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Prediction of the long-term performance of vacuum insulation panel installed in real building environments

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ABSTRACT

Vacuum insulation panels (VIPs) are high-performance insulating materials constructed by covering a core and adsorbent with an envelope and evacuating the air from the inside. VIPs have used to enhance the energy efficiency of devices including refrigerators, vending machines, and cooler boxes. In order to apply VIPs as heat-insulation materials in buildings and houses, it is necessary to predict the long-term performance of the VIPs and verify the accuracy of the prediction using actual measurements. VIPs using glass fiber as a core material are spreading in Japan, and VIPs using glass fiber core material as the core is also likely to be the mainstream in building applications. Therefore, in this paper, we report the comparison of the measurement results of the long-term performance in the building environment of VIPs using glass fiber and the calculation result. We also describe the calculation method of long-term performance prediction.

KEYWORDS

Vacuum insulation, Thermal conductivity, Long-term performance,

1. Introduction

Vacuum insulation panels (VIPs) are high-performance insulating materials constructed by covering a core and adsorbent with an envelope and evacuating the air from the inside. The VIP core is composed of glass fiber core or fumed silica core and covered by a laminated film. Upon evacuating the air from the VIPs, the gas thermal conductivity can be reduced to near zero, resulting in good thermal performance. Because it has high insulation performance, it is expected to be able to reduce wall thickness and enhance energy-saving when used for building applications. However, in many studies, long-term performance of VIPs under a constant environment had been discussed, but the long-term performance of VIPs itself in the building environment was not measured. Since there is no actual measurement data, accuracy of long-term performance prediction in the building environment cannot be confirmed. In addition, most of these studies are fumed silica core, and there are few studies on glass fiber core [1-6]. In order to solve this problem, we have been started to measure the thermal conductivity of VIPs that installed under the raised floor of a building. Glass fiber was used as the core material. VIPs was taken out from under the raised floor once every three months and measured the thermal conductivity by heat flow meter method. Furthermore, we measured the temperature and humidity of the front and back of VIPs, and examined the influence of environmental condition on long-term performance of VIPs.

2. Aging model[7-10]

The parallel model is widely used to predict thermal conductivity. Heat transfer in the core material can be expressed as the conduction through solid and through gas in case of its presence and radiation:

$$\lambda_{cop} = \lambda_s + \lambda_g + \lambda_{r,} \tag{1}$$

Where λ_{cop} is the thermal conductivity of the center of panel, $\lambda_s$is the thermal conductivity of the solid skeleton, λ_r is the radiative thermal conductivity, and λ_g is the thermal conductivity of the gas within the pores. The units for all variables are provided in the Symbols section at the end of the paper. The thermal conductivities of the solid and gaseous components of the VIP are affected by the internal pressure and adsorption of water vapor on the core material.

2.1. Thermal conductivity of the VIP with desiccant

The thermal conductivity of the VIP containing desiccant can be expressed as,

$$\lambda_{cop} = \lambda_{sr,ini} + \lambda_{g(P_a,T)} = \lambda_{sr,ini} + \lambda_{ga.} \tag{2}$$

2.2. Permeability of dry air

Based on the mass-balance equation for air permeation into the VIPs and the state equation of an ideal gas ($P_iV_{eff} = m_i/M_iRT$), the change in internal pressure resulting from the permeation of dry air can be expressed b

$$\frac{dm_a}{dt} = \frac{M_a \cdot V_{eff}}{R \cdot T} \cdot \frac{dP_a}{dt} = K_{a,total} \cdot (P_{a,atm} - P_a) \tag{3}$$

$$P_a = P_{a,atm} - (P_{a,atm} - P_{a(0)}) exp\left(-\frac{K_{a,total}RT}{M_aV_{eff}}t\right) \tag{4}$$

2.3. Relation of dry air pressure and thermal conductivity

Since the thermal conductivity of the VIPs relate to the internal pressure of VIPs, it can be expressed as follows using the Eq.(2)and (4).

