Aging Model by Permeation of Moist Air on Service Life of Vacuum Insulation Panels (VIPs) with Fibrous Glass Core

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Abstract

Thermal conductivity of vacuum insulation panels (VIPs) is lower than 2.0 mW/(m·K), about 1/10 of that of traditional thermal insulation materials. Nowadays, VIPs has been universally employed in some long-time applications, such as cold chain logistics and building skin insulation. The gas barrier envelopes play a vital role in maintaining the vacuum during the service life of the whole VIPs. In present paper, an aging model, employing the influence of moist air, has been developed to predict the long-term performance of VIPs. Three typical VIPs were produced with 3 different barrier envelopes, namely A, B and C. and 2 groups VIPs were put in 2 thermostat cases, which were maintained at 50 and 70°C respectively. The experiment lasted for a month to evaluate the reliability of aging model. Comparing the theoretical calculation with the experimental data, conclusion was made that, the variation trends of thermal conductivity were almost the same for 3 envelopes. The higher the temperature was, the faster the thermal conductivity increases. At 50°C, the initial thermal conductivity of A was the highest, and the thermal conductivity was increased by 0.00015 W·m⁻¹·K⁻¹ after a month in aging tests. The initial thermal conductivity of B was the lowest, but its permeability was high. The increment was 0.0003 W·m⁻¹·K⁻¹, which was about twice as much as A. The performance of C was moderate, but its performance was greatly compromised at 70°C. The results indicated that the long-term performance of VIPs with A at 50°C is superior to others.

Keywords: Vacuum insulation panels (VIPs); Service life; Barrier envelope; Thermal conductivity; Vacuum degree.

Received: 24 July 2020; Accepted: 03 September 2020.

Article type: Research article.

1. Introduction

The largest global problems and challenges on the 21st century are energy and environment.^[1] The development of renewable energy is urgent, and the priority should be given to the development of energy-saving and energy efficiency.^[2] It can be found that the optimum thickness of the insulation layer for the present conventional insulation materials always sacrifices the insulation effect to obtain the available volume.^[3]

Vacuum insulation panels (VIPs) whose thermal conductivity is about 1/10 of that of traditional thermal insulation materials, due to their super insulating capacity can offer larger place for the same inner volume of the box or building, thereby save cost by thinning thickness and enabling a larger volume. VIPs have been widely used in refrigerators, cold chain transport, vending machines and other need for thermal insulation occasions. It made by

covering the core and adsorbent with an envelope and vacuuming the inside (see Fig. 1). However, its uncertain service life is a defect. The most important features of evaluating service life of VIPs are the permeation of gases and water vapor through the barrier foil, and the response to the core material to these alterations.^[4] At present, accelerated aging is usually used to study the service life of VIP. Biswas *et al.*^[5] investigated thermal and aging characterization of stand-alone and foam-embedded VIPs by aging experiments under natural weatherization, room and accelerated aging conditions. Mao *et al.*^[6] established a theoretical model to predict the thermal conductivity of VIPs and experimentally validated it. Dublley, *et al.*^[7] put the VIPs in climatic chambers at 70 °C/90 % relative humidity (RH) and 50 °C/90 %RH up to 400 and 1000 days respectively and predicted the VIP durability from the degradation state of barrier envelope.

Although the accelerated aging experiment of the VIPs has been mainly researched, there are few studies on

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influence of barrier films by permeation of moist air. Schwab *et al.*^[8] developed a calculation model to predict the service life, which is defined as the period during which the thermal conductivity of the VIP has risen 50% due to the infusion of air and moisture. It shows that VIPs used in buildings are the most efficient only at right temperature and humidity. In order to take into account the panel aging, studies have recently been carried out. The paper introduces the principle of permeability of barrier film briefly and establishes an aging model of the VIPs. A horizontal comparison of three different barriers was made to investigate the effects of different film materials on service life of VIP. At the same time, vertical comparison method of the thermal conductivity in different VIPs after the accelerated aging experiment is applied, so as to determine the importance of gas barrier envelop materials to the service life of VIP and to verify our theoretical model. The model can be used to predict service life of VIP, so as to ensure its application scope and expected endurance. At the last, some advice is discussed to improve the thermal insulation performance and prolong service life.

