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# A simple and effective model for prediction of effective thermal conductivity of vacuum insulation panels

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## Abstract

The excellent thermal insulation performance of vacuum insulation panels (VIPs) make them widely applied in energy conservation fields, especially in buildings engineering. This research work proposes a simple, yet extremely effective, alternative model for prediction of the effective thermal conductivity (ETC.) of VIPs. The ETC. of VIPs is function of the thermal conductivity of the core materials, the equivalent thermal conductivity of the rarefied gas embraced in the core and the equivalent thermal conductivity of radiation in the early studies. The micro structure of the porous core materials and vacuum degree are taken into consideration and the prediction numerical model for the ECT of VIPs is developed. The relationship of the vacuum degree versus the ETC. is theoretical analyzed. Three types VIPs are made from the polyurethane foam materials, superfine fibrous materials and nano-granular silica materials as the core materials. For each type, the vacuum degree and the thermal conductivity are collected, including the comparison between the testing results and the prediction model. The agreement between the model and the experimental results is fairly well when the air pressure is very low. The vacuum maintaining and service life of the VIPs are also discussed. The research work is meaningful for the enhancement of stability and the development of vacuum insulation panels.

**Keywords:** Vacuum insulation panels; Thermal conductivity; Vacuum degree; Numerical analysis and prediction

## Introduction

Nowadays, vacuum insulation panels (VIPs) are regarded as one of the optimum thermal adiabatic materials for the energy conservation purpose on the market. The thermal insulation performances observed, even ten times better than common heat insulation materials can be achieved by applying VIPs, resulting in a great potential for the reduction of energy loss in thermal space with slim exterior-protected walls (Fricke et al. 2008; Baetens 2010; Nussbaumer et al. 2006; Nussbaumer et al. 2005; Brunner et al. 2012; Caps et al. 2001). The flat VIPs contain a porous core material which withstands the atmospheric air pressure, a gas-tight barrier envelope that is optimized for low air & moisture leakage rate and for a long service life to maintain the internal vacuum level, and getter or gas absorption materials, if necessary, to absorb internal gas from leakage or other sources. That is, the VIPs make use of vacuum to suppress heat transfer due to rarefied gaseous conduction (Bouquerel et al. 2012a; Bouquerel et al. 2012b; Alam et al. 2011). So the thermal adiabatic property of VIPs dramatically depends on the core materials and the internal gas pressure. The porous materials, such as, micro-open foam, nano-structured power and fine fiber, are commonly used as core materials of VIPs, which are easily evacuated and have minimum thermal conduction effect (Kwon et al. 2009). The heat transfer processing in VIPs is via solid conduction, rarefied gas conduction, radiation and convection occurring at interface of gas and solid wall which is nearly zero, is always ignored in calculation. The solid conduction and radiation depends on the structure, the porosity and properties of core materials, while the gas conduction by the residual gases embraced in the caves depends on the internal gas pressure which maybe increased with time. So the ETC. of VIPs must be function of the variables mentioned above.

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Various models to predict the ETC. of VIPs can be founded in the literature. The typical models for VIPs with different core materials have been presented by Jae Sung Kwon *et al.* (Kim & Song 2013; Caps & Fricke 2000; Di et al. 2013; Di et al. 2014). Special emphasis on the solid conduction is theoretically investigated and transport mechanisms of three core materials are numerically analyzed. Separate calculation for solid conductivity, gaseous conductivity and radiative conductivity is also studied. However, separate research of these contributions is not easy in practice because any of them cannot be fully eliminated. There are also many variables in the models that should be determined by experiments. Based on an empirical approach, Kan and Han (2013) proposed a fractal model to estimate the ETC. of open-cell polyurethane foam. This model consists of fractal dimension and fractal diameter which are not easily obtained. Wang (Wang & Pan 2008a; Wang & Pan 2008b; Wang et al. 2007) presents a lattice Boltzmann method, that is, a random generation-growth method to produce micro morphology of porous media. Different parameters of different porous materials are involved in the statistical models and the simulation porous materials are self-similarity in the micro space. A simplified model are proposed by Miguel A. A. Mendes *et al.* (Mendes et al. 2013; Mendes et al. 2014) to estimate the ETC. of open-cell foam-like porous materials and the serial and parallel arrangements are simulated in the model. They concluded that the ETC. strongly depends on the porosity and the ratio of thermal conductivities of solid and fluid phases. The results are compared with the experimental data, and the correlation for the model is also obtained.

