Innovation on Thermal Conductivity Measurement Device of Vacuum Insulation Panel with Double Hemispheres Chambers

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Abstract

The performance of Vacuum Insulation Panel (VIP) is always characterized by a vital parameter, that is, thermal conductivity. The precise measurement of thermal conductivity provides excellent quality assurance for VIP application. But the VIP in service, especially embedded in thermal envelopes, always cannot be evaluated by normal device. In this paper, a double hemispheres chambers device, based on thermal protection method, is proposed to measure the thermal conductivity of VIP in use. The device is portable and can be employed to measure VIP in various sizes. What is more, the device can also be used to evaluate VIP aging extent. The Experiments were carried out to prove the accuracy and the influencing factors were also analyzed. The results implied that the developed device had good precision and practicability. This method can be operated on spot and was not limited by the size of insulation materials, which overcomes the shortcomings of common testing techniques. The test results of the device have high credibility and small measurement error. Therefore, this device can be widely used for field testing and aging degree determination of VIP samples. The method and device proposed in this paper can achieve excellent performance and was more practical than the well-known ones.

Keywords: Vacuum insulation panel; Thermal conductivity; Double hemispheres chambers device; Thermal protection method.

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1. Introduction

On September 22, 2020, China proposed at the United Nations that CO2 emissions strive to peak by 2030 and work towards carbon neutral by 2060. The use of advanced insulation materials is one of the most effective measures to achieve the double carbon goal. In this context, more and more attention has been paid to vacuum insulation panel. Vacuum insulation panel (VIP) is a kind of efficient thermal insulation material, which has been embraced worldwide as a key sign of insulation materials1,2 especially in the field of architecture. VIP is mainly composed of core material, membrane and getter, if necessary.3 The generation of any harmful gas doesn’t occurred in the process of making and using it. Therefore, it has the advantages of energy saving and environmental protection at the same time. The thickness of the VIP is generally about 20mm, which can replace 250 mm traditional insulation materials and the thermal resistance is 10 times higher than traditional insulation materials such as polystyrene with the same thickness.4,5 VIP has proved to be a promising option to meet the demand for thin and high-performance building insulation materials.6-12 Meanwhile, VIP is widely used in refrigerator,13 marine reefer container,14 and other fields.

As new materials are developed and new applications of existing materials are found, studies on the determination of thermal conductivity of insulation materials have increased in recent years.15-17 Thermal conductivity is an important parameter to evaluate the thermal insulation performance of the VIP18,19. Its vacuum will be damaged after a long period of service time which can result in the thermal conductivity increasing. Therefore, the thermal conductivity is needed to be measured periodically for detecting the aging degree of VIP. According to the American ASTM C1484-01 standard, the service life of VIP is the maintenance time for the center thermal conductivity to meet the specified value of super insulation material, which is 11.5 mW/(m·K).20 That is to say, when the VIP thermal conductivity is higher than 11.5 mW/(m·K), VIP can be recognized failure. The accurate measurement of the thermal conductivity of VIP provides a basis for choosing different insulation materials on different occasions.
The widely used method for measuring thermal conductivity is guarded hot plate method.\[^{[23]}\] The method deduces the thermal conductivity of VIP based on one-dimensional steady state by Fourier law, which has characteristics such as high detection accuracy, long system stability and long test cycle. HFM436 produced by NETZSCH company in Germany is designed based on this principle, which provides the advantages of excellent repeatability, remarkable stability, high accuracy.\[^{[22]}\] Therefore, it is a good choice for measuring thermal conductivity. However, there are some noteworthy constraints. This method has certain limitations on the size of the VIP, which can only be carried out in the laboratory generally. It is very important to overcome the disadvantage of size limitation under the premise of accurately determining the thermal conductivity of VIP.

In this paper, the method proposed for measuring thermal conductivity of VIP, based on steady-state by double chamber thermal protection method, overcomes the shortcomings of traditional testing technology. It can be operated on site and is not limited by the size of thermal insulation materials.

