction gas permeation and the lateral one depending on the path as shown in Fig. 2. Normal direction gas permeation is made through envelope surface. Gas permeation in the lateral direction occurs since the polymer side cut of the heat-sealed flange is exposed to atmospheric pressure. The greatest factor for these processes is gas permeability. From fick's first law, the gas permeation rate Q through polymer film is expressed as follows

$$Q = K\frac{A_s}{\delta}\left(P_H - P_L\right) \tag{3}$$

where K is the permeability, P_H and P_L are the gas pressure at high pressure side and at low pressure side, respectively, and A_s is the cross-sectional area of the film and δ is the permeation length The units of Q and K are taken as the volumetric gas flow rate at STP (298.15 K, 101.3 kPa). Assuming ideal gas behavior, (3) is modified as

$$\frac{dP_L}{dt} = \frac{K}{C_0}\frac{A_s}{\delta}\frac{R_u T}{V}\left(P_H - P_L\right) \tag{4}$$

where $\frac{dP_L}{dt}$ is pressure increase rate, C_0 is mole-to-volume conversion factor at STP, V is the volume, and R_u and T are the universal gas constant and the absolute temperature, respectively. Applying (4) to the practical VIP for gas species i, it is re-written as follows:

$$\frac{dP_{i,in,VIP}(t)}{dt} + \left(C_{i,n} + C_{i,l}\right)\cdot P_{i,in,VIP}(t) = \left(C_{i,n} + C_{i,l}\right)\cdot P_{i,atm,VIP} \tag{5}$$

$$C_{i,n} = \frac{K_{i,n}}{C_0}\frac{A_n}{\delta_n}\frac{R_u T}{V}, \quad C_l = \frac{K_{i,l}}{C_0}\frac{A_l}{\delta_l}\frac{R_u T}{V},$$

where $P_{i,in,VIP}(t)$ is the partial pressure in VIP, $K_{i,n}$, A_n and δ_n is gas permeability, permeation area and permeation length for normal direction of envelope, respectively, and $K_{i,l}$, A_l and δ_l is gas permeability, permeation area and permeation length for lateral direction of envelope, respectively.

The partial pressure with time t for gas species i in the VIP can be expressed by solving (5) as,

$$P_{i,in,VIP}(t) = P_{i,atm,VIP}\cdot\left[1 - \exp\left\{-\left(C_{i,n} + C_{i,l}\right)\cdot t\right\}\right] \tag{6}$$

The total pressure $P_{in,VIP}(t)$ in the VIP can be estimated by summation of the partial pressures for separate gas species for each permeation direction as

$$P_{in,VIP}(t) = \sum_{i}^{gases} P_{i,in,VIP}(t). \tag{7}$$

when $P_{in,VIP}(t)$ is equated to a pre-defined critical pressure P_{cr}, the service life is determined. Here, N_2, O_2, CO_2 and H_2O which accounts for large portion in the atmosphere are considered.

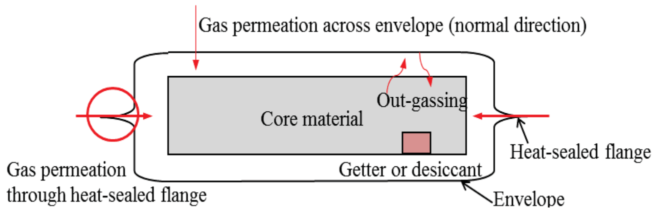


Fig. 2 Inner pressure increase factors

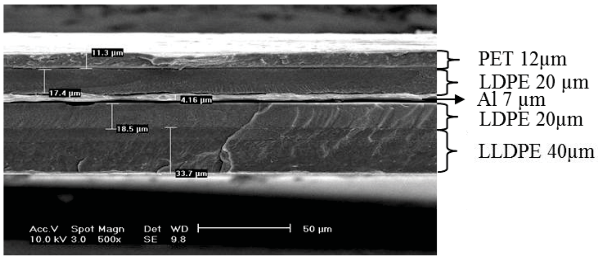
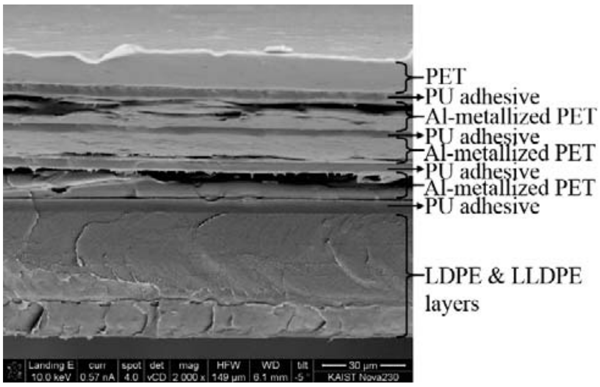
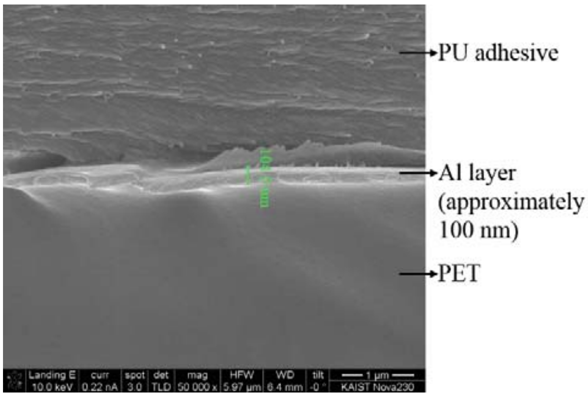