$$\lambda_{cop} = \lambda_{sr,ini} + \lambda_g = \lambda_{sr,ini} + \frac{\lambda_{ga,0}}{1 + \frac{P_{1/2}}{P_a}} \tag{5}$$

$$\lambda_{cop} = \lambda_{sr,ini} + \frac{\lambda_{ga,0}}{1 + \frac{P_{1/2}}{P_{a0} + P'_{a,t} \cdot t}} \tag{6}$$

2.4. Thermal conductivity owing to difference in dimensions (metallized film)

Unlike the aluminum foil VIPs, considering the transmittance from the surface, the transmittance of the metallized VIPs is expressed as

$$K_{a,total} = K_{a,A} \cdot A + K_{a,L} \cdot L \tag{7}$$

From the time rate of the internal pressure, the relation of time rate of thermal conductivity can be obtained. Based on the measured value at a certain dimension, for asurface area A_{ref} and perimeter length L_{ref}, the change in internal pressure is expressed as

$$\frac{dP_{Aref,Lref}}{dt} \cong \left(P_{a,atm} - P_a(0)\right) \frac{K_{a,total(ref)}RT}{M_aV_{eff(ref)}} \tag{8}$$

$$\frac{dP_{A,L}}{dt} \cong \left(P_{a,atm} - P_a(0)\right) \frac{K_{a,total} \cdot L_{ref}RT}{M_aV_{eff(ref)}} \cdot \frac{V_{eff(ref)}}{V_{eff}} \cdot \frac{K_{a,total}}{K_{a,total(A_{ref},L_{ref})}}$$

$$= \frac{dP_{A_{ref},L_{ref}}}{dt} \cdot \frac{V_{eff(ref)}}{V_{eff}} \cdot \frac{K_{a,total}}{K_{a,total(A_{ref},L_{ref})}} \tag{9}$$

$$= \frac{dP_{A_{ref},L_{ref}}}{dt} \cdot \frac{V_{eff(ref)}}{V_{eff}} \cdot \frac{K_{a,total}}{K_{a,total(A_{ref},L_{ref})}} \tag{10}$$

2.5.Estimation of transmittance under different conditions (Arrhenius plot)

Supposing that the temperature and pressure of the environmental conditions to be found areT_{ex},P(T_{ex}), from Eq. (8), the gas permeability $K_{a,total}$ of dry air is as follows:

$$K_{a,total} = \frac{1}{(P_{a,atm} - p(0))} \cdot \frac{M_a V_{eff}}{RT_{ex}} \cdot \frac{dP(T_{ex})}{dt} \tag{11}$$

When calculating the time rate of internal pressure from the measurement result of the thermal conductivity, it is necessary to convert by the average temperature at the time of measuring the thermal conductivity and the pressure （λ_c, $P(T_c)$).

$$\mathrm{P(T_{ex})} = \frac{\mathrm{P(T_c)}}{\mathrm{T_c}} \mathrm{T_{ex}} \tag{12}$$

Substitute this equation into Eq.(11),

$$K_{a,total} = \frac{1}{(P_{a,atm} - p(0))} \cdot \frac{M_a V_{eff}}{RT_c} \cdot \frac{dP_a(T_c)}{dt} \tag{13}$$

3. Long term performance

In order to confirm the gas permeability (K_{air_total}) of the dependence of temperature and humidity, we carried out the aging test with thermostatic chamber. The Arrhenius plot was obtained based on Eq. (13). The details of the experimental VIPs are shown in Table 1. The Arrhenius plot does not consider the gas absorbed by the getter material.