Fig. 1 The structure of VIPs.

Fig. 2 Adsorption-diffusion-desorption mechanism for mass transfer.

2. Principle of permeability of barrier film

The insulating structure film is generally composed of three parts, namely: Protective Layer, Barrier Layer and Sealing

Layer. Different layers were glued together to suitable adhesive such as polyurethane (PU) adhesive.^[9] Metal film and metalized film are the most widely used insulating structures. The barrier of VIPs consists of different layers according to the type of the envelope, and the property of anti-gas-permeating is not the same.

In essence, the gasproof membrane of polymer material has certain permeability to gas. The membrane is still permeable though its barrier property is good and the permeability rate of small molecules is slow. This is because the insulating membrane is a polymer material, which mainly is formed by intervening polymer chains, and the molecular chains will perform thermal action constantly. As a result of thermal motion, the junctions fluctuate locally, creating a "free volume", in which there is a lot of space between or within the molecules.

All gases have the characteristic of diffusion from high concentration to low concentration. When there is a concentration difference between the two sides of the barrier membrane, the gas will diffuse from a gap on one side of the membrane to the other side for diffusion motion. Therefore, most studies believe that the gas permeation to the film is a unimolecular diffusion process, which belongs to the mass transfer process, following the gas separate-solid permeation process: adsorption-diffusion-desorption (see Fig.2):

- 1) The gas molecules are adsorbed on the surface of the membrane and then dissolved in it.
- 2) Then the gas molecules migrate and diffuse from the high concentration area to the low concentration area along the concentration gradient.
- 3) At last, the gas molecules reach the other side of the membrane and desorption stripping.

3. Establishment of mathematical model of service life

It's known that the thermal conductivity of VIPs is not invariable, but changes through time. The increase in the thermal conductivity is mainly due to the increase in the water vapor mass and the increase in the gas pressure. Water vapor permeation can increase the solid conduction of core materials and internal pressure of the VIPs, while air permeation contributes to internal pressure. An increase in internal pressure will lead to an increase in thermal conductivity from less than 1 mbar up to 100 mbar.^[10] This paper is devoted to establish a theoretical analysis model for the establishment of the service life model of the VIP plate. Assuming that the influences of the increase in water vapor content and the change of gas pressure on the thermal conductivity of VIP plate are independent of each other, the superposition calculation method can be used for the thermal conductivity of VIP plate:^[8]

$$\lambda(\tau) = \lambda_0 + \lambda_g(\tau) + \lambda_{wv}(\tau) \quad (1)$$

where $\lambda(\tau)$ is instantaneous thermal conductivity of VIPs, λ_0 is the original thermal conductivity of VIPs, $\lambda_g(\tau)$ is the

thermal conductivity of VIPs plate caused by dry air penetration increases and $\lambda_{wv}(\tau)$ is the thermal conductivity of VIPs plate caused by water vapor penetration increases, respectively.

3.1 Water vapor penetration

The water vapor permeation of VIPs is mainly determined by the hygroscopicity of the core materials of VIPs, ambient temperature and relative humidity. Under specific environmental conditions, the water vapor growth rate of VIPs can be obtained by measuring the mass m_{wv} increased by water vapor in a certain period of time:

$$\frac{dm_{mv}}{d\tau} = MVTR_A \times A_{VIP} + MVTR_C \times C_{VIP} = \Delta P_{mv} \times Q_{wv} \quad (2)$$

where m_{mv} is the increased mass of water vapor, τ is time. $MVTR_A$ is water vapor permeability on the surface of the VIP plate, $MVTR_C$ is water vapor permeability at the seal of the insulating structure film, A_{VIP} is VIP surface area, C_{VIP} is VIP perimeter. ΔP_{mv} is the differential pressure of steam inside and outside VIP plate and Q_{wv} is water vapor permeability per unit pressure difference.

