International Journal of Heat and Mass Transfer 64 (2013) 783–791

Contents lists available at SciVerse ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Vacuum insulation properties of glass wool and opacified fumed silica under variable pressing load and vacuum level

Jongmin Kim, Tae-Ho Song *

School of Mechanical, Aerospace and Systems Engineering, Korea Advanced Institute of Science and Technology, Guseong-dong 373-1, Yuseong-gu, Daejeon, Republic of Korea

ARTICLE INFO

Article history:
Received 27 November 2012
Received in revised form 10 April 2013
Accepted 4 May 2013
Available online 3 June 2013

Keywords:
Vacuum insulation panel
Fumed silica
Glass wool
Thermal conductivity
Pressing load

ABSTRACT

Insulation properties of glass wool (GW) and opacified fumed silica (OFS) as fillers of vacuum insulation panel are experimentally investigated for variable pressing load and vacuum level. Density change of the specimen as a function of the pressing force is measured. The thermal conductivity at center of panel is measured under various vacuum levels and pressing loads. To evaluate the radiative conductivity separately, the diffusion approximation is adopted and the extinction coefficient is measured by an FT-IR apparatus. As the density increases, the solid conductivity increases, while the radiative conductivity decreases to have their sum increased. Pore size is inversely proportional to the density of the material; however, the relation is not consistent in the case of OFS at very low density because of the highly heterogeneous porous structure at that density. Comparing the materials in terms of initial insulation performance at center of panel, we find that GW is superior at low pressing load and the other one is better at high pressing load. Also, OFS turns out to have a longer service-life.

1. Introduction

Energy consumed in building sector takes the greatest portion among the whole energy consumption [1]. Especially, nearly half of the building energy is used for space heating and cooling [2]. This energy is finally dissipated to the environment. Thus, huge amount of energy can be saved if the building insulation is enhanced.

Many countries are trying to regulate insulation of building wall more strictly. In Republic of Korea, for example, the thermal transmittance of building wall is limited to 0.36 W/m^2·K currently and will be reduced to 0.15 W/m^2·K by 2017, and 0.08 W/m^2·K by 2025 [3]. Since any conventional insulator has a thermal conductivity of 0.03–0.04 W/m·K, it needs thickness of more than 40 cm to satisfy the strict regulation. This is nearly impossible, especially for existing buildings which need insulation renovations. For this reason, a superior insulator with much lower thermal conductivity is urgently needed. It will save tremendous amount of energy and at the same time, the valuable building spaces.

As a new insulation method, vacuum insulation panel (VIP) is actively researched recently, as it has very low thermal conductivity (0.002–0.004 W/m K at center of panel) thanks to the evacuated inner space. It is generally composed of an envelope and a core. The envelope helps VIPs to be maintained at a vacuum state. It comprises laminated metal layers on polymer to prevent surrounding gas molecules from penetration. Conduction through the metal layers, in other words, the edge effect is very important issue because high thermal conductivity of them can significantly lower the insulation performance. However it is closely related to the envelope thus not treated in this paper.

Due to the outside atmospheric pressure, VIPs are always pressed. Thus, the core must sustain the pressing force. Insulation performance and service-life of VIPs are heavily dependent on the core material. Porous materials are frequently adopted because they can be evacuated easily. GW and OFS are typical examples in these days [4]. Insulation foams such as polystyrene and polyurethane foam have been used since the early stage thanks to their low price but they have relatively poor insulation performance and large pore size [5]. Phenolic foam may be also employed, but has large pore size, too [6].

Heat transfer in the core takes place by the solid conduction through skeleton of the core, the gas conduction through residual gas, and by the radiation. Each heat transfer mode can be represented by an equivalent conductivity and the total thermal conductivity of the core k_{cop} can be approximated by the sum [7–10];

$$k_{cop} \approx k_g + k_s + k_r, \quad (1)$$

where k_g, k_s and k_r are the gas, solid and radiative conductivities, respectively. The coupling term needs to be considered if water vapor pressure or working temperature is high in OFS-based VIPs [11,12], which effect is not considered in this paper. The gas conductivity is dependent on the gas pressure and can be neglected at a high vacuum. Therefore, the minimum k_{cop}, in other words,

* Corresponding author. Tel.: +82 42 350 3032; fax: +82 42 350 3210.
E-mail address: thsong@kaist.ac.kr (T.-H. Song).

0017-9310/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2013.05.012

Nomenclature

A	area, m^2
e_R	specific Rosseland mean extinction coefficient, m^2/kg
E	extinction coefficient 1/m
H	height of a specimen, m
k	thermal conductivity, W/m·K
l_m	mean free path of a gas molecule, m
P	gas pressure, Pa
P_{ext}	external pressing load, Pa
q	heat transfer rate, W
T	temperature, K

Greek symbols

Π	porosity
ϕ	pore size, m
ν	Poisson's ratio
ρ	density, kg/m^3
λ	wavelength, μm
σ	Stefan–Boltzmann constant, W/m^2·K^4
τ	transmittance

Subscripts

cr	critical
cop	center of panel
eff	effective
g	gaseous
r	radiative
R	Rosseland
s	solid

sum of k_s and k_r is achieved at high vacuum. This value is usually the catalog insulation performance of a VIP. Both k_s and k_r strongly depend on the packing density which again depends on the pressing load. If the pressing load is controllable, the insulation performance may be enhanced significantly. Unfortunately, the pressing load on VIPs is fixed at 0.1 MPa as far as the core must withstand the atmospheric pressure. This is true until lately and thus, the initial performance improvement of VIPs has been limited to the suppression of radiation.

Recently, a new type of core is proposed by Kim et al. [13]. It is composed of an artificial structure to support the atmospheric pressure fully or partially, and a separate porous material. Thanks to the artificial structure, the porous material is compressed by 0–0.1 MPa of pressing load. It is anticipated that the insulation performance of this type VIP can be significantly enhanced.

The objective of this paper is to investigate the