From the considered models mentioned above, it can be easily concluded that the numerical prediction models, where the effective structural cell is generated based on the real morphology of the porous media, are the function of the porosity, the thermal conductivities of the phases, the radiation conductivity and additional empirical parameters in some case. However, such models can be found in the references, but they do not directly provide explicit expressions for the ETC. of VIPs because of the vacuum conditions. As the wide application of VIPs, the needs of the ETC. prediction are urgent for manufacture, development and research. In view of above discussion, the main objective of this study is to provide an effective model to predict the ETC. of VIPs with alterable core materials. Based on the morphology of the core materials and the vacuum degree, the appropriate simplified numerical models are investigated for alterable VIPs.

## Mathematical methods

For the general porous insulation materials under the normal condition, the heat transfer flux is composed of four parts, according to the traditional heat transfer theory, that is, heat conduction by the solid matrix itself $\lambda_s$, heat conduction by the filled phases (mainly gas, vapor or other fluent) in the cavities $\lambda_{\mathrm{g}}$, heat convection between solid phase and filled phases $\lambda_c$ and radiation equivalent thermal conduction among the phases $\lambda_y$. Neglecting the coupling effect by all the phases, the effective thermal conductivity of the porous media can be express as:

$$\lambda_{\mathrm{e}} = f\left(\lambda_{\mathrm{s}}, \lambda_{\mathrm{g}}, \lambda_{\mathrm{c}}, \lambda_{\mathrm{r}}\right) \tag{1}$$

However, for VIPs, the air pressure in the cavities of the core materials is very small, nearly zero. So the fluent phase is always gas, under the normal temperature. The thermal convection between the solid wall and the filled phases can be ignored.

### The conductivity of solid matrix

The heat conduction for the nonmetal solid matrix can be achieved by the vibration of the lattice morphology. So the certain porous materials, the ETC. is usually regarded as the function of the mean temperature. In fact, the ETC. also has the relationship with the materials density, the micro structure, the characteristics, the porosity, and so on. The calculation formula is so very complex that it is nearly impossible to get the accuracy value. So the value is always provided by vendors or collected from experiment.

### The conductivity of rarefied gas

Free motion of gas molecules makes the heat transfer complex in the open cells of the core porous materials. According to the gas kinetic theory, we can acknowledge that, the smaller the cavity dimension, the harder the gas molecules move in it. For the VIPs core materials, the pore dimension scales are micron or even nanometer level. While the pore dimension is no larger than 100 μm and the air pressure is under 100 Pa, that is, the Reynolds is smaller than 1000 and Knudsen number is bigger than ten, the equivalent conductivity of gas can be ignored, $\lambda_c \approx 0$.

Based on the rarefied gas heat transfer theory, the ETC. of the rarefied gas embraced in the cavities is given by (Kwon et al. 2009; Kan et al. 2013):

$$\lambda_g = \frac{\lambda_0}{1 + 2\beta K_n} \tag{2}$$

Where: $\lambda_0$ is the ETC. of static gas under the normal temperature and normal air pressure condition, $\mathrm{W/(m \cdot K)}$, here $\lambda_0 = 0.0230\ \mathrm{W/(m \cdot K)}$;$\beta$ is a constant number, which is used to express the grade the gas molecules collide the solid walls, and its value is always between 1.5 and 2, depending on the gas type, core material characteristics and mean temperature, here $\beta = 1.5$; $K_n$, Knudsen number, is the ratio of the gas molecule mean free path $l_m$ and the mean diameter of the pore $\delta$, that is $K_n = l_m/\delta$; and $l_m$ is determined by (Kwon et al. 2009):

$$l_m = \frac{K_B T}{\sqrt{2}\pi d_g^2 p_g} \tag{3}$$

Where $T$ is the mean temperature of the porous material in thermodynamic scale, K; $d_g$ is the diameter of the gas molecule, m, here, for air, $d_g = 3.72 \times 10^{-10}\, m$;$K_B$ is the Boltzmann constant, and $K_B = 1.38 \times 10^{-23}\, m$ J/K;$P_g$ is the rarefied air pressure, Pa.

