A Review of Maintenance of Vacuum inside Vacuum Insulation Panels

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The growing concerns over global energy crisis and the phasing out of polyurethane foams blown with CFC-11, which has high Ozone Depletion Potential(ODP), have pushed thermal insulation technology to improve its efficiency. Vacuum Insulation Panel(VIP) has been regarded as a super thermal insulation material with a thermal resistance of about 5–10 times higher than conventional thermal insulation. Appropriate vacuum in VIP is one of the most important factors contributing to the long term heat insulation performance of VIP. In this paper, the researches on three factors, which influence internal pressure inside VIP, including gas and water vapor permeation through the barrier, gas absorption by getters and desiccants and out-gassing of the kernel, were reviewed respectively. Following this, the research emphasis and suggestions, which should be paid attention to, were summarized.

1. Introduction

VIP consists of a filler material that is encapsulated by a thin, super-barrier film. The encapsulated system is then evacuated to a vacuum about between 0.1 and 100 Pa and sealed. The actual vacuum required depends on the specific core material used and the desired thermal resistance of the finished panel^{1,2)}. In addition, getters or desiccants are essential to absorb residual gases in order to maintain the vacuum level. When 40% polyurethane foam in the wall of a refrigerator is replaced with VIP using open-cell polystyrene foams as core materials, the energy factor (L/kWhr/Month) (energy performance in Chinese national standards, the energy consumption per Litre per month in a refrigerator) for the refrigerator can be enhanced about 30%³⁾.

The basic heat transfer mechanisms are conduction, convection and radiation, while in VIP, heat transfer occurs through the modes of conduction of the core material and the residual interstitial gas, and radiation through absorbing, scattering and emitting filler materials⁴⁾. The other basic heat transfer mode, convection, is usually considered to be negligible due to vacuum condition. For gas conduction, the mean free path of the gas molecules is smaller or approximately equal to the pore size because of vacuum condition, which makes the gas conduction very weak. The special porous structure of the kernel makes the heat conduction through the solid in VIPs much weaker too. In addition, the porous solid in VIP provide effective resistance to heat radiation. From the analysis above, three basic heat transfer modes in VIP have been eliminated greatly, as a consequence, an excellent performance in heat insulation of VIP can be obtained. The thermal insulation performance of VIP is greatly depending on the vacuum level.

Fig. 1 Thermal conductivity of fibers, powders and foams as a function of gas (air) pressure.

When interior pressure surpassing 100Pa, thermal conductivity of a VIP with core materials of foams or glass fibers will increase sharply. While regarding kernel of silica powders, the pressure at which thermal conductivity of a VIP starts to increase significantly will be postponed to about 1000 Pa for precipitated silica and 10000 Pa for fumed silica respectively, as shown in Fig. 1⁵⁾.

During the service life, climatic conditions have a great influence on the degradation of VIP. Firstly, permeation of dry atmospheric molecules (O_2 , N_2 , CO_2 , etc.) through a more or less permeable barrier film surface or the edges and seams will contribute to the vacuum deterioration. Secondly, water vapor infusion will cause the total pressure increase⁶⁾. Not only the pressure increase within the VIP but also the penetrated water vapor that is adsorbed by the core material will lead to a direct increase in the thermal conductivity of the evacuated porous core materials⁷⁾. Thirdly, temperature factor will enhance the permeation influence. In addition, the degradation effect is also related with panel size or circumference of a VIP, the performance of getters and the outgassing rate of the core materials.

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2. The influence of gas and water vapor permeation through barrier

2.1 Structure of barrier films commonly used in VIP

One of the most critical components of a Vacuum Insulation Panel is the barrier envelope, which is responsible for the maintenance of vacuum inside VIP, especially for long-term application like in building sector. An excellent barrier film for VIP can provide sufficient resistance against the penetration of O_2 , N_2 and H_2O , etc., although it will also result in thermal bridging across the edges of the VIPs. The barrier material selection must balance several important qualities. First, they must offer high resistance to gas transfer, something that metals excel at. Second, the skin must offer high resistance to heat transfer through the barrier material itself, an area where plastics are better than metals. The third consideration is that the barrier must be cost effective to form and must be relatively easy to seal.

Polymer and metal barrier alone do not meet the requirements of VIP such as low gas and water vapor permeability, low thermal conductivity, strength, toughness, formability and sealability. Metal layers are usually regarded as the most excellent gas and vapor barriers so far. Rolled aluminium layers of $9\text{ }\mu\text{m}$ and more are considered as air and moisture tight⁶⁾. As for the foils used in VIP, there is a strong thermal bridge effect along the VIP circumference caused by the more lager thermal conductivity of aluminum compared with that of evacuated core⁷⁻¹⁰⁾, so the metal layer must be as thin as possible. Generally, there are two types of films used in VIP. Metal film (AF): a central aluminium layer with a thickness up to $10\text{ }\mu\text{m}$. The aluminium layer is laminated between an outer polyethylene terephthalate (PET) layer (that offers some scratch resistance) and an inner

Fig. 2 Schematic view of barrier film used in the fields of refrigeration in Japan.