3.1. Long-term performance in a thermostatic chamber

The VIPs was removed from the thermostatic chamber and cured at room temperature. The thermal conductivity was then measured using a heat flow meter (HC074 600, EKO instruments), and the results are shown in Fig. 3. The results of Arrhenius plot obtained from Eq.13 and experimental results are shown in Fig.4. The Arrhenius plot confirmed the temperature dependence of the VIPs air permeability under the tested aging conditions (23°C50% RH and 50°C). The comparison of the aging conditions of 50°C and 50°C with 70% RH confirmed that the gas permeability increased by approximately 6% shown in table2. The transmittance of dry air increased with relative humidity, which may be influenced by the material of the film. The metallized film is provided with a vapor deposited layer based on Ethylene vinyl alcohol (EVOH), probably because the barrier property of the EVOH layer decreased under high temperature and high humidity. When estimating the transmittance using Arrhenius plot, it is also necessary to consider film properties of EVOH.

Table 1. Details of the VIPs and aging condition

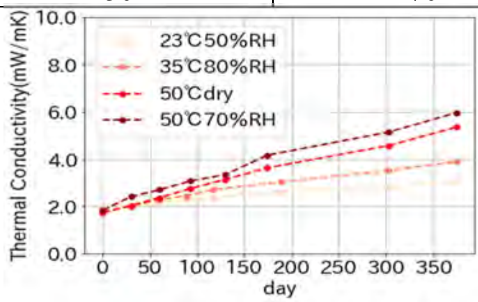
VIP Size	① t10 x 495 x 495 *[1]	
Core	Glass fiber	
Film	Hybrid Type*[2]	
Desiccant	Calcium Oxide 20g	
Getter	Zeolite type 5g	
Protection	Covered by polyvinyl chloride(PVC) 75μm film	
Aging condition	1) 23°C, 50% RH 2) 35°C, 80% RH 3) 50°C4) 50°C, 70% RH	

*[1]: The four corners of the VIP contain 90-mm cutouts

*[2]: One side is an aluminium foil film and the other side is a metallized film with EVOH

Table2. Overall air permeability (*Kair_total*) of the VIP aged under different conditions

Temperature (T; °C)	Relative Humidity (RH; %)	$1/T$	*Kair_total* ［×10–12g/day･Pa］
23	50	0.00337	14.3
35	80	0.00325	21.0
50	-	0.00309	35.8
50	70	0.00309	37.7



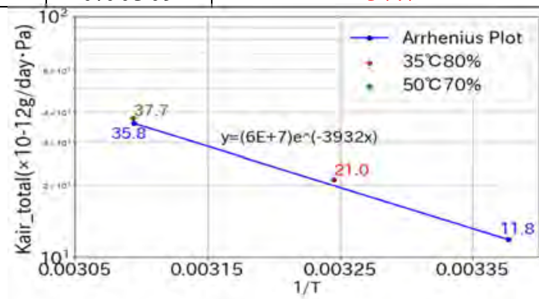


Fig.3: Long-term performance of the VIP under different static conditions
Fig.4: Arrhenius plot of the VIP

3.2. Long-term performance in a building condition

The VIPs were constructed on the concrete slab under the raised floor of a new building, the details of VIPs are shown in Table3. The VIPs were removed from under the floor every three months, and thermal conductivities were measured before reinstallation (Fig.5). The construction period and measurement period are shown in Table4. Thermo-hygrometers were installed on the front and back of each VIP to measure the temperature and humidity (Fig.7 and 8). Half of the VIPs installed in Room 2 (VIP01) was placed in the reverse of the front and back, and the effect of the orientation of the MF surface on the long-term VIPs performance was evaluated. First of all, we obtained the total gas permeability (K_{air_total}) based on the values of internal pressure which is calculated from measurement value of thermal conductivity. Secondly, Table5 shows a comparison of the internal pressure obtained from the time rate of thermal conductivity "ΔP_m" and the time rate of temperature data "ΔP_{cal}". ΔP_{cal} was obtained total gas transmittance on site conditions which is calculated from Arrhenius plot and average temperature every 2 hours. As the result of calculating the among ΔP_{cal} obtained using the temperatures on the upper and lower surfaces of the VIPs in the room2, the error from the measured value was smaller in the result calculated by referring to the temperature on the metallized film's side than the aluminum foil's side. This is attributed to the higher temperature dependence of the transmittance of dry air on the metallized film compared to that on the aluminum foil. However, the error of this result should also consider that the exposure environment during the measurement period is ambiguous. In order to prevent errors, for example, it can be solved if pressure of inside the VIPs can be directly measured at the real building environment.

