Vacuum Insulation Panel: Green Material and Healthy Life

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第十二届国际真空绝热材料会议论文集

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Preface

The 12th International Vacuum Insulation Symposium (IVIS 2015) is being organized and hosted by the Nanjing University of Aeronautics and Astronautics (NUAA), Nanjing, Jiangsu, China, 19 – 20 September 2015. IVIS 2015 is a continuation in a series of symposiums, which was originally started by the former Vacuum Insulation Association (VIA). The last symposium was held in Dubendorf, Switzerland in 2013. Traditionally held in Europe or North America, IVIS 2015 is the first one organized in Asia.

Global construction industry is now strongly focused on energy efficiency and sustainability, and Asia, led by China, is the fastest growing building construction market in the world. More importantly, for the first time in the modern history of building construction, energy efficiency is being considered as equally important, if not more, as other traditional design criteria such as structural stability and durability. The role and importance of high performance thermal insulations such as vacuum insulation panels (VIPs) in the global construction industry at this opportune moment cannot be overemphasized. There are opportunities and challenges which can and should be converted into game changing examples. In this context, IVIS 2015 and associated events in Nanjing aim to provide a global platform for discussion and collaboration among researchers, manufacturers, building designers, project managers and, last but not the least, the end users. A total of seventy seven (77) papers and posters will be presented during the symposium days. These papers authored by academic and industry researchers from Asia, Europe and North America focus on comprehensive issues ranging from materials, systems, applications and long-term performance. It is important for all of us, the VIP research community, to remember that IVIS is the primary international research forum for VIPs and we remain fully engaged with the stakeholders during the symposium to provide directions and identify scopes for future research, development and collaborations. More specifically, the presence of the members of newly formed Vacuum Insulation Panel Association (VIPA International, http://vipa-international.com/), the global trade association representing the interests of companies that manufacture and supply equipment and/or materials to the Vacuum Insulation Panel industry, and EBC Annex 65 on Long Term Performance of Super-Insulating Materials in Building Components and Systems (http://www.iea-ebc.org/projects/ongoing-projects/ebc-annex-65/) during the symposium days provides a unique, not to be missed, opportunity to foster collaboration between industry and academic researchers.

Finally, as the Chair, and on behalf of the Advisory, Organizing and Scientific Committees of this symposium, I would like to thank and express my gratitude to all authors, reviewers, sponsors and exhibitors for their support, sincerity and hard work.

I hope your days in Nanjing become enriching and pleasant experience.

Sincerely

Prof. Chen Zhaofeng, Ph. D
Nanjing, China, September 2015
Chair, IVIS 2015

Contents

Influence of Al Foil Layers on Thermal Conductivity and Flexural Strength of Glass Fiber Core VIPs

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Abstract

Vacuum insulation panels (VIPs) are regarded as the most promising high-performance thermal insulation products on the market today. A high and stable vacuum state within VIP enclosure provides a durable service life for VIP. Its core is typically made of laminated glass fiber (GF) due to its low thermal conductivity, high modulus, high toughness, light weight and non-combustible property. However, fiber-bridging significantly exist under the low-pressure condition inside VIP, resulting in solid heat conduction intensified between the layers. Also, the VIP with pure GF core is comparatively soft. In this paper, aluminum foils were orderly arranged in 30 cascading layers of GF core, 10 different new structural VIPs with "1－10GF＋1Al" were got to compare with the pure 30GF core VIP. The influence of different layers of Al foil on the thermal conductivity and flexural strength of VIPs were discussed. Thermal conductivities of the as-prepared VIPs with proportion of 490mm×210mm were evaluated by the heat flow meter thermal conductivity instrumentation Netzsch HFM 436. Flexural strength was compared between the different samples by electronic universal testing machine. Results showed that Al foil layers laminated in the core can make a contribution to the flexural strength of VIP. The thermal conductivity of the pure 30GF core VIP was 2.278 mW/(m·K), while the data of "1－8GF＋1Al" structure were higher than 2.278 mW/(m·K). The thermal conductivity of "9GF＋Al" and "10GF＋Al" structure were 2.330 mW/(m·K) and 2.146 mW/(m·K) respectively. Theoretical and experimental analysis showed that the optimum layers of Al foil for 30GF core are 2, and the structure is "10GF＋1Al".