Fig. 3 Schematic view of barrier film used in the fields of building.

polyethylene (PE) sealing layer. Metallized films (MF): they also have an inner PE layer for sealing purposes. To this layer, up to three layers of PET film with a one-side aluminium coating are laminated. The thickness of each aluminium coating usually varies from 20 to 100 nm ¹¹⁻¹³⁾. Due to such small thickness of the metal layer, some pin hole defects will exist while manufacturing, which will increase the probability of gas and vapor permeation^{14,15)}. As a consequence, generally, two or three such Al layers are integrated into the laminate with specific purpose respectively. Typical diagrams of MF used in Japan¹⁶⁾ for freezers and Europe¹³⁾ for buildings are shown in Fig. 2 and Fig. 3 respectively.

2.2 Recent experimental researches on gas and vapor permeation through barrier films

The anti-permeation performance of barrier films has been investigated deeply and comprehensively in Germany and Switzerland. Especially in Germany, the rate of pressure rise and mass increase in VIPs with different foils and panel sizes were tested under specified conditions of different temperatures and relative humidities by Schwab etc¹⁷⁾. It can be concluded that the air and vapor transmission rates of the foil covers depend on temperature, relative humidity, foil type and panel size. The higher the temperature and humidity, the lager pressure increase occurs in VIP, which can be contributed to the concentration difference and the transmission ability of gas and vapor. It is interesting that If the panel circumference L is doubled, approximately one half of the rate of pressure increase occurs. The author indicated that the pressure increase is mainly caused by the length-related gas transmission rate¹⁷⁾. The influence of moisture on thermal conductivity also has been investigated. The increase is about $0.5 \times 10^{-3}\text{ W/(mK)}$ per mass% of water. For typical middle European climate, a maximum moisture content of about 6 mass% can be expected, which corresponds to a maximum increase of thermal conductivity of about $3 \times 10^{-3}\text{ W/(mK)}$ for VIPs with fumed silica kernels^{18,19)}. Martin etc.²⁰⁾, from a real construction perspective, gave an overview of the requirements for and the behaviours of VIPs integrated into building components and constructions according to the results of predecessors.

Brunner²¹⁾ focused on the deterioration of the barrier function of two different MF laminates with defects in the laminates visualized by means of focused ion beam etching. Simmler and Brunner²²⁾ did an experiment for

VIP used in a real terrace building on a hill side to investigate the aging mechanism and results for different temperature and humidity induced deteriorations. A larger temperature and humidity range was adopted than that of Schwab's in order to evaluate the more practical applications. The trends of all factors are same as Schwab's. There is a new discovery when using a cyclic condition (8h at 80°C/80% R.H. and 4h at 25°C/50% R.H.), in which pressure and moisture content increase rate are more severe than a constant 80°C/80% R.H.. This may arise either from shear strain or by cyclic condensation of water on the "cold" VIP surfaces being delayed in temperature-humidity rise periods.

2.3 Recent models to predict pressure increase and resultant increase in thermal conductivity of VIP

A linear increase in pressure in VIP was got on the assumption of a constant climatic conditions and pressure difference across VIP¹⁸⁾. Based on the total gas transmission rate, which includes the surface-related (gases permeate through the surface of barrier film) and length-related (gases permeate through the sealings) transmission rate, the pressure -related gas transmission rate, called permeance, was got. Through that, accompanied by ideal gas equation, the pressure increase with time was obtained. The change of water content with time can be calculated based on sorption isotherm of different cores¹⁷⁾. Then, the total thermal conductivity, which consists of the thermal conductivity of the core in the evacuated and dry state, gaseous thermal conductivity at a certain gas pressure caused by gas permeation and thermal conductivity induced by water content, can be calculated. A dynamic thermal model to predict the internal pressure in VIP was also developed on the basis of experimental results for different temperature and humidity induced deteriorations of MF and AF barrier films^{22,23)}. In the model, the influences of temperature and humidity on the pressure increase were described by Arrhenius function and sorption isotherm respectively. With the model, the thermal conductivity of VIP over time of 25 years was calculated with some measured data.

Some numerical models were also developed to predict the degradation of barrier films. The pinhole theory introduced by Decker²⁴⁾ was the basis of numerical models. A 3 dimensional diffusion problem was modeled through standard Finite Element Analysis software²⁵⁾. Focused on the oxygen transmission rate (OTR), the model provides an approximate OTR for barriers that have an OTR below the current limits of testing, as well as an alternate barrier construction design direction. A promising application of VIPs in buildings with extruded polystyrene (EPS) foam as protective layer was analyzed both numerically and experimentally¹⁾. It is indicated that the integration of VIP with EPS foam as protective layer in construction can greatly decrease insulation thickness by 3.5 times compared with the traditional insulating material with a thermal conductivity of 0.036 W/(mK). In addition, the protective foam added can reduce the edge effect of the VIPs caused by the aluminum layers within their barrier envelope.