Table3. Characteristics of VIPs used in the test of building condition

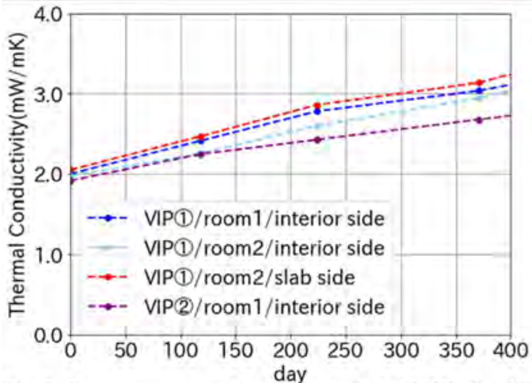
VIP Size	① t10 × 495 × 495 *1 in table1 ② t10 × 372 × 385 ③ t10 × 372 × 385		
Core	① Glass fiber 1 ② Glass fiber 2 ③ Glass fiber 1		
Film	Hybrid Type		
Desiccant	Calcium Oxide		
Getter	Zeolite type	VIP①	VIP②③
Protection	Covered by PVC 75-µm film		

Table4. Installation periods of the different VIPs used in the test of building condition

	Day installed	Day removed	Days after product was manufactured
VIP①	333	48	381
VIP②	331	58	389
VIP③	333	48	381

Table5. Comparison of measured and calculated values of internal pressure for each room

Place	Metallized film side	Reference temperature	Internal pressure (measured, ΔPm)		Internal pressure (calculated, ΔPcal)		Error (%)	
		day	244	381	244	381	244	381
Room1	Upside (interior side)	Upside	10.3	13.8	9.98	17.42	9.80	26.2
		Lower			9.94	17.16	9.70	24.4
Room2	Lower (slab side)	Upside	8.18	12.9	10.3	17.73	40.0	37.4
		Lower			8.73	15.98	11.5	23.9
Room2	Upside (interior side)	Upside	10.74	14.5	10.3	17.73	7.3	22.3
		Lower			8.73	15.98	-14.9	10.0



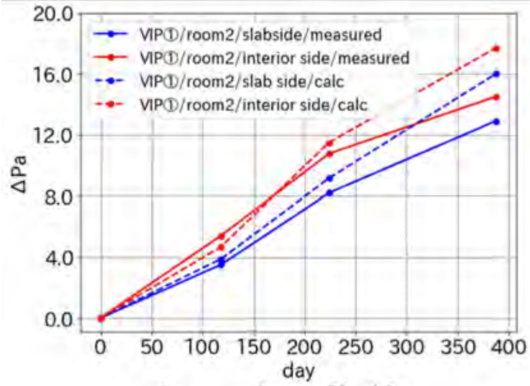
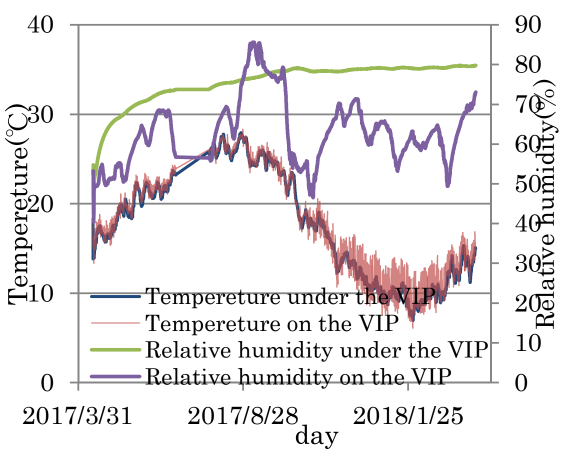