2. Theoretical analysis

The effective thermal conductivity of a porous medium is composed of thermal conduction in the solid (λs), thermal conduction in the gases (λg), thermal radiation (λr), convective thermal conductivity (λcv), and coupling conduction (λcoup). Therefore, the effective thermal conductivity λtotal can be expressed as Eq.(1).

\[
λ_{\text{total}} = λs + λg + λr + λ_{\text{cv}} + λ_{\text{coup}}
\]  

(1)

Compared with others, λcoup is very small and not considered.\[^{[26]}\] From previous studies, it can be found that at pore sizes less than 1mm, convective heat transfer can be negligible.\[^{[27]}\] Since thermal radiation, thermal conduction in the solid and gases dominate the thermal conductivity of VIP, these factors can be used to evaluate the total thermal conductivity of VIP. Eq.(1) can be simplified as Eq.(2).

\[
λ_{\text{total}} = λs + λg + λr
\]  

(2)

The thermal conductivity of gases depends on, to a considerable extent, temperature, porosity, pressure. It is defined as:

\[
λg = \frac{λg,0}{1 + \sqrt{2}Kn}
\]  

(3)

The free path of gas molecules and Knudsen number Kn can be described by the Eqs.(4) and (5):

\[
Kn = \frac{\ell_m}{\ell_n} = \frac{\ell_m}{\sqrt{2KnTm/\pi d^2 g_P}}
\]  

(4)

\[
\ell_m = \frac{\ell_n}{\sqrt{2KnTm/\pi d^2 g_P}}
\]  

(5)

The thermal conductivity of the gases in VIP can be described by the Eq.(6):

\[
λg = \frac{λg,0}{1 + \sqrt{2}KnTm/\pi d^2 g_P}
\]  

(6)

Heat conduction and convection can only be achieved in the presence of the medium. However, thermal radiation can be realized in vacuum. The radiation thermal conductivity in VIP can be defined as:

\[
λr(T) = \frac{16n^2σT^4}{3E(Tm)}
\]  

(7)

The total thermal conductivity of VIP can be expressed in Eq.(8):

\[
λ_{\text{total}} = λs + \frac{λg,0}{1 + \sqrt{2}KnTm/\pi d^2 g_P} + \frac{16n^2σT^4}{3E(Tm)}
\]  

(8)

3. Experiments

3.1 Device design

Fig. 1 shows 3D structure of the double hemispheres device. In order to meet experimental requirements, the height of the external chamber designed by the double hemispheres device is about twice as that of the internal chamber. Even if the device is slightly inclined, the liquid in the external chamber can cover the internal chamber wall completely. In this paper, the internal chamber radius rn 50 mm and the external chamber radius rw is 130 mm. The testing device mainly consists of an external chamber heating device for thermal protection and an internal chamber heating device for testing. The external and internal chambers are filled water or grease with good heat capacity, and the heat is adjusted by electric resistance and heating wire. A physical diagram of the double hemispheres device is shown in Fig. 2.

![Fig. 1 Internal and external compartment structure.](image)

The main heating cycle is mainly to maintain the temperature tn in the internal chamber so that the heat generated pass through the VIP area covered by it in the way of one-dimensional heat conduction. It is composed of the power source, the main heating resistance regulator, the main heating resistance and the heating wire. The auxiliary heating system, composed of power source, auxiliary heating resistance regulator and auxiliary heating wire, is mainly used to keep the temperature of the external chamber consistent with that of the internal chamber.

3.2 Instrument overview

3.2.1 Double hemispheres device

The double hemispheres device is shown in Fig. 2. The choice of material for the double hemispheres device is based on the following.
(1) In consideration of welding problems, material hardness and other issues, stainless steel was selected as the material for the external and internal chambers.

(2) As the welding of aluminum is difficult and hardness is not enough, the brass was chosen as base plate material.