The differential pressure (ΔP_{mv}) can be expressed as:

$$\Delta P_{mv} = (\varphi_{out} - \varphi_{in}) P_{mv, T_m} \quad (3)$$

K is defined as the adsorption coefficient, which represents the core material's ability to absorb water vapor. It has the following relationship to relative humidity:

$$X_{mv} = \frac{m_{mv}}{m_{VIP, dry}} = K \varphi_{in} \quad (4)$$

According to the above equation, the relation of X_{mv} with time can be described as:

$$X_{mv}(\tau) = K \varphi_{out} \left(1 - e^{-\frac{-(MVTR_A \cdot A_{VIP} + MVTR_C \cdot C_{VIP}) P_{mv, T_m} \tau}{K m_{VIP, dry}}} \right) \quad (5)$$

Because of the relationship between the thermal conductivity value of the VIP plate increased by water vapor penetration and X_{mv} , we can obtain:

$$\lambda_{mv}(\tau) = b X_{mv}(\tau) = K b \varphi_{out} \left(1 - e^{-\frac{-(MVTR_A \cdot A_{VIP} + MVTR_C \cdot C_{VIP}) P_{mv, T_m} \tau}{K m_{VIP, dry}}} \right) \quad (6)$$

where b in the formula is a known parameter, and it is measured experimentally. In this paper, $0.05 \text{ W} \cdot \text{m}^{-1} \text{K}^{-1}$ is taken.

3.2 Dry air penetration

The thermal conductivity increment of VIP caused by gas permeation follows the formula below:^[11]

$$\lambda_g = \frac{\lambda_{g,0}}{1 + 2\beta K_n} \quad (7)$$

β is a constant to characterize the efficiency energy transfer and its range is 1.5~2.0, 1.7 in this paper; K_n is the Knudsen number, which is the ratio of the average free path l_m of gas components to the characteristic size of pores δ under this pressure, as shown in the following equation:

$$K_n = \frac{l_m}{\delta} \quad (8)$$

And:^[12]

$$l_m = \frac{K_B T_m}{\sqrt{2\pi} d_g^2 P_g} \quad (9)$$

The gas pressure in the VIP plate is related to GTR, the permeability of the insulating structure film:

$$\frac{dp_g}{d\tau} = \frac{GTR_{tot}}{V_e} \cdot \frac{T_m}{T_0} (P_0 - P_g) \quad (10)$$

The total transmission rate GTR_{tot} is the sum of GTR_A (on the whole surface A) and an edges' contribution GTR_C (on the whole perimeter C) for each of these gases.^[13] When calculating air permeability to VIPs, only oxygen and nitrogen can be considered because two gases account for the majority of air. And nitrogen permeability is 1/5 of oxygen, so the value of GTR can be calculated from the oxygen permeability:

$$GTR_{tot} = GTR_A A_{VIP} + GTR_C C_{VIP} = \left(\frac{OTR_A + OTR_A}{5} \right) A_{VIP} + \left(\frac{OTR_C + OTR_C}{5} \right) C_{VIP} \quad (11)$$

By integrating Equation (10), we can obtain:

$$P_g(\tau) = P_0 - (P_0 - P_{in}) e^{-\frac{T_m GTR_{tot} (P_0 - P_{in}) \tau}{T_0 V_e}} \quad (12)$$

Combined with Equations (7), (8), (9) and (12), the increased thermal conductivity caused by gas permeability can be obtained by Equation (13):

$$\lambda_g(\tau) = \frac{\lambda_{g,0}}{1 + \frac{\sqrt{2\beta K_B T_m}}{\pi d_g^2 \delta \left[P_0 - (P_0 - P_{in}) e^{-\frac{T_m GTR_{tot} (P_0 - P_{in}) \tau}{T_0 V_e}} \right]}} \quad (13)$$