Keywords VIP, glass fiber, Al foil, thermal conductivity, flexural strength

1. Introduction

Vacuum insulation panels (VIP) are regarded as one of the most upcoming high performance thermal insulation solutions. At delivery, thermal conductivity for a VIP can be as low as 0.002～0.004 W/(m·K) depending on the core material[1]. The purpose of the core material is to provide the VIP's insulating and mechanical properties. Hence, there is a lot of focus on the core material, as this is important for a VIP to attain the highest possible thermal resistance. To optimize the conditions of the VIPs, the core needs to fulfil certain requirements. These are described in a comprehensive review by Baetens et al. [2]. Several different materials are being tested for use as core materials in VIPs, such as fiber-powder composites [3], polycarbonates [4], phenolic foam [5] and ultrafine glass fibers [6]. Different core materials have different advantages and drawbacks.

The laminated glass fiber (GF) is a typical core material of VIP developed in Asia due to its low thermal conductivity, high modulus, high toughness, light weight and non-combustible property. However, fiber-bridging significantly exist under the low-pressure condition inside VIP, resulting in solid heat conduction intensified between the layers. Also, the VIP with pure GF core is comparatively soft. In this paper, aluminum foil were orderly arranged in 30 cascading layers of GF

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core, 10 different new structural VIPs with "1−10GF+1Al" were got to compare with the pure 30GF core VIP. The influence of different layers of Al foil on the thermal conductivity and flexural strength of VIPs were discussed to obtain the optimum layers of Al foil in 30GF core material. These provide a new way of improving the VIP's flexural strength and heat-insulating property, resulting in a great significance for exploiting the use level and application market of glass fiber core VIPs.

2. Experimental details

Raw materials, including core materials, aluminum foils, envelope materials and getters used in this study were provided by Suzhou V. I. P. New Material Co., Ltd. (Taicang City, P. R. China). Glass fiber core material layers with dimensions of 490mm × 210mm × 0.4mm were fabricated by wet method. The wet method included the following steps: ①Providing slurry of glass fibers; ②Dewatering the slurry to form a wet-laid mat; ③Drying the mat; ④Cutting the mat to form the finished glass fiber core material layers [7,8]. VIP core materials were made up of 30 pieces of as-prepared glass fiber core material layers and aluminum foils with dimensions of 490mm × 210mm × 0.007mm were orderly added in the 30 cascading GF layers.

The layered core material samples were dried at 150℃ for 1 hour. VIPs with core materials which were structured at different layered conditions (In Tab. 1) were produced after the same vacuum process. The barrier membrane with one side aluminum foil and the other side aluminum plating film were used. The used getter was smart combo getter from Italy SAES Company. The initial thermal conductivities of VIP samples were evaluated by EKO thermal conductivity detector HC - 120 quickly. And the accurate measurements of thermal conductivities were evaluated by the heat flow meter thermal conductivity instrumentation Netzsch HFM 436.

Flexural strength was compared between the different samples by electronic universal testing machine CTM 2200, according to GB/T 1456−2005 standard [9]. Flexural strength tests were carried out using rectangular samples with proportion of 490mm × 210mm, while the span and velocity of the machine grips were 490 mm and 2 mm/min, respectively. Surface morphology of the core materials was observed by scanning electron microscopy (SEM, Model SU8010).

Tab. 1 VIPs with core materials which were structured at different layered conditions

Sample No.	Structural Units	Total GF layers	Total Al layers
1	Pure GF	30	0
2	10GF+1Al	30	2
3	9GF+1Al	30	3
4	8GF+1Al	30	3
5	7GF+1Al	30	4
6	6GF+1Al	30	4
7	5GF+1Al	30	5
8	4GF+1Al	30	7
9	3GF+1Al	30	9
10	2GF+1Al	30	14
11	1GF+1Al	30	29