Combined Eqs. (2) and (3), the ECT of rarefied gas embraced in pore can be obtained as the follow:

$$\lambda_g = \frac{\lambda_0}{1 + \frac{\sqrt{2}\beta K_B T}{\pi d_g^2 P_g \delta}} \tag{4}$$

### The equivalent thermal conductivity of radiation

Thermal radiation, in the form of electromagnetic wave for energy transfer, can occur without any medium, even in the vacuum case. And the equivalent thermal conductivity of radiation can be calculated by the Eq. (5) (Mendes et al. 2013):

$$\lambda_r = 4 l_c \sigma (T_1 + T_2)\left(T_1^2 + T_2^2\right)/3\phi \tag{5}$$

Where, $l_c$is the thickness of the plate core materials, m; $\phi$ is the attenuation coefficient for porous media, and here $\phi = 445\ \mathrm{m}^{-1}$;$\sigma$ is Steve Boltzmann constant, and $\sigma = 5.6697 \times 10^{-8}\ \mathrm{W/(K^4 \cdot m^2)}$; $T_1$,$T_2$ are respectively both sides of the VIPs temperature in thermodynamic scale, K.

### The ETC. of VIPs

To calculate the ETC. of the VIPs, the explicit mathematical model is derived from Eq. (1) to yield the following Eq. (6):

$$\lambda_e = (1-\xi)\lambda_s + \xi\lambda_g + \lambda_r \tag{6}$$

Where, $\xi$ is the porosity of the core materials.

Combined with Eqs. (4), (5) and (6), the ETC. of the VIPs can be expressed as the following:

$$\lambda_\mathrm{e} = (1-\xi)\lambda_\mathrm{s} + \xi \frac{\lambda_0}{1 + \frac{\sqrt{2}\beta K_B T}{\pi d_g^2 P_g \delta}} + \frac{4 l_c \sigma (T_1 + T_2)\left(T_1^2 + T_2^2\right)}{3\phi} \tag{7}$$

## Numerical analysis and discussion

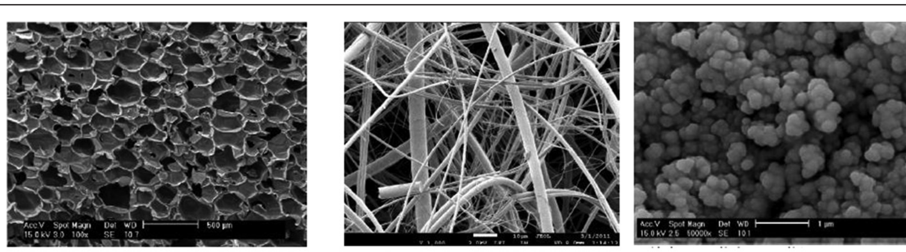
### Porous materials and simulation

Three typical porous media, that is, open cell foam structure, granular porous structure and fibrous porous structure, as the core material for VIPs, are involved in the simulation. The micro structures are shown in Fig. 1.

The thickness of VIPs, assuming is 20 mm, is employed in the simulation. And the simulation boundary conditions of the ETC. testing, which involves the heat guarded method, is that the hot plate temperature is 35 °C while the cold side is 15 °C, taking the GB/T3399-2009 as the simulating reference. The core porous materials, the open cell polyurethane which has the thermal conductivity of the solid phase 0.5832 W/(m · K), the pore size range is 1-100 μm and the porosity is 95 %, superfine glass fiber with the thermal conductivity of the solid phase 1.3 W/(m · K),the diamter range 100 nm-100 μm and the porosity 95 %, the nano-grain silica with the thermal conductivity of the solid phase is 0.27 W/(m · K),the diameter range 10 nm-10 μm and porosity 95 %, are taken in the theoretical calculation. The results are illustrated in Fig. 2.

### Results and discussion

Barrier membrane with good air-blocking and heat-sealing properties, gas getters and driers putting inside the core media, are helpful for the vacuum maintenance. Combined with the physical properties parameters of porous media, the vacuum degree inside the VIPs and



a b c

**Fig. 1** The micro profiles of three typical porous materials as VIPs core materials. (**a**) micro section of open cell foam structure (**b**) micro section of fibrous porous structure (**c**) micro section of granular silicon dioxide porous structure