3. The outgassing influence of core and getters effect

3.1 Outgassing influence of the core

Pressure increase due to outgassing of the core into the panel will influence the long-term performance of the VIPs, especially for VIPs with core of open-celled foams²⁶⁻³¹⁾, which were commonly used in refrigerators (open-celled foam is in contrast with the traditional close-celled foam used as heat insulation material. Up to 95% cells in the open-celled foam are not closed but connected with atmosphere). Open-celled foams will absorb water vapor and other atmospheric gases after being produced, and the absorbed gases will dissolve and diffuse into the interior space of a VIP, which will lead to a pressure increase in VIP gradually. So pretreatment of the core before it is enveloped in vacuum condition is needed for decreasing the negative effect of outgassing as well as gas permeation through barrier films. WEI-HAN TAO²⁶⁾ and C. G. Yang²⁷⁾ investigated the baking effect of open-celled foams on weight loss and outgassing rate respectively. The weight of 24.3 g for an open-celled PU foam became constant after baking at 120°C for 15 min with a weight loss of 0.7 g. The specific outgassing rate can be decreased significantly compared with that of unbaked foams. Also, The specific outgassing rate of the foam was tested not only at room temperature but also at low and high temperature by an orifice known-conductance method²⁷⁾. It has been found that the specific outgassing rate is large for PU-foam, and has a decreasing trend with decreasing temperature. In a log-log plot of specific outgassing rate versus time, the decay exponent ranges from 0.62 to 0.8 with temperature changes from 20°C to 70°C. Related research works are also shown in other papers^{28,29)}, in which the outgassing rates for specified gas type are given by means of quadrupole mass spectrometer.

3.2 Getters and desiccants

Getters are necessary to ensure the required vacuum level during the service life of a VIP, which will effectively adsorb gases like H₂O, N₂, O₂, CO, CO₂, H₂ as well as blowing agent gas used in producing the foams. Without getters, even not accounting for water, the total pressure in a 0.5 m × 0.5 m × 0.02 m VIP with open-celled foam as core will exceed 300Pa after 20 years²⁹⁾. Getters can be either evaporable or nonevaporable. The former type of getters is commonly based on Ba alloy and Ni powders, filling a ring- or wire-shaped container. BaAl₄ is used instead of pure Ba because of the reactivity with moisture. Nonevaporable getters are metal alloys usually based on Zr and Ti and used in powder form to increase their surface area and improve their sorption capacity and speed³⁰⁾. Both the two type getters need to undergo a heat treatment with high temperature called activation process. Due to the high temperature pre-heat treatment and the limited sorption capacity for above chemical getters as well as physical adsorbents like molecular sieves, zeolites and activated charcoal, SAES Getters S.p.A has made great progress and manufactured products branded as COMBOGETTER with good properties used in VIP with foam core. The getter is a new alloy composed

of barium and lithium in a 1 to 4 atomic ratio³²⁾, with which, most gases and water vapor can be absorbed with moisture adsorbents (Co₃O₄ and CaO) added²⁹⁾.

4. Outlook and Suggestions

VIP technology has experienced a great progress in insulated shipping containers, refrigerators and freezers, refrigerated trucks and buildings. Especially, Technology of VIPs with core material of fumed silica used in building construction has been researched comprehensively and deeply in terms of thermal properties and aging problems etc. in last decade since ZAE Bayern manufactured about 100 VIPs and integrated them into the facade of its new building in 1999. Although VIPs have great advantages over traditional insulating materials in reducing energy consumption, there are some problems should be solved as soon as possible to promote the application of this advanced technology.

(1) Detailed research on VIPs with real built-in environment

As for VIPs used in building constructions, the real built-in environment is somewhat different from that in lab because VIP is only one of the layers inserted into the whole roofs, floors and walls with protective layer, waterproof layer etc., which will influence the aging process of VIPs. In addition, in the real environment, VIPs are subjected to a certain mechanical stress, which will also stimulate the degradation. With respect to VIPs with foam material, for instance, there is a foaming process to fill the residual space after the VIP is inserted into the wall of a refrigerator. The high temperature during the foaming process will put effect on the degradation process of VIPs.

(2) Much higher cost problem

This is the most critical obstacle, which greatly hinders the use of VIPs on a large scale. It is known that the cost of materials (core, high barrier film and getters) represent a high portion of total cost, in addition to expensive manual work. So, adequate financial support should be provided by governments to ensure the continuous research on cheap materials with high quality related with VIPs. With respect to expensive manual work, automatic production process emerged has weakened the negative influence. In addition, governments should stimulate the use of VIPs by means of compensating consumers due to the additional cost in order to deal with the globally environmental change and energy crisis.

(3) Quality control

As is known, VIPs have very sensitive and vulnerable barrier film, which is essential and will be damaged in handling and installation processes. So, regulations related to this problem should be established and effective corresponding monitor measures should be developed and implemented during the whole process from production to installation.

(4) Standard establishment

Compared with traditional insulation products, production process, quality control, and declaration of properties for VIPs have not been standardized, which is

another factor to block the production and application of VIPs.

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