Fig. 3 SEM image of the cross-section of Al-foil envelope

From (5), it can be found that the pressure increase rate in the VIP is affected by volume, heat sealed length, permeation area and gas permeability. Therefore, the service life depends on the type of envelope and VIP shape. The VIP envelope is mostly composed of polyethylene terephthalate (PET) as the protective layer, Al-foil or Al-metallized PET layer as the gas barrier, and LLDPE and LDPE as the heat-seal layers as shown in Figs. 3 and 4, respectively [8], [9]. As mentioned earlier, because both of the service life and thermal performance is closely related with the inner pressure of VIP, Al-layer, as a vacuum-seal metal barrier, is usually inserted in the envelope to protect it from water vapor and gas transmission [10]. Envelope is classified into two types: Al-foil envelope and Al-metallized envelope [11]. The Al-foil layer is usually 5 to 10 μm thick. And single to four Al-metallized layers of only 30 to 100 nm are used in the latter case. While Al-metallized envelope has a lot of pin-holes, it is known that there is no appreciable pin hole if Al-foil of thickness greater than about 10 μm is used [12], [13]. Therefore, Al-foil envelope is better than Al-metallized envelope in terms of gas barrier, though the contrary is true regarding the edge conduction.



(a) Three-layer Al-metallized envelope



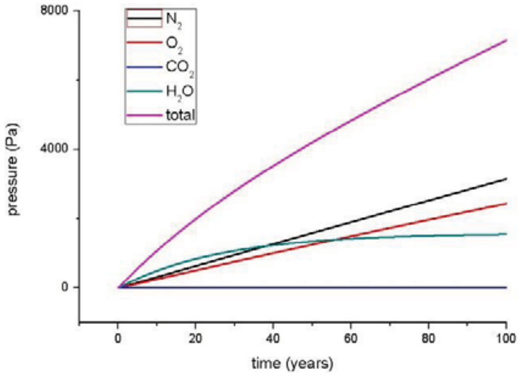
(b) Enlarged image of Al-metallized layer

Fig. 4 SEM image of the cross-section of Al-metallized envelope

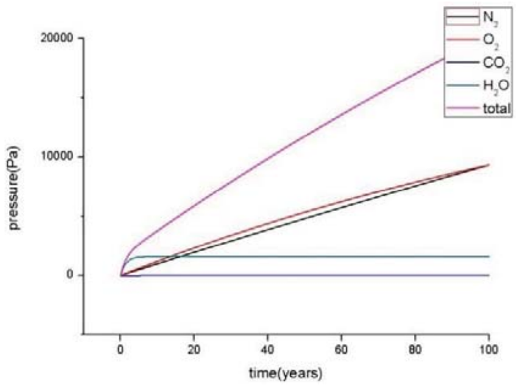
B. Service Life and Thermal Insulation Performance of Single Enveloped VIP

The service life for a 0.3 m x 0.3 m x 0.01m (heat sealed length δ_l =0.01m) VIP is calculated at 23°C and R.H. 50% assuming that it is packaged with Al-foil envelope and three-layer Al-metallized envelope, respectively. Also, It is assumed that glass wool (ϕ =15 μm, 30 μm and 50 μm) is used as core materials and pressure corresponding to 13 mW/m·K (about half of k_{eff} at atmospheric pressure) is the critical pressure.

Pressure increase with time for each case is shown in Fig. 5. Based on the calculated pressure increase with time and (2), effective thermal conductivity with time is described in Fig. 6. The service lives of VIP packaged with Al-foil and three-layer Al-metallized envelopes are indicated in Table I.