3.3 Thermal conductivity mathematical model of VIPs:

Based on the equations (1),(6),(13) can be obtain the thermal conductivity of VIPs change with time:

$$\lambda(\tau) = \lambda_0 + \frac{\lambda_{g,0}}{1 + \frac{\sqrt{2\beta K_B T_m}}{\pi d_g^2 \delta \left[P_0 - (P_0 - P_{in}) e^{-\frac{T_m GTR_{tot} (P_0 - P_{in}) \tau}{T_0 V_e}} \right]}} + K b \varphi_{at} \left(1 - e^{-\frac{-(MVTR_A \cdot A_{VIP} + MVTR_C \cdot C_{VIP}) P_{mv, T_m} \tau}{K m_{VIP, dry}}} \right) \quad (14)$$

The thermal conductivity of VIP is related to the performance parameters of the core materials and the external barrier film,

and the temperature and humidity of the environment where the VIP is located. In practice, the desiccant will be placed in the VIP plate according to the need, which has an impact on the change of water vapor content and pressure in the plate. The VIPs studied in this paper are the condition of not adding desiccant. The permeability of the structural membrane is studied without considering the inner material of the VIP plates and the isolation of the structural membrane itself. The service life of VIPs can be predicted according to Equation (14) and the following paper will verify the accuracy of the aging model through experiments.

4 Experiment

4.1 Experimental Materials

Fig. 3 Micro section of 3 kinds of barrier laminates.

To evaluate the importance of barrier film materials to internal pressure, VIPs used in this experiment are manufactured with barrier films produced by three different manufacturers, i.e., A, B and C. The parameters of the films are shown in Table 2 and SEM images of the cross section of the three research subjects are shown in Fig. 3. The standard ultrafine glass fibers serve as core materials (see Table 3).

The experimental samples were prepared with the same size of 300×300×8.5mm and the preparation process of all the samples is the same, including: cutting glass fiber mat into core material, drying in oven and putting in envelope, vacuum, and sealing.^[14]

Table 2. Parameters of the films.

	A	B	C	Testing standard
Material	PET12/NY1	NY15/PET1	NY15/HBV	—
Structure	5/AL7/PE50	2/AL7/PE50	EPET12/AL7/PE50	—
Thickness (μm)	93	100	95	—
Peel Strength ($\text{N}/15\text{mm}$)	greater than 7.8	greater than 8.5	greater than 4.5	—
MVTR_A ($\text{g m}^{-2}\text{d}^{-1}$)	0.02	0.03	0.012	ASTMF1249-90
MVTR_C ($\text{g m}^{-2}\text{d}^{-1}$)	0.012	0.02	0.008	ASTMF1249-90
OTR_A ($\text{cm}^3\text{m}^{-2}\text{d}^{-1}$)	0.0064	0.005	0.03	ASTMD398-5
OTR_C ($\text{cm}^3\text{m}^{-2}\text{d}^{-1}$)	0.002	0.003	0.02	ASTMD398-5
λ_0 ($\text{W m}^{-1}\text{K}^{-1}$)	0.071	0.04	0.068	GB/T10294-2008

Table 3. Parameters of glass fibers.

Ultrafine glass fibers	
Density (Kg m^{-3})	218
Porosity (%)	92
Fiber Diameter (μm)	7
Adsorption Capacity	0.0008

4.2 Experimental setup

The methods of penetration experiment are generally divided into direct method and indirect method. The principle of the direct method is to measure and calculate air permeability

after compensating the pressure difference between the inside and outside of VIPs until the balance is reached. Measuring air permeability is more complicated than measuring the permeability of water molecules. At present, Yrieix and Pons^[10] also came up with a way called "The cold lift-off method", which can directly measure the air pressure. Eddie and Yoash^[15] used Helium permeation to measure the thermal conductivity of FG panels exposed to He atmosphere, which can determine the air permeation rate in just twelve hours.