3. Results and discussions

3.1 Experimental results of thermal conductivity

The EKO thermal conductivity detector HC - 120 was used to quickly eliminate the nonconforming products. Then, the thermal conductivities of effective samples 1~11 were evaluated and the data were shown in Fig. 1. Sample 1 represents the pure 30GF core VIP, its initial thermal conductivity tested 3 days after production was 2.278mW/(m · K). The data of sample 3, 5~11 were much larger, which were 2.330mW/(m · K), 2.340mW/(m · K), 2.343mW/(m · K), 2.409mW/(m · K), 2.667mW/(m · K), 2.589mW/(m · K), 2.864mW/(m · K) and 3.908mW/(m · K), respectively. While sample 2 with the structural unit "10GF + 1Al" had the lowest thermal conductivity 2.146mW/(m · K), sample 4 with the structural unit "8GF + 1Al" second, its thermal conductivity was 2.283 mW/(m · K). The curve of the test data 25 days after production demonstrated the same trend.

Centre of panel thermal conductivity (λ_{cop} of a VIP core) is a summation of the solid conductivity, gaseous conductivity and radiative conductivity and can be expressed using Eq. (1) [10].

$$\lambda_{cop}=\lambda_S+\lambda_R+\lambda_G+\lambda_{coup} \quad (1)$$

Where λ_S is the solid thermal conductivity, λ_R is the radiative thermal conductivity and λ_G is the gaseous conductivity. Here λ_{coup} is the thermal conductivity caused by a complex interaction between gas and laminated construction in the composite. This term, λ_{coup} rises exponentially at higher pressures. However, at low pressure this term can be negligible. Solid conduction takes place through the structure of core material where heat is transmitted through the physical contact of fibers of core material. Solid conductivity is a material property and its value depends upon material structure, density and external pressure on the core. Materials with low density are preferred for achieving low solid conduction. Thermal conductivity in VIP core can be lowered by restricting the gaseous and radiative conductivities [11].

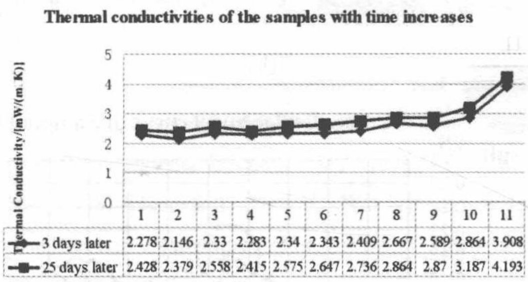
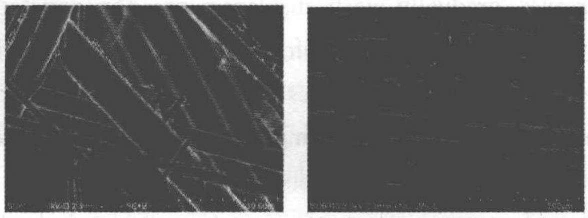


Fig. 1 Thermal conductivities of the 1～11 samples evaluated at 3 days and 25 days after production

Glass fiber, owing to its very small aperture size and low bulk density has a low solid conduction, but suffers from a lower resistance to radiative heat transfer. Aluminum foil can be added effectively to restrict the gaseous and radiative conductivities. Nonetheless, caution has to be exercised when using aluminum as these typically have high solid thermal conductivity which means higher content of aluminum will lead to a higher solid thermal conductivity offsetting any benefit it provides by reducing the radiative conductivity; on the other hand, an insufficient amount of aluminum in a VIP core will lead to a higher radiative conductivity. Hence, an optimum mass proportion of a given aluminum needs to be identified to achieve a minimum radiative conductivity in VIP cores. Experimental results showed that the optimum layers of Al foil for 30GF core are 2, and the structural unit is "10GF+1Al".

3.2 Microstructure and microstructural model of core material

The properties of VIP core material are closely related to their structure, which depends on the preparation method, the microstructure, chemical composition, and the phase of VIP core materials [12]. The SEM micrographs of VIP core material were shown in Fig. 2. As seen in Fig. 2(a), fiberglassVIP core material consisted of a mass of randomly oriented, super-cooled glossy fibers of varying lengths and diameters. The average diameter of the fiberglass was about 2～6 mm [13]. As shown in Fig. 2(b), the VIP core material was made up of continuous fiber layers which were parallel to each other. These horizontally oriented fiber layer faces were perpendicular to the direction of heat flux. Thus, the thermal conductivity of VIP core material could decrease [14, 15].