(3) Because the device contains small devices that can be easily damaged, such as heating tube, sensor, so the spherical gear with PTFE (poly tetra fluoro ethylene) rods tapping screw as shown in Fig. 2, formed the removable structure, so that even if the device is damaged, can also be painless change device, and the use of PTFE rods can also effectively prevent the leakage, to strengthen the sealing device.

![Fig. 2 A physical drawing of the double hemispheres device.](image)

3.2.2 Control box
As shown in Fig. 2, the main components of the control box are PID control device, multi-function power meter and relay. PID control heating unit was used to stabilize the heating temperature of the main heating device, which could make the liquid in the internal chamber reach the set value first. Generally, the set temperature is higher than the current ambient temperature, preferably at 25 °C. In order to improve the accuracy of the measurement, the liquid temperature in the external chamber is guaranteed to be equal to the liquid temperature in the internal chamber. A power meter was employed to measure the power of the heating circuit. PID controllers was responsible for receiving and processing the signals from the sensor and outputting the signals to the relay by calculation. The relay was responsible for receiving the signal emitted by the PID controller and controlling the current of the heating circuit through processing to control the heating pipe to heat.

3.3 Principle
As is shown in Fig. 3, the principle of the double hemispheres chambers method is that, the heat transferred was all through the thermal insulation material domain covered by the one-dimensional heat conduction, due to the temperature of the internal chamber and the external chamber are equal. Thermocouples were selected to collect the temperature of the liquid in the space between the internal and external chambers, the temperature of the liquid in the external chamber, the temperature at the center of the surface of the VIP domain covered by the internal chamber, and the temperature of the center of the corresponding external surface. The liquid was heated by turning on the internal and external chamber heating devices, and the resistance regulator of the internal and external chamber heating devices is adjusted to maintain the liquid temperature inside and outside the chamber at the set value. The temperature difference between the internal and external chamber was selected as a positive and negative feedback quantity to adjust the resistance value of the auxiliary heating device so that the liquid temperature in the external chamber is equal to the liquid temperature in the internal chamber. It can ensure that the heating heat in the internal chamber is transferred in a one-dimensional manner according to the thickness direction of the insulation material.

![Fig. 3 schematic diagram of the double hemispheres chambers thermal protection test device.](image)

![Fig. 4 Temperature field distribution of VIP.](image)
The thermal conductivity of VIP can be calculated from measuring the effective heat transfer area, thickness and the temperature of cold and hot end temperatures. In this paper, mesh division and finite element calculation of the vacuum insulation heating device were carried out, and the calculation results were shown in Fig. 4. As can be seen from the Fig. 4, when one side of the VIP is heated and the temperature is maintained constant with a double sphere device, the isotherm of the VIP is distributed in a radian on both sides while the temperature in the middle is distributed in a gradient.

In the VIP heat transferred, relaxation time was required to establish a stable heat transfer temperature gradient. The relaxation time indicates the time required for the system to converge from an unstable stationary state to a stable stationary state. It was necessary to judge the steady state of the test in order to eliminate the effect of relaxation time. This experiment selected a larger test space for the cold end, ignoring the effect of ambient temperature fluctuations on the experiment. In this experiment, the steady state was judged by difference method, and the data were collected every 10 seconds. When the data measured at the measuring points on the external surface of the insulation material conform to

\[ |T_{wi, i+1} - T_{wi, i}| / T_{wi, i} \leq 10^{-3} \]

it can be recognized that the system has been in a steady state and can be calculated according to the test data.

\[ Q = W_i = U I = Q \] (9)

where \( W_i \) denotes the internal heating wire adds heat, \( W \). \( U \) is the voltage through the internal chamber heating wire, \( V \). \( I \) is the internal chamber heating loop current, \( A \). \( Q \) is the heat flow rate of the internal chamber through the thickness of the insulation material, \( W \).

