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Gas permeation characteristics through heat-sealed flanges of vacuum insulation panels

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ABSTRACT

Application of vacuum insulation panel (VIP) is becoming more practical to reduce the thermal energy loss and to reduce CO_2 emission. Outstanding insulation performance and extended service life are the two critical factors in the VIP engineering. Thermal insulation performance of a VIP is degraded with time due to gradual increase of pressure in the VIP. Keeping the effectively low pressure is a key technique to improve the service life. Permeation of gases through heat-sealed flanges in the lateral direction has the greatest effect in it, together with permeation of gases through normal direction to the envelope sheets. This study is made to investigate the permeation characteristics of the envelope seal materials (typically linear low density polyethylene, LLDPE, and low density polyethylene, LDPE). A measurement apparatus using multiple radial permeation passages is designed to measure the gas permeation rate through the polymer films. The measurement shows reliable accuracy compared with other reported results. Inner pressure change in the VIP, which is enveloped with Al-foil-based film, is calculated based on the experimental results of gas permeabilties of seal materials. It is found that the permeation characteristics of heated LLDPE is the same as heated LDPE and unheated LLDPE. H_2O, O_2, and N_2 show greatest permeations in this order. Unlike fumed-silica VIPs, glass wool VIPs may exhibit short service life due to this permeation.

1. Introduction

Recently, energy crisis and environmental issues have come to the fore as the major problems that can threaten human life. While researches for renewable energy as the solution are extensively conducted, ratio of the renewable energies to the total energy consumption is only about 8% [1]. This is far from sufficient considering the explodingly increasing energy demand and limited resources of economical energy. Alternatively, improving the energy efficiency is more practical, considering that as much as 40% of the total energy is spent in buildings to compensate the heat loss [2]. More specifically, enhancement of thermal insulation for the buildings, refrigerators, low temperature storage tanks, and so on is the thought to be a major solution, which can be made possible through the use of VIPs. Conventional insulation materials such as EPS (expanded polystyrene), PU (polyurethane) and glass wool contain gases inside the pore so that their thermal conductivities impose lower limits of thermal conductivity ($k_{air} \approx 0.026$ W/m K). On the other hand, thermal conductivity of a VIP is about 1/5 to 1/10 of k_{air}; energy consumption can be virtually reduced to zero even with a thinner insulation [3].

Nevertheless, VIP has a few technical problems, one of which being that the thermal performance is degraded with time due to permeation of air from outside. The service life of the VIP must be guaranteed for 10–15 years for home appliances or more than 50 years for buildings, which is currently a formidable goal. Accordingly, this research is made to investigate the permeation of gases in the VIP.

Here, it is appropriate to introduce the mechanism of residual gas conduction in VIPs. Thermal transport in a VIP is made by three modes [4,5]: conduction via core material and the envelope, residual gas conduction and radiation. Among these heat transfer modes, the service life of the VIP is related with the gas conduction, while it is widely conceived that the others do not change with time. (Lately, however, it is reported by S. Brunner et al. that solid conduction can be increased in a few years due to growth of the interfacial area between the nanosized SiO_2 in case of pyrogenic silica core [6]). Gas conduction in rarefied state is a function of pore size and inner pressure. The resulting gas conductivity k_g is derived by Kwon et al. as follows [7].

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Nomenclature

a	outside radius of the annulus film, m
A_s	surface area, m^2
b	inside radius of the annulus film, m
C	gas concentration, mol/m^3
C_0	conversion factor from mole to volume
D	diffusion coefficient, m^2/s
J	gas permeation flux, mol/m^2 s
k	thermal conductivity, W/m K
K	gas permeability m^2/s Pa
L	total thickness of the annulus films, m
P	pressure, Pa
P_H	pressure at high pressure side, Pa
P_L	pressure at high pressure side, Pa
Q	gas permeation rate, m^3/s
R_u	universal gas constant, J/mol K
S	solubility, 1/Pa
t	time, s
T	temperature, K
V	volume, m^3