Fig.5. Long-term performance of the VIPs in different rooms and comparison of inside out
*VIP No/room No/Metallized film side
Fig.6. Comparison of measured value and calculated values of internal pressure (room2)
*VIP No/room No/Metallized film side/measured value or calculated value



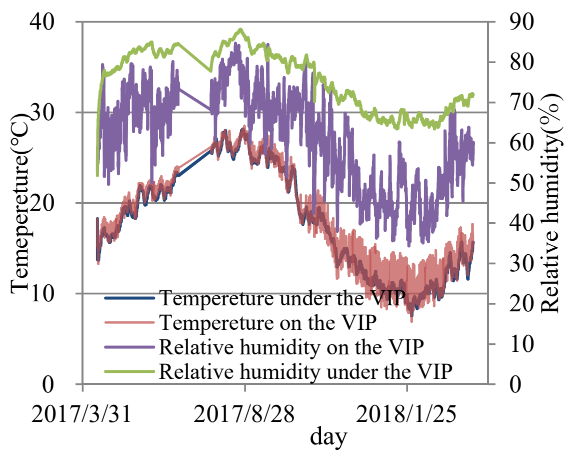


Fig.7. Temperature and relative humidity measured in room 1 on and under the VIPs
Fig.8. Temperature and relative humidity measured in room 2 on and under the VIPs

4. Summary

We constructed a VIPs under the raised floor of the building and periodically measured the thermal conductivity and the weight increase and the environmental conditions. We compared

the time change of internal pressure which was calculated by the relationship of thermal conductivity and internal pressure (Eq.6) using measurement result of thermal conductivity with calculated data which was obtained by temperature of environmental condition and Arrhenius plot (Eq.13). The results were roughly in agreement with the calculation results, but the prediction result of about 10% error as a whole at 227days increased further by 10% or more at 381 days (Fig.6). We consider the following three reasons why errors occurred.
(1) It is necessary to separate the gas permeation of surface and edge.
(2) Since the actual measurement range of Arrhenius plot is 23℃to50℃, it is necessary to confirm the accuracy at 23 ° C. or less.
(3)The influence of humidity in the actual measurement environment is expected to be low from the Arrhenius plot, but in order to make more accurate prediction it is necessary to consider the influence of humidity.

5. Future work

We will continue to measure and continue to verify whether long-term performance can be predicted from the measurement of environmental conditions. Meanwhile, we plan to develop a method that can be measured while it is being constructed on site. Specifically, we will consider improving the accuracy of prediction of durability by comparing it with the result of thermal conductivity measurement using VIPs equipped with micro pressure sensor. We will discuss the relation between external environment and internal pressure. And we will also study the influence of getter material, folded edges on gas permeability calculation, time rate of transmittance due to material deterioration, and another size of VIPs.

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Symbols λ_{cop}: thermal conductivity at the center of the panel [W/mK]; λ_{ini}: initial thermal conductivity[W/mK], λ_s: solid thermal conductivity [W/mK]; λ_g: gaseous thermal conductivity [W/mK]; λ_r: radiative thermal conductivity [W/mK]; M_i: Avogadro's constant [kg/mol]; V_{eff}: volume of VIP [m^3]; R: gas constant [J/Kmol]; K_i: mass transfer coefficient [g/h・Pa]; $P_{i,atm}$: partial pressure of gas under atmospheric pressure [Pa]; P_i: pressure inside the VIP [Pa]; P_{wv}: water vapor pressure inside the VIP [Pa]; $K_{i,total}$: overall transmittance ($i = a$, v) [g/day・Pa]; $K_{i,A}$: transmittance per unit area [g/m^2・day・Pa]; $K_{i,L}$: transmittance per unit length [g/L・day・Pa]; A: surface era of VIP [m^2], L: : circumference of VIP [m].