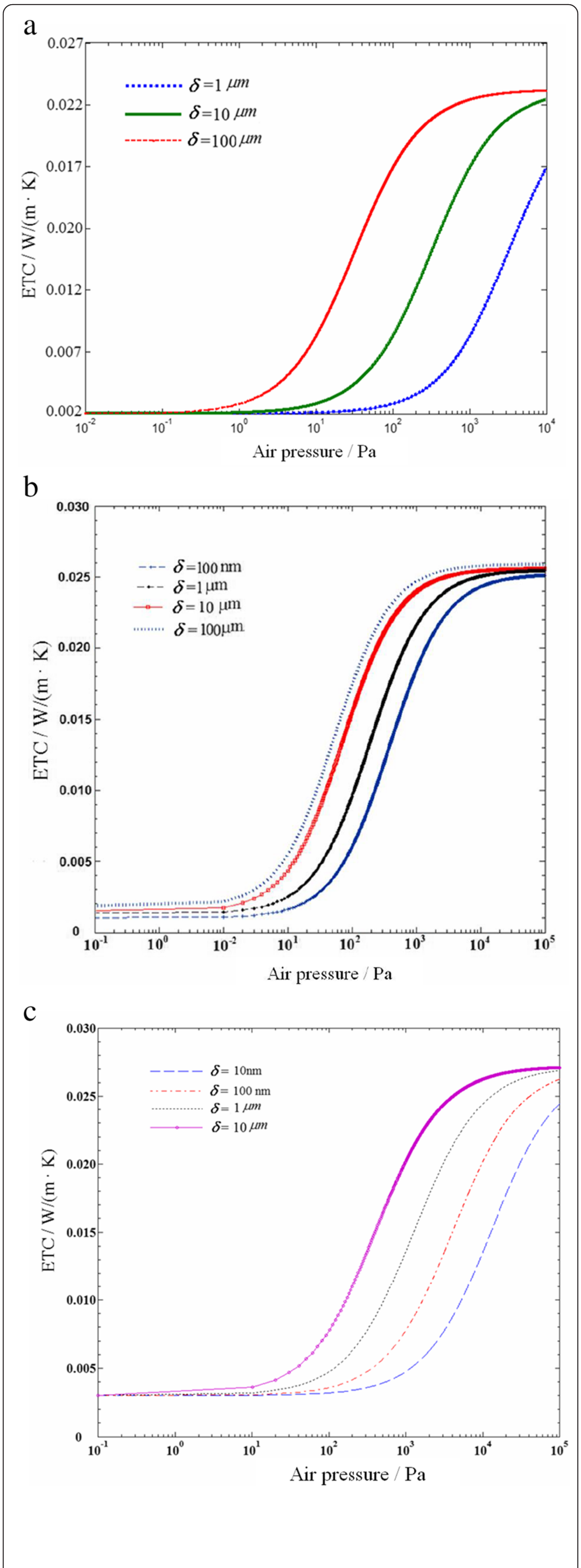



**Fig. 2 a** The vacuum degree in open micro cell polyurethane and the pore diameters versus the ETC. in simulation **b**) The vacuum degree in superfine glass fiber and the fiber diameters versus the ETC. in simulation **c**) The vacuum degree in nano-grain silica dioxide and the pore diameters versus the ETC. in simulation

the gas permeability ratio of barriers, the service life of the VIPs can be modeled and predicted.

(1) The relationship of the vacuum degree versus the ETC.

Figure 2 shows the predicted ETC. of three typical porous media under vacuum condition. The curves in the simulation for the open micro cell polyurethane, superfine glass fiber and nano-grain silica dioxide are very similar. In the relevant simulation figure, the curve is nearly flat while the static air pressure in the cavities is over a certain value $P_{low}$, that is, the ETC. is nearly constant. But there is a sharp decline of the ETC. with the reducing of the static air pressure while the vacuum value is less than the certain value $P_{low}$ mentioned above. When the static air pressure in the cavities reaches for another certain value $P_{low}$, the air in the cells is so rarefied that thermal convection can be negligible, and the curve line is flat again with the air pressure decreasing. For the VIP manufacture and application, the certain air pressure $P_{low}$ is meaningful and critical. When the air pressure inside the porous core materials is below the critical $P_{low}$, the VIP will take a good adiabatic thermal performance in the usage. Taking into account the information in Fig. 2, one can easily make the conclusion that, if one wants to get the ideal insulating VIPs, the air pressure inside the core materials, for corresponding micro cellular polyurethane, should be reduced to below 1 Pa, for superfine glass fiber, below 10 Pa, for the nano-grain silica dioxide, below 100 Pa.