(a) (b)

Fig. 2 SEM micrograph of VIP core materials

(a) Fibers of varying lengths and diameters;

(b) Horizontal oriented fiber layers

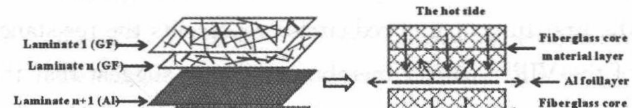


Fig. 3 Microstructural model of laminated core material

Fig. 3 shows the microstructural model of core material. Each core material layers consisted of continuous parallel fibers and aluminum foil laminates. The real morphology of core material could be described by a simplified model [16], i. e., multiphase medium model [17]. Representative elemental volume [18, 19] in the model at microscopic level consisted of solid phase (i. e. glass fibers), gas phase (i. e. air, water vapor and other gases), and impurity phase (small water droplets and specially introduced additions). Gas phase filled in the voids among solid phases while the impurity phase attached to the surface of solid phase.

Aluminum foils have low emissivity and density, commonly used as the reflector screen in multi-layer insulation and outer protective structure for thermal insulation. Hence, adding aluminum foil laminates artificially to block vertical thermal bridge is an effective way to restrict the gaseous and radiative conductivities between GF layers. But the laminates are not the more the better, there are an optimum laminates of Al foil in the core as mentioned in 3. 1. This is because vacuum resistance and solid thermal conductivity increases with the layer and/density, resulting in an increase in thermal conductivity of residual gas.

3. 3 Measured results of flexural strength

According to the charts, the flexure strength of sample 1, 2 and 11 is 3MPa, 3MPa and 4MPa, respectively. As shown in Fig. 4 (a), the bending force increases gradually with displacement, the resistance distribution is relatively uniform, and is consistent with the structure characteristics of pure glass fiber core material. Two obvious turning points (tag in red circle) can be found in the force-displacement curve of Fig. 4 (b), each turn represents the resistance of aluminum foil layer, which is also consistent with the structural characteristic of "10GF + 1Al" sample. Due to the alternating layers of aluminum foil and glass fiber, there are a lot of twists and turns in the curve of Fig. 4(c), the first turn (tag in red circle) represents the resistance of the VIP's barrier membrane. These suggest that the core material of aluminum foil may increase the bending strength of VIP.

4. Conclusions and outlook

Al foil layers properly laminated in the core can make a contribution to the insulating performance and flexural strength of VIP. To balance solid, residual gas and heat conductivity, there is an optimum number of laminates of Al foil in the core, for instance, the optimum Al layers for 30GF core are 2, and the structure is "10GF+1Al". This provides a new way to increase the stiffness and the service life of GF core VIP, further promoting GF VIPs' application in the top field like aerospace and navigation.