(a) Al-foil envelope



(b) Three-layer Al-metallized envelope

Fig. 5 Pressure increase with time of the single enveloped VIP

TABLE I
SERVICE LIFE OF THE SINGLE ENVELOPED VIP DEPENDING ON PORE SIZE

[years]	50 μm	30 μm	15 μm
Al-foil envelope	4.1	7.1	15.1
Three-layer Al-metallized envelope	0.4	0.7	1.8

It is found that when the pore size of core is small, the thermal conductivity remains low from Fig. 6. As shown in Fig. 5, gas permeation of water vapor is dominant initially. Because water vapor can be perfectly adsorbed using various desiccants or getters, it is calculated again assuming that water vapor is perfectly adsorbed. In this case, service lives are presented in Table II.

TABLE II
SERVICE LIFE WITH PERFECT H_2O-GETTER ENCLOSED WITH SINGLE ENVELOPE DEPENDING ON PORE SIZE

[years]	50 μm	30 μm	15 μm
Al-foil envelope	8.1	13.5	27.2
Three-layer Al-metallized envelope	2.1	3.5	7.1

When H_2O-desiccants are inserted, service life is significantly extended. In case of Al-foil based the VIP, the service life is longer compared with Al-metallized envelope based the VIP. While service lives of a VIP needed for home appliances and buildings are 10 to 20 years and 50 years, respectively, the calculated service lives are still short. Thus,

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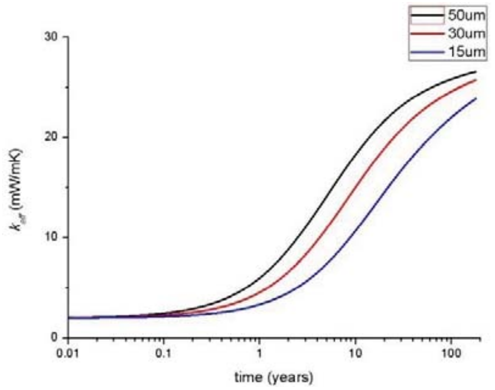
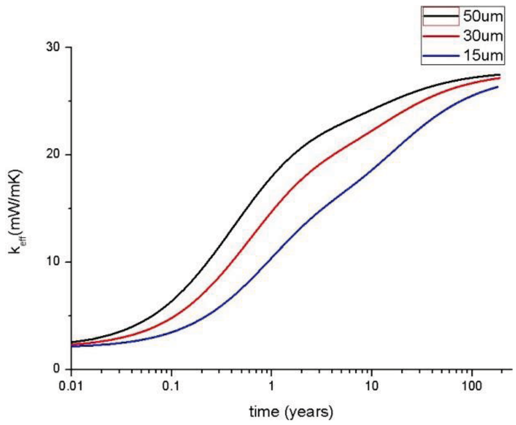
countermeasures are required to extend the service life of the VIP.



(a) Al-foil envelope



(b) Three-layer Al-metallized envelope

Fig. 6 Effective thermal conductivity with time of the single enveloped VIP depending on pore size

C. Methods to Enhance the Long-Term Thermal Insulation Performance

To minimize the edge conduction with assuring extended service life, the metal-barrier- added enveloping method and the double enveloping method is proposed [14]. In the first method (see Fig. 7), Al-foil films can be bonded on the outside of the VIP. Also, a stainless steel cover plate can be inserted to the inside of VIP. These can block normal direction gas permeation almost completely. Double enveloping is to package the conventional VIP with outer core material once more as shown in Fig. 8. Because it includes a buffer volume, it is helpful to reduce gas permeation into inner volume comparing with VIP enclosed with two envelopes without a buffer in between.

Effective thermal conductivity and pressure increase for two methods are calculated under the same conditions with single enveloping methods. In case of a double enveloping method, it is assumed that inner and outer volume are filled with glass wool (ϕ =15 µm, 30 µm and 50 µm).