The critical factor for the thermal properties and thermal stability of VIP is the vacuum degree inside the core materials, as can be seen from Fig. 2. So the vacuum maintenance, that is, below the $P_{low}$, is essential and vital for the manufacturing and application of the VIPs. Water, embraced in cavities of the core materials, will change into vapor when the air pressure is very low at the normal temperature. And the vapor, if presents, will deteriorate the thermal property of VIPs. Therefore, core materials pre-treating proceeding for the manufacturing VIPs is important for the vacuum maintaining through the service life. The barrier membrane and the numerical model in this paper, the service life of VIPs can be deduced for further research work (Kim et al. 2012; Schwab et al. 2005a; Schwab et al. 2005b; Jung et al. 2013; Tenpierik & Cauberg 2007).

(2) The relationship of the feature size of the porous medium versus the ETC.

a b c

**Fig. 3** The samples of VIPs with three typical porous core materials: (**a**) micro open cellular foam polyurethane; (**b**) superfine fibrous glass mate (**c**) nano-grain silica dioxides mixed with a few short glass fibers

From the Fig. 2, one can also easily recognize that, the ETC. greatly reduces with the reduction of the feather size of the porous core materials, as the occupancy of solid matrix increases and the corresponding air molecules free path decreases, and the movement of air embraced in the pore is restricted in the narrow spaces. With the feather size decreasing, the porosity decreases but the corresponding $P_{low}$ increased. In practice, the improvement of the $P_{low}$ is meaningful for the special equipments, especially for the vacuum heat sailing machines. But it is also the obstacles for the vacuum degree to create.

Actually, the recommending vacuum value for the open cellular polyurethane, as the core materials, is within $100\,\mu m$, for super fine glass fiber, within $10\,\mu m$, and super nano- grain silica dioxides within 100 nm.

## VIPs samples and experiments

### Samples of VIPs with different core materials

Three typical porous core materials were selected and the same making craft was taken to make the VIPs samples, in order to compare the texting ETC. with that of the simulation results. And every five samples were made with different inside air pressure. The three typical VIPs samples are illustrated in Fig. 3 and the main parameters of core materials are demonstrated in Table 1.

The pre-treating procedure of the core material is essential and vital for the VIPs samples making, to remove the water and vapor embraced in the cavities (Di et al. 2013). However, the treating crafts are a little different for different core materials. After the pre-treating (in Fig. 4a), the core mate should be promptly carrier into the barrier envelopes prepared in advance and the vacuum heating seal should be taken in the special machine (in Fig. 4b).

The vacuuming, heat sealing, cooling and air charging proceeding are program controlled by the computer, and the setting air pressure is the final vacuum degree in the vacuum space. The setting rank of air pressure in these experiments are 0.1 Pa, 1 Pa, 10 Pa, 100 Pa and 1000 Pa. And then we got five VIPs samples with five different kind of inside air pressure. And the final vacuum inside the core materials are estimated by the anti- air pressure method (Di et al. 2013).

### ETC testing and data collection

The ETC. of VIPs samples are strictly collected based on the Chinese standard GB/T3399-2009., and the ETC. measurements were conducted with a thermal conductivity meter (Fig. 5). The ETC. measurements in our laboratory can confirm values even lower than 1 $mW/(m \cdot K)$. As the thermal conductivity of barrier laminate is much bigger, even 1000 times, than that of the core materials under the vacuum condition, some heat may transfer from the edge of the VIPs but not through the panels, that is, thermal bridge effect (Tenpierik & Cauberg 2007). So the ECT collected by the equipment is a little deviation from the whole body's thermal conductivity. Here, we take the thermal conductivity of the center region as the ETC. of VIPs samples and the effect of thermal bridge is ignored. The data were collected in the Table 2.

Because the thickness of the barrier films (always several micro meters) is much smaller than that of core materials mate (in centimeter) and the thermal conductivity is much bigger than that of core materials under vacuum

**Table 1** The main parameters of the core materials

| | Parameters | | | | | |
|---|---|---|---|---|---|---|
| | Dimension mm × mm × mm | Density Kg/m$^3$ | Pore diameter | Porosity | Mean diameter | Barrier membrane |
| open cellular foam polyurethane | 300 × 300 × 20 | 50 ~ 75 | 80 ~ 100 μm | 95 % | 72 μm | High barrier laminates |
| superfine fibrous glass mate | 300 × 300 × 20 | 200 ~ 250 | 2 ~ 10 μm | >90 % | 6 μm | High barrier laminates |
| nano-grain silica dioxides mixed with a few short glass fibers. | 300 × 300 × 20 | 180 ~ 200 | 10 ~ 40 nm | >95 % | 32 nm | High barrier laminates and nylon film |

a b

**Fig. 4** The VIPs making equipments: (**a**) The vacuuming and heating alternation pre-treating equipment; (**b**) program controlling VIPs making machine

condition, the thermal resistance of the barrier films is ignored in the calculation and the further analysis. However, if the numerical model is used to predict the ETC. when the inside air pressure is near the barometric pressure, the thickness and thermal resistance should been taken into account.