The indirect method is measuring weight increase of VIPs. In this paper, the indirect weight measurement method is adopted to calculate the water vapor permeability through the formula (15) and ignore the dry air permeability because the proportion of dry air is less than 2% in total weight increase of VIPs. The weight gain (Δm (kg)) is recorded every 7 days (Δt (s)).

$$\frac{dm_{wv}}{dt} = Q_{wv,tot} \cdot \Delta P_{mv} = WVTR_{tot} \quad (15)$$

In this study, twelve VIP plates made from three different films were produced. In other words, four plates were manufactured with each film.

The three kinds of samples were exposed to two different constant temperatures (i.e., 50, and 70°C) chamber, in which the relative humidity was ambient humidity for experiment. The model of thermostat used in this paper was FCD-3000 Serial 101-3A. The samples were taken out every seven days to measure the weight for penetration experiment and the thermal conductivity for aging experiment. The thermal conductivity of VIPs was measured by thermal conductivity tester called IMDRY3001-II. The measurement system was composed of hot plate, cold plate, guarded plate and thermostatic water bath according to GB/T10294-2008. The specimen was placed between hot plate and cold plate to be measured.

Table 4. Penetration experimental design.

No.	Serial number	Temperature(°C)
Experiment1	A1, A2	50
Experiment2	B1, B2	
Experiment3	C1, C2	
Experiment4	A3, A4	
Experiment5	B3, B4	70
Experiment6	C3, C4	

The penetration experimental design is shown in Table 4. Two of each same VIP board were put in the same test environment and the average weight of the two boards was used in this paper to ensure the accuracy of experimental data. The average value of mass change of A1 plate and A2 plate is defined as A11 plate, the average value of A3 plate and A4 plate is defined as A12 plate. In the same way, the mass change of plates of B film and C film at 50 and 70°C is defined as B11, C11, B12 and C12 plates respectively.

The aging experimental design is shown in Table 5. In this experiment, A50 and A70 respectively represent the thermal conductivity of VIP plate of A kinds of film aging in 50 °C and 70°C thermostats, while LA50 and LA70 represent the idealized thermal conductivity values of A film theoretically calculated from formula (14). B film and C film are the same expression as A.

Table 5. Aging experimental condition.

No.	Temperature(°C)	Barrier Film	Tag
Experiment1	50	A	A50
Experiment2	70	A	A70
Experiment3	50	B	B50
Experiment4	70	B	B70
Experiment5	50	C	C50
Experiment6	70	C	C70

5 Results and discussions

5.1 The permeance through gas barrier film

Table 6. Test results of weight measurement.

Serial number Days	0 day	7 days	14 days	21 days	28 days
A1	233.515	233.450	233.437	233.455	233.474
A2	232.468	232.413	232.370	232.389	232.409
A3	235.125	235.046	235.001	235.020	235.044
A4	234.768	234.694	234.655	234.675	234.698
B1	232.958	232.871	232.813	232.838	232.870
B2	235.089	235.013	234.951	234.980	235.012
B3	233.547	233.451	233.406	233.438	233.473
B4	235.017	234.941	234.892	234.923	234.955
C1	237.093	237.045	233.993	237.004	237.016
C2	234.038	233.990	233.951	233.960	233.973
C3	236.234	236.174	236.132	236.146	236.161
C4	236.630	236.589	236.557	236.572	236.591

Table 6 is the test results and Fig.4 is the variation law of mass change of A, B and C films with time at different temperatures. Although the size of each VIP board and the use of core material are the same, but its initial quality will be slightly different. Because it will be a slight difference in the cutting and quality of each film inevitably, this has little effect on the accuracy of the experiment.

Table 6 shows the weight measurement results of VIP panels. It can be seen that A, B and C barrier films all have similar changing laws with time: each membrane changes over time, losing mass first and then gaining weight whether at 50 or 70°C.