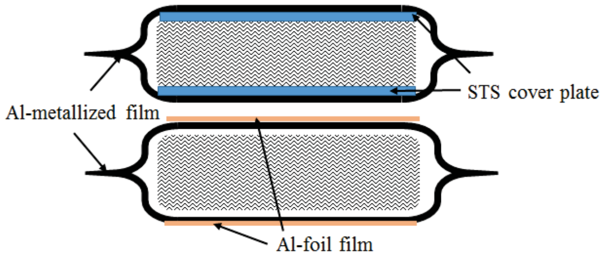


Fig. 7 Metal-barrier-added enveloping method

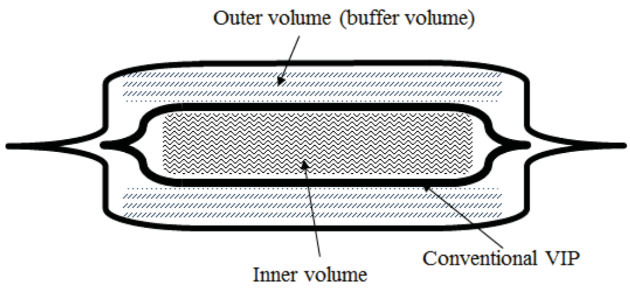
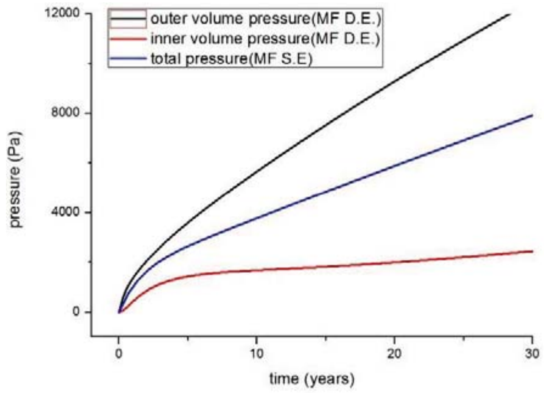
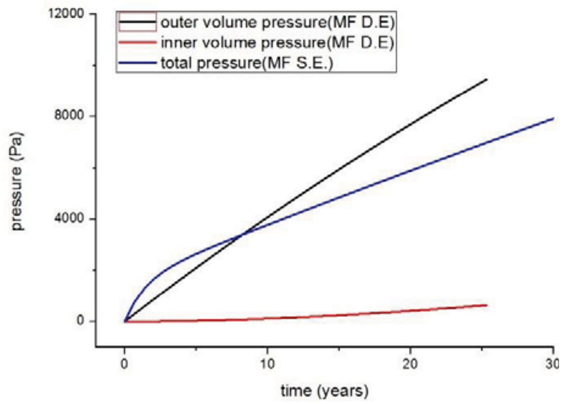


Fig. 8 Double enveloping method



(a) Ungettered VIP



(b) Getter-inserted VIP

Fig. 9 Pressure increase with time of ungettered VIP and getter-inserted VIP

For a double enveloping method, variations of inner volume pressure and outer volume pressure are shown in Fig. 9. Outer volume pressure is rapidly increased compared with a single enveloping method, whereas inner volume pressure is slowly increased. Thus, although thermal conductivity of outer volume is slightly high, it can be compensated because thermal conductivity of inner volume is fairly low. When water vapor is perfectly removed by getters or desiccants, the inner volume and outer volume pressures are lower than those of ungettered VIP. Since, for ungettered VIP, outer volume pressure in the initial stages of VIP is dramatically increased by water vapor, double enveloping is less effective. As shown in Fig. 9, inner volume pressure increase in getter-inserted VIP is little.

For metal-barrier-added enveloping method, thermal conductivity with time is close to Al foil envelope, especially, in case of getter-inserted VIP. For cases of various VIPs, service lives are summarized in Table III. Double enveloping VIP and metal-barrier-added enveloping VIP can have service life of maximum 22.1 years and 26.6 years, respectively. It is analytically proved that service life is improved using the two new enveloping methods.

TABLE III
SERVICE LIFE OF DOUBLE ENVELOPING VIP AND METAL-BARRIER-ADDED ENVELOPING

[years]		50 μm	30 μm	15 μm
Double enveloping VIP	ungettered	0.7	1.1	2.7
	getter-inserted	10.4	14.2	22.1
Metal-barrier-added enveloping VIP	ungettered	2.3	5.0	11.3
	getter-inserted	6.9	13.3	26.6
Al-foil based VIP	ungettered	4.1	7.1	15.1
	getter-inserted	8.1	13.5	27.2
Al-metallized film based VIP	ungettered	0.4	0.7	1.8
	getter-inserted	2.1	3.5	7.1

III. CONCLUSION

In this paper, VIPs with various enveloping method are investigated. At first, the VIPs enveloped with Al-foil film or three-layer Al-metallized film is studied. For three-layer Al-metallized envelope, it has very short service life. For Al-foil envelope, it has relatively long service life at the expense of increased edge conduction. As new methods to reduce pressure increase, metal-barrier added enveloping method and double enveloping method are analyzed. For the first, gas barrier characteristics are roughly similar to case of Al-foil enveloping. For a double enveloping method, gas permeation into inner volume is delayed because pressure difference between inner and outer volume pressure is small. When water vapor in the VIP is totally absorbed by a getter, the delay effect is maximized. The VIPs to employ these two enveloping methods can guarantee more than 20 years of service life.

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