Greek symbols

δ	permeation length, m
φ	pore size, m

Subscripts

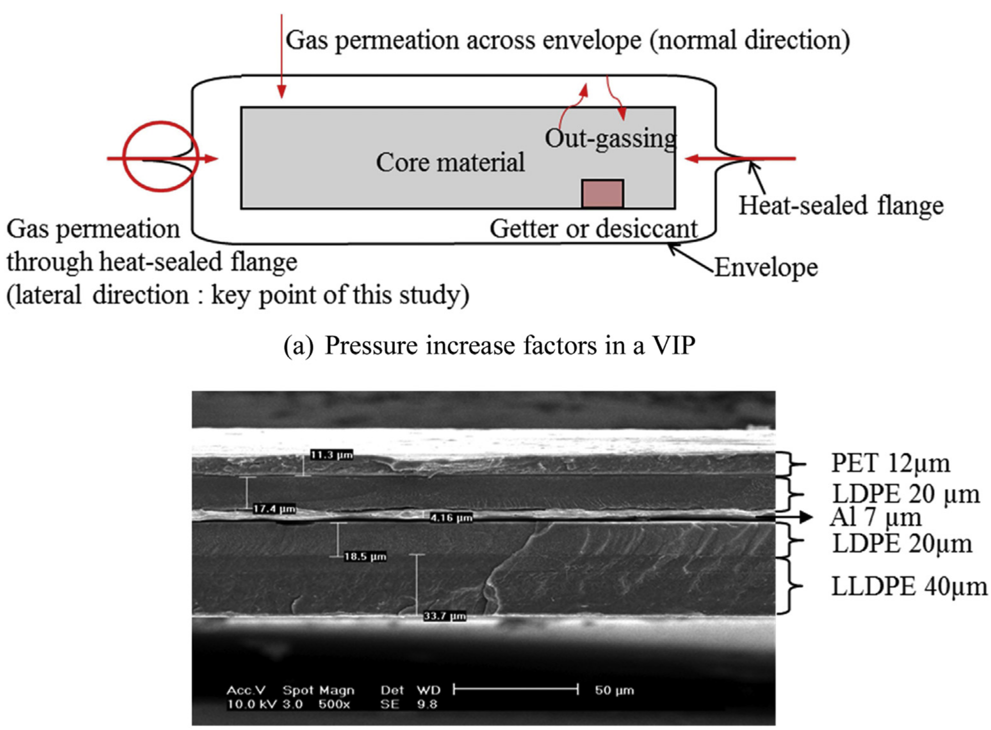
atm	atmospheric
cr	critical
g	gaseous
i	gas species

$$k_g = \frac{k_{g0}}{1 + \frac{0.032}{P\phi}}, \quad (1)$$

where k_{g0} is the thermal conductivity of the gas in continuum state, P is the inner pressure in Pa (N/m^2) and φ is the pore size (m) of the core material. The relation between inner pressure, pore size and effective thermal conductivity is demonstrated in Ref. [8]. The critical pressure P_{cr} here is be defined as the pressure at which the effective thermal conductivity reaches half of k_{g0}. It is smaller when the pore size is larger, which again means a shorter service life.

In practice, fumed silica powder and glass wool are mostly used as the core material. Both of them have advantages and disadvantages. While the initial thermal performance at the center of a VIP with glass wool is 2.0–3.5 mW/m K, which is better than that with fumed silica powder of 3.5–5.0 mW/m K, the service life of the VIP with glass wool is significantly shorter than that with the other one. This is because of their different pore sizes and thus, selection of the VIP should be made considering these two conflicting characteristics. Note that thermal conductivity at the center of the VIP which is mentioned earlier is lower than overall thermal conductivity because edge conduction is excluded. (This edge conduction cannot be neglected considering that metal layer of envelope is indispensable.). Consequently, more fundamental studies are necessary regarding the increase of the pressure and the change of thermal conductivity in the VIP.

Pressure increase factors are [9]: a) outgassing from inner surface of envelope and the core material and, b) gas permeation through the envelope. In case of outgassing, dissolved gas in the material can be effectively eliminated by baking it in vacuum at high temperature (above 80 °C). A more practical process is to add a



(a) Pressure increase factors in a VIP

(b) SEM image of the cross-section of a VIP envelope

Fig. 1. Schematic diagram of a VIP.