Fig. 4 shows the average mass increase with time for VIPs with different films. In the first 14 days, the quality of the film gradually decreases with time, and the mass

reduction is relatively large at the beginning, but it tends to decrease over time. This is because it is impossible to remove all the water vapor and gas inside the VIPs when making it, where some residual gas will remain even after the drying and vacuum-pumping. At the beginning of the experiment, part of the moisture contained in core materials will evaporate into gas due to the high temperature in the thermostat, which will permeate through the surface of the envelop, resulting in the mass reduction of the VIPs. The mass begins to increase gradually over time until the balance between inside and outside the plate is reached. In the early stage of the experiment, the quality of the VIP plate decreases, proving that most of the moisture evaporates from the plate. With the increase of time, during the period of 7 to 14 days, the absolute value of the quality change of the VIP plate is smaller than that of the 7 days before. In other words, after seven days of the experiment, the evaporation capacity of water gradually decreases inside the VIP plate, reaching the internal and external balance.

Fig. 4 Average mass increment of three films changing with time

After 14 days, the increment of mass increased with time, that is, $MVTR_{tot}$ increased with time. The longer the time, the greater the $MVTR_{tot}$, the faster its mass increases. The growth rate of different films at the same temperature is also different, which is related to the material and property. This is consistent with the results of experiment by Pons *et al.*^[16]

Moreover, the permeability rate of each film varies with the temperature. As can be seen from Fig. 4, the mass increase rate of each membrane is lower at 50°C than at 70°C, that is, the permeability of each film will increase with the increase of temperature.

The membrane permeability is measured by the quality change of VIPs. The lower the weight gain, the lower the permeance and therefore the better the barrier properties of the laminate as the VIP envelops. From Fig. 4, C film tops the list as the best barrier property film. Coming up behind C film is A film. B film ranks the third.

5.2 Estimate of service life for VIPs

After aging experiment for one month, the VIPs in this experiment had no wrinkles or other damage in its appearance, and no separation occurred in the heat-sealed part of the barrier structure film. Therefore, the VIP boards in the experiment meet the requirements. The following are the experimental results (Fig. 5, 6, 7).

Fig. 5 Thermal conductivity of VIP plate of film A changing with time.

Fig. 6 Thermal conductivity of VIP plate of film B changing with time.

Fig. 7 Thermal conductivity of VIP plate of film C changing with time

The data presented in Fig.5-7 clearly demonstrate that the thermal conductivity of every barrier film is known to increase over time. The increase rate of thermal conductivity of each film will vary due to its own permeability, and the thermal conductivity of VIPs of each kind of film increases differently at different temperatures. Figs 5-7 showed a small increase in all of the samples, and an abrupt change in slope occurred after about 21 days, corresponding to the results of the permeability test above.

The increase rate of thermal conductivity of VIPs used in three different films in 50°C thermostat was relatively lower than that in 70°C thermostat. We can obtain that at 50°C, the value increment of thermal conductivity of A, B and C is 2.2×10^{-4} , 3.7×10^{-4} and $1.6 \times 10^{-4} \text{ W} \cdot \text{m}^{-1} \text{K}^{-1}$, respectively. At 70°C, the value increment of thermal conductivity of A, B and C is 3×10^{-4} , 4.2×10^{-4} and $2.5 \times 10^{-4} \text{ W} \cdot \text{m}^{-1} \text{K}^{-1}$, respectively. The high temperature not only reduces the barrier film's barrier property, but also causes the collision frequency between gas molecules to increase and the diffusion speed to increase. All these will increase the penetration rate of water and gas molecules into the board, which will increase the thermal conductivity and reduce service life of VIPs. The impact of the temperature on the thermal insulation performance of VIPs has been clarified, proving that the higher the usage temperature of the VIP, the shorter its service life.

Fig. 5-7 show that the increasing trend of thermal conductivity with time agrees well with the experimental data and the theoretical calculated data. However, most of the ideal thermal conductivity for aging is smaller than experimental value at same aging temperature due to several reasons related to the mechanical damage in different degrees on VIPs and also due to the aging of the barrier films and core materials, which will accelerate the increase of thermal conductivity of the VIP plate. The development of barrier materials requires the development of sensitive permeation detection methods, which has the possibility to detect different defects and permeation moieties.^[17] It is noted that the relative humidity of the aging experiment in this paper is not constant, but depends on the environment. Therefore, it will also affect the experimental results.