### Comparisons and discussions

The numerical prediction results and the testing results are compared in Fig. 6.

When the inside air pressure is lower than 10 Pa, the ETC. curved line of the open cellular polyurethane is flat, basically around a constant value 4 mW/(m · K), and the theoretical calculation value is nearly the same, but slightly lower than the measured one. When the inside air pressure reaches for 100 Pa and continues to rise, the ETC., both of numerical prediction value and measurement one, sharply increased and over 11 mW/(m · K)(the limited value for so called adiabatic materials). The deviation between the theoretical calculations and the measured values gradually increases with the air pressure increases. The reason is that, the number of the air molecules in the pores increases and the frequent collision of the air molecules makes the free air path smaller than the cell feather size. The air thermal convection occurs and plays an important role by degrees. So the measured value is higher than that of the calculated one. So, the numerical ETC. prediction model for VIPs with the open micro cellular polyurethane, is much accurate when the inside air pressure is lower than 100 Pa.

**Fig. 5** Laboratory measurement meter of thermal conductivity

For the superfine fibrous glass materials, the measured ETC. is agreeable with the calculated one when the inside air pressure is lower than10Pa and the ETC. value is around 3 mW/(m · K). As the inside air pressure exceeds 20 Pa and continues to rise, ETCs, both measured value and theoretical calculated one, sharply rise with the increasing of air pressure. And the difference between the two values also enlarges. One reason is that, the air molecules gathered in the pore leading to the thermal convection gradually intensified, as mentioned above. Another reason is that, the fibrous glass mate is flexible and compressible. The connected thermal resistance exists between two superfine fibrous pips and changes with the various air pressure differences between air pressure inside and outside the panels. The connected thermal resistance decreasing along with the inside air pressure increasing makes the measured ETC. value is slightly higher than that of calculated ones. So, the numerical ETC. prediction model for VIPs with the superfine fibrous glass core materials, is much accurate when the inside air pressure is lower than 10 Pa.

The ETCs of the nano grain silica dioxide powder as the core materials under the vacuum condition, both of the numerical prediction value and the measured one, are nearly the same and not more than 4 mW/(m · K) when the inside air pressure is no more than 100 Pa and theoretical calculation and measured values are in good agreement. The same trend is also displayed the similarities with the other two core materials. The reason is also mentioned above. The numerical ETC. prediction model for VIPs with the nano grain silica dioxide core materials is more accurate when the inside air pressure is lower than 100 Pa.

## Conclusions

(1) The vacuum degree is one of the key external effect factors of the VIPs thermal property. Vacuum maintenance is an important and vital for the

**Table 2** ETC. of VIPs samples and the inside air pressure in the measurements

| | Core porous materials | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | open cellular foam polyurethane | | | | | superfine fibrous glass mate | | | | | nano-grain silica dioxides | | | | |
| NO. | PU1 | PU2 | PU3 | PU4 | PU5 | FG1 | FG2 | FG3 | FG4 | FG5 | SI1 | SI2 | SI3 | SI4 | SI5 |
| Setting air pressure/Pa | 0.1 | 1 | 10 | $10^2$ | $10^3$ | 0.1 | 1 | 10 | $10^2$ | $10^3$ | 0.1 | 1 | 10 | $10^2$ | $10^3$ |
| Final air pressure/Pa | 5 | 13 | 45 | 140 | 713 | 0.6 | 7 | 25 | 165 | 763 | 15 | 38 | 80 | 241 | 892 |
| Testing ETC./mW/(m · K) | 4.12 | 4.15 | 5.04 | 16.23 | 21.16 | 2.68 | 2.96 | 3.19 | 5.84 | 14.63 | 3.06 | 3.82 | 4.14 | 4.75 | 8.24 |
| Calculated ETC. mW/(m · K) | 4.03 | 4.42 | 4.84 | 14.33 | 19.21 | 2.61 | 2.83 | 2.94 | 4.86 | 10.44 | 3.23 | 3.35 | 3.98 | 4.12 | 8.08 |

thermal stability and service life of VIPs. From the numerical simulation, the conclusions can be made that:

➢The feature size of micro open cellular polyurethane as the core materials for VIPs, should be within 100 $\mu m$ and the inside air pressure should be not more than 1 Pa;

➢The feature size of superfine fibrous glass should be within 10 $\mu m$, and the inside air pressure should be not more than 10 Pa;

➢The feature size of nano- grain silica dioxide power should be within 100 nm, and the inside air pressure should be not more than 100 Pa.

(2) Compared the theoretical prediction value with the measured one, the agreement is very well when the inside air pressure is low. Even the ETC. same change trend, both of the numerical model and the measured values with increasing the air pressure, displaying in the research work, the deviation between the two gradually enlarged. So the numerical model can accurately predict the ECT of porous media under the low air pressure, especially under the $P_{low}$.

(3) Taking into consideration the properties of the core materials and vacuum degree, combined with the gas permeability rate of the barrier membrane, this numerical model can also be used to predict the service life of VIPs for further research, for the purpose of manufacture, engineering design and application.

## Nomenclature

$d_g$ the diameter of the gas molecule, m
ETC. effective thermal conductivity W/(m · K)
$K_B$ Boltzmann constant, $1.38 \times 10^{-23}$ $m$J/K
$K_n$ Knudsen number
$l_c$ the thickness of the plate core materials, m

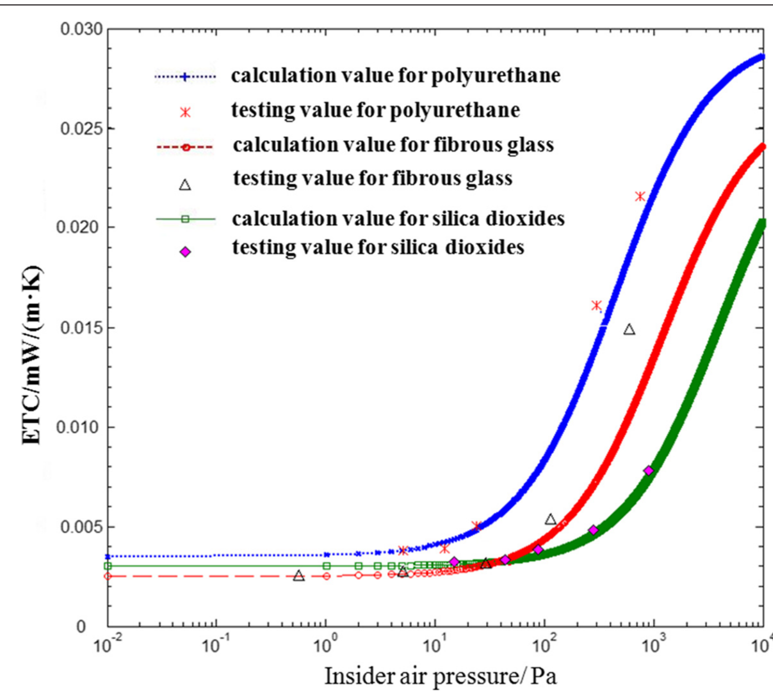



**Fig. 6** The ETC comparison of the numerical calculations and experimental measurements for the three typical VIPs samples at different insider air conditions

$l_m$ gas molecule mean free path, m
$P$ Air pressure, Pa
$T$ temperature in thermodynamic scale, K

Greek symbols

$\beta$ universal constant, 1.5
$\delta$ the mean diameter of the pore, m
$\sigma$ Steve Boltzmann constant, $5.6697 \times 10^{-8}$ $\mathrm{W/(K^4 \cdot m^2)}$
$\phi$ the attenuation coefficient,445 $\mathrm{m^{-1}}$
$\xi$ the porosity of the core materials
$\lambda$ thermal conductivity $\mathrm{W/(m \cdot K)}$

Subscripts

c thermal conduction
e effective
g gas
r thermal radiation
s solid phase

**Competing interests**
The authors declare that they have no competing interests.

**Authors' contributions**
AK and LK carried out the experimental and theoretical studies, and drafted the manuscript. CW and DC participated in the sequence alignment and drafted the manuscript. All authors read and approved the final manuscript.

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