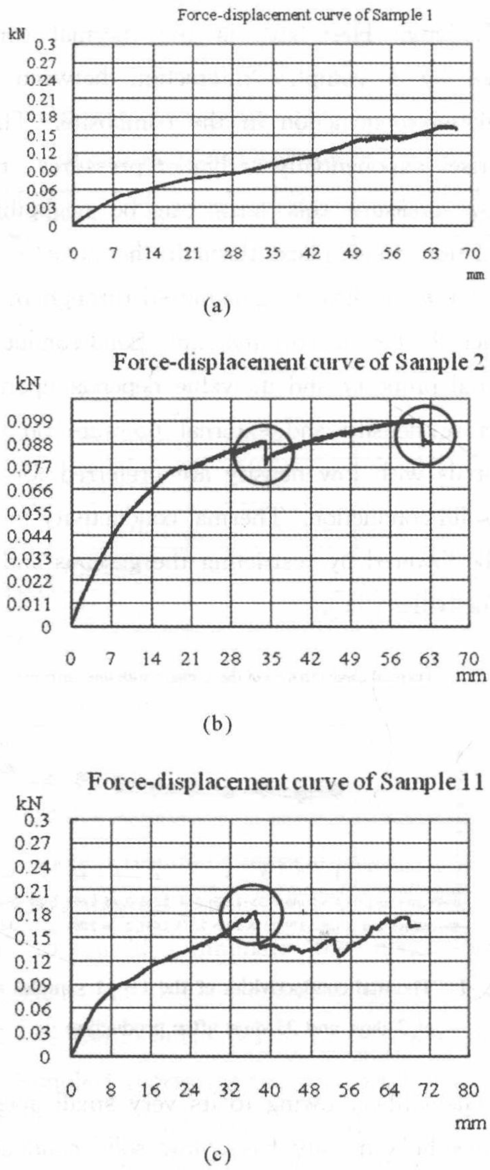


Fig. 4 Force-displacement curve of sample 1, 2 and 11

(a) Force-displacement curve of Sample 1;

(b) Force-displacement curve of Sample 2;

(c) Force-displacement curve of Sample 11

Acknowledgements

The authors would like to express their gratitude to the Suzhou V. I. P. New Material Co., Ltd. for the facilities provided during the experiments and all their valuable support. This work was carried out with the scientific research innovation projects for ordinary university graduate students in Jiangsu Province (No. SJLX_0126) and the Jiangsu Project BA2013097 and National Project 2015DFI53000.

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Effect of the Number of Core Material Layers on the Interior Pressure and Thermal Conductivity of Glass Fiber Vacuum Insulation Panel

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Abstract

Compared with other types of vacuum insulation panels (VIPs), glass fiber VIPs (GF - VIPs) have better initial thermal insulating properties and lower price but need a higher vacuum to ensure their durable service life. In this paper, the core materials for GF - VIPs were made up of 8, 16, 24 and 32 pieces of 1mm-thickness core material layers (CMLs). The microstructure and compression ratio of each core material was recorded. The interior pressure of the as-prepared GF - VIPs possessing 8 pieces of CMLs rose rapidly from initial 6.1 Pa to 10.2 Pa in 10.5 hours while that possessing 16 and 24 pieces of CMLs almost grew linearly from original 1.4 Pa to 10.2 Pa in 120 hours and from incipient 1.3 Pa to 10.4 Pa in 409 hours, respectively. Conversely, GF - VIPs possessing 32 pieces of CMLs had an excellent pressure holding ability, having maintained at a low interior pressure of less than 5 Pa for 300 hours. Thermal conductivity of GF - VIPs with 8 pieces of CMLs was at among the highest while that of GF - VIPs with 16, 24 and 32 pieces of CMLs increased with the thickness of the core. In order to obtain high-quality GF - VIPs with long-term service life and low thermal conductivity, the number of CMLs in a GF - VIP should be between 16 and 32.

Keywords vacuum insulation panel, core material layers, interior pressure, thermal conductivity

1. Introduction

In recent decades, energy-saving technology has been widely investigated in order to mitigate climate change triggered by the increase of CO_2 emissions [1]. A superior thermal insulation system called vacuum insulation panels (VIPs), which have about 5 to 10 times higher thermal resistance than the conventional insulators such as polystyrene or polyurethane foams, provides alternative solution for the worldwide problem [2]. Compared with other types of VIPs such as fumed silica VIPs, glass fiber VIPs (GF - VIPs) exhibits a distinguished low thermal conductivity of less than 0.004 W/(m · K) and become an ideal thermal insulation materials in refrigeration and cryogenics [3, 4].

Generally speaking, the core material for GF - VIPs (GF - CM) consist of several or dozens of parallel glass fiber core material layers (CMLs). It was reported that the thermal conductivity of GF - VIPs greatly increases with the interior pressure when the interior pressure is higher than 10Pa. An extremely low and stable interior pressure of less than 100Pa is the prerequisite for high-quality GF - VIPs with low thermal conductivity. Due to the specific characteristics of the GF - CM, both the structures of the overlay core material and the single CML affects the thermal insulation properties of the GF - VIPs. Kim et al. [5] studied the relationship between pore size of GF - CM and density and the thermal insulation performance of GF - VIPs under variable pressing load and vacuum level. Di et al. [6] investigated the dependence of thermal conductivity of two different types of GF - VIPs on gas pressure theoretically and experimentally while Li