5.3 Suggestions for selecting VIP panels

The thermal conductivity changes of VIPs with three kinds of film were measured. The experimental data is shown in Fig. 8. The performance of the VIP, and thus its durability, can be related to the resistance to the degradation of the first PET layer of the barrier envelope, because only the external PET layer is exposed to high humidity.^[16] Comparing the SEM images of A,B and C, it can be found that the biggest difference is that PET is placed in the outermost layer of A barrier, which makes the permeability of gas and water vapor low and has excellent water and gas resistance. This can prove that there is a good correlation between the material

and placement order of laminated plate and the change of permeability of laminated plate.

From Fig.8, though the initial thermal conductivity of A barrier is the highest, the permeability is relatively low and the thermal conductivity increases gently. The initial thermal conductivity of the B film is the lowest, but the mass increases is the fastest, that is, the permeability is very high, which may not guarantee its long-term performance. C film is not resistant to high temperature and the thermal conductivity growth rate is the highest at 70°C among the three, which is easy to fail. But it works better at 50°C. To keep high service life of VIPs, A film should be considered at first, using C film when temperature is not high. For short-term use, B film is preferred to minimize the thermal conductivity.

Fig. 8 Experimental thermal conductivity curves of three kinds of films over time

6. Conclusions

The gas permeation and moist air through envelope surface are investigated based on theoretical calculation and experiments. To estimate the service life of VIPs at different temperatures, the service life model is presented. The experimental results show that the thermal conductivity of VIPs will decrease faster and the service life will be shorter with the increase of temperature, which is consistent with the theoretical model established in this paper. The experimental model data established are smaller than the experimental data due to unavoidable reasons, but the average difference is less than $0.00006 \text{ W} \cdot \text{m}^{-1} \text{K}^{-1}$. Thanks to the model and the determined end service life, VIP durability can be determined for a variety of application environment conditions, especially in long-term architectural applications. It is recommended to adopt VIP with different barrier films according to different situations.

Acknowledgement

This research is a grants program supported by the National Natural Sciences Foundation of China (Project No. 51679107).The author extend cordial thanks to scientist Dr. Samuel Brunner for his assistance in the measurement of data.

The author thank to Qingdao Kerui New Environmental Materials Groups Co., Ltd. for the materials supply.

Supporting information

Not applicable

Conflict of interest

There are no conflicts to declare.

Nomenclature and units

Variables	Units
T	Temperature
T_0	The environment temperature
P_0	The environment pressure
P_g	pressure inside the VIPs
τ	Time
m	Mass
λ_0	The original thermal conductivity of VIPs
$\lambda(\tau)$	Instantaneous thermal conductivity of VIPs
$\lambda_g(\tau)$	The thermal conductivity of VIPs plate caused by dry air penetration increases
$\lambda_{wv}(\tau)$	The thermal conductivity of VIPs plate caused by water vapor penetration increases
$MVTR_A$	Water vapor permeability on the surface of the VIP plate
$MVTR_C$	Water vapor permeability at the seal of the insulating structure film
A_{VIP}	VIP surface area
C_{VIP}	VIP perimeter
ΔP_{mv}	Differential pressure of steam inside and outside VIP plate
Q_{wv}	Water vapor permeability per unit pressure difference
P_{mv, T_m}	The partial pressure of water vapor when the temperature in the VIP plate is T_m
ϕ_{in}	The relative humidity inside the VIPboard
ϕ_{out}	The relative humidity outside the VIP board
X_{mv}	Increased amount of water vapor as a percentage of the mass of the dry VIP plate
$m_{VIP, dry}$	Dry VIP board quantity
GTR	Permeability of the insulating membrane
OTR_A	Oxygen permeability on the surface of VIP plate
OTR_C	Oxygen permeability at VIP plate seal
V_e	Sum of stomatal volume of VIP board core material constant
$\lambda_{g,0}$	The thermal conductivity of still air at normal atmospheric pressure. This paper is taken as $0.024 \text{ W m}^{-1} \text{ K}^{-1}$ is taken in this

paper.