According to Fourier’s law, the Eq.(10) can be obtained \(^{[23]}\):

\[ Q = \lambda \frac{A_n}{\delta} (T_n - T_w) = \lambda \frac{\pi r_n^2}{\delta} (T_n - T_w) \] (10)

where \( T_n \) and \( T_w \) denote are the temperature of the central measuring point and the corresponding temperature of the external measuring point in the insulation material area covered by the internal chamber, respectively. \( \lambda \) is thermal conductivity, \( W/(m \cdot K) \). \( A_n \) the bottom surface of the internal chamber is round and covers the area of the insulation material in \( m^2 \). \( \delta \) is the thickness of the insulation material in \( m \). The thermal conductivity of VIP can be sorted out according to Eq. (9) and Eq. (10) mentioned above.

\[ \lambda = \frac{\delta}{\pi r_n^2} \frac{U I}{T_n - T_w} \] (11)

3.4 Measurement uncertainty

In this paper, based on the national standard for testing temperature difference, the internal room temperature was selected as 35 °C and the ambient temperature is selected as 15 °C. The measurement uncertainty of apparatus is listed in Table 1.

<table>
<thead>
<tr>
<th>Type</th>
<th>Error</th>
</tr>
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<tbody>
<tr>
<td>Thermocouple</td>
<td>±0.27K</td>
</tr>
<tr>
<td>Thickness sensor</td>
<td>±1.2%</td>
</tr>
<tr>
<td>Press sensor</td>
<td>3%</td>
</tr>
<tr>
<td>Power meter</td>
<td>±0.05W</td>
</tr>
</tbody>
</table>

4. Results and discussion

In present paper, three types of VIP were selected, which were fumed silica, glass fiber and PU foam. Fig. 5 shows the comparison of the measured and theoretical thermal conductivity.
conductivity. As can be seen from Fig. 5, at the beginning of the experiment, the measured thermal conductivity appears to increase due to the instability of the power meter. As the temperature of the internal chamber increases, the mean temperature increases and the thermal conductivity of the insulation material decreases. From Fig. 5(a), it can be seen that the fumed silica panel reached steady state at about 45 min. From Fig. 5(b), it can be shown that the glass fiber panel reached steady state at about 45 min; From Fig. 5(c), it can be observed that the PU foam panel reached steady state at about 45 min. It is concluded that the smaller the thermal conductivity of the insulation material, the more time is needed to reach steady state. As shown in Fig. 5, the error between the measured and theoretical values is relatively small. Hence, the device mentioned in this paper is highly accurate.

5. Conclusion

Double hemispheres chambers thermal protection method is proposed to measure the thermal conductivity of VIP. The method can be operated on site and is not confined by the size of insulation materials, which overcomes the shortcomings of traditional testing techniques. The test results of the device have high credibility and small measurement error, so the device can be widely used in the field testing and aging degree judgment of VIP. The thermal conductivity of VIP should be measured by the double hemispheres chambers thermal protection method with the following notes: (1) During the test, the theoretical values were compared with the measured values at steady state (2) it is generally recommended to select VIP with a minimum size of 300mm × 300mm to avoid the influence of thermal bridge effect.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

Nomenclature

<table>
<thead>
<tr>
<th>Symbols</th>
<th>Description</th>
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<tbody>
<tr>
<td>A</td>
<td>heat transfer area (m²)</td>
</tr>
<tr>
<td>λ</td>
<td>thermal conductivity (W/m K)</td>
</tr>
<tr>
<td>T</td>
<td>temperature (K)</td>
</tr>
<tr>
<td>Q</td>
<td>heat flow (W)</td>
</tr>
<tr>
<td>W</td>
<td>heating wire adds heat (W)</td>
</tr>
<tr>
<td>U</td>
<td>voltage (V)</td>
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References

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Kan Ankang (1981-) male, Ph.D./Senior engineer/postdoctoral. mainly engaged in the research, experiment, teaching and engineering practice in the fields of heat and mass transfer in porous media, vacuum insulation technology, food vacuum precooling and decompression preservation technology, refrigeration and air conditioning technology, transportation safety and energy saving technology of refrigerators.

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