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et al. [7] explored the mass transfer within GF - VIP enclosure in a vacuum and the influence of pressure holding time of extraction process on thermal conductivity of the GF - VIPs. Although vacuum-pumping system can reduce the interior pressure within VIP enclosure to a minimum, it is difficult to achieve a high vacuum between all layers in the GF - CM [8]. Moreover, the gases in the surrounding environment may slowly permeate into the GF - VIPs, resulting in an increase in interior pressure of GF - VIPs. The gases within VIP enclosure may desorb on the warm side and adsorb on the cool side in the closed system and aid on an increase in thermal conductivity of the GF - VIPs. Glass fibers may function as a wick and block the movement of the gases within VIPs and thus suppress the thermal conductivity. However, to the best of the authors' knowledge, few literatures analyzed the dependence of thermal conductivity of GF - VIPs on the microstructure of core material. Again, there are few literatures that have analyzed the effect of the number of CMLs on the thermal conductivity of GF - VIPs.

In this paper, the GF - CMs were composed of different numbers of CMLs. The cross-sectional morphologies, pore parameters and compression ratios of the GF - CMs were investigated. The changes in the interior pressure of GF - VIPs with time were recorded and the thermal conductivity of each GF - VIP was compared. The aim of this paper is to obtain a high-vacuum-state and long-term GF - VIPs.

2. Experimental

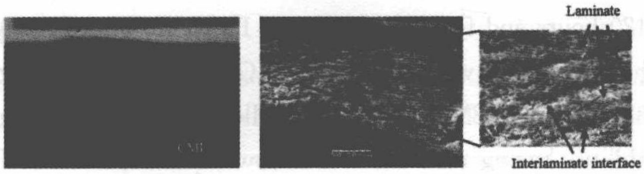
Raw materials, including GF - CMs, envelope materials and getters used in this study were provided by Suzhou V. I. P. New Material Co., Ltd. (Taicang, P. R. China). Among them, GF - CMs, consisting of 70% centrifuged glass wool and 30% flame attenuated glass wool, were produced by wet method (described in Ref. [7]). The length, width, and thickness of each CMLs was 410mm, 290mm, and 1mm, respectively. The GF - CMs were composed of 8, 16, 24 and 32 pieces of 1mm-thickness CMLs. The envelope materials were made up of four layered film with an overall thickness of 95 μm, i. e., polyamide film (PA, 15μm), polyethylene terephthalate film (PET, 12μm), aluminum film (Al, 7 μm) and polyethylene film (PE, 55 μm). Firstly, the GF - CMs were dried at 150℃ for 60 mins, and then bagged in envelope materials. Afterwards, the GF - VIPs were produced by vacuum process.

The cross-sectional morphologies and the pore parameters of GF - CMs were analyzed by scanning electron microscopy (SEM, JEOL JSM - 6360) and mercury injection apparatus (AutoPore IV 9510), respectively. The as-prepared GF - VIPs were placed in a closed room at 35℃ and 37% R. H. The interior pressure and thermal conductivity of each GF - VIP were measured by convection vacuum gauges (CVM201 Super Bee TM) and heat flow meter (Netzsch HFM 436), respectively.

3. Results and discussion

3. 1 Microstructure

Fig. 1 shows the cross-sectional morphology of the GF - CMs. At the macroscopic level (see Fig. 1(a)), the GF - CM was made up of continuous CMLs which were parallel and in contact with each other. The CMLs were flat, thin, rough, and flexible, but could not be coiled beyond a certain limit because of low strength. There was nearly a straight small space called "interlayer interface" between two CMLs. At the microscopic level (see Fig. 1(b)), each CML possesses a stable structure. Glass fibers within each CML were randomly oriented. There were also some parallel micro-spaces called "interlaminate interface" existing in each CML. Actually, each CML was touched at isolated microcontacts which were interspersed with gaps; and the real contact area between two CMLs was the sum of these microcontacts. The limited number and size of the microcontacts resulted in an actual contact area which was significantly smaller than the apparent contact area.



(a) Macrostructure (b) Microstructure

Fig. 1 Cross-sectional morphology of the GF - CMs

Fig. 2 shows the pore diameter distribution of the CMLs. Most of pores diameter concentrated between