K_B Boltzmann constant $1.38 \times 10^{-23} \text{ J K}^{-1}$

d_g Air molecular diameter $3.72 \times 10^{-10} \text{ m}$

References

- [1] Z. Chen, Z. Chen, Z. Yang, J. Hu, Y. Yang L. Chang L. Lee and T. Xu, *Energy*, 2015, **93**, 945-954, doi:10.1016/j.energy.2015.08.105.
- [2] F. E. Boafu, Z. Chen, C. Li, B. Li T. Xu, *Energy Buildings*, 2014, **85**, 644-653, doi: 10.1016/j.enbuild.2014.06.055.
- [3] K. Roman, *J. Mech. Eng.*, 2012, **58**, 598-606, doi:10.5545/sv-jme.2012.539.
- [4] E. Wegger, B.P. Jelle, E. Sveipe, S. Grynning, A. Gustavsen, R. Baetens, J. V. Thue, *J. Building Phy.*, 2011, **35**, 128-167, doi: 10.1177/1744259111398635.
- [5] K. Biswas1, R. Jogineedi, A.O. Desjarlais, D. Smith and J. Jones, *Proceedings of the 14th International Vacuum Insulation Symposium (IVIS2019)*, Japan, 2019.
- [6] S. Mao, A. Kan, W. Zhu, Y. Yuan, *Energy Buildings*, 2020, **209**, 109699, doi: 10.1016/j.enbuild.2019.109699.
- [7] F. Dublley, E. Planès, C. Bas, E. Pons, *Proceedings of the 13th International Vacuum Insulation Symposium (IVIS2017)*, Paris, 2017, doi: 10.13140/RG.2.2.30097.12644.
- [8] H. Schwab, U. Heinemann, A. Beck, H. Ebert, J. Fricke, *J. Thermal Envelope Building Sci.*, 2005, **28**, 357-374, doi:10.1177/1097196305051894.
- [9] M. Alam, H. Singh, M. C. Limbachiya, *Appl. Energy*, 2011, **88**, 3592-3602, doi: 10.1016/j.apenergy.2011.04.040.
- [10] B. Yrieix, E. Pons, *Vacuum*, 2018, **148**, 265-271, doi: 10.1016/j.vacuum.2017.11.033.
- [11] H. Simmler, S. Brunner, *Energy Buildings*, 2005, **37**, 1122-1131, doi: 10.1016/j.enbuild.2005.06.015.
- [12] J. Kwon, C. Jang, H. Jung, and T. Song, *Inter. J. Heat Mass Transfer*, 2009, **52**, 5525-5532, doi:10.1016/j.ijheatmasstransfer.2009.06.029.
- [13] Bouquerel M, Duforestel T, Baillis and D, Rusaouen, *Energy Buildings*, 2012, **55**, 903-920, doi: 10.1016/j.enbuild.2012.09.004.
- [14] T. Xu, Z. Chen, Y. Yang, Z. Chen, *Fibers Polym.*, 2018, **19**, 1032-1038, doi: 10.1007/s12221-018-7949-x.
- [15] S. Eddie, C. Yoash, *Proceedings of the 14th International Vacuum Insulation Symposium (IVIS2019)*, Japan, 2019.
- [16] Pons E, Yrieix B, Heymans L, F. Dubelley, E. Planes, *Energy Buildings*, 2014, **85**, 604-616, doi: 10.1016/j.enbuild.2014.08.032
- [17] G. Nisato, H. Klumbies, J. Fahlteich, L. Müller-Meskamp, P. Weijer, P. Bouten C. Boeffel, D. Leunberger W. Graehlert, S. Edge S. Cros P. Brewer E. Kucukpinar J. Girolamo, and P. Srinivasan, *Organic Electronics*, 2014,15(12):3746-3755. doi: 10.1016/j.orgel.2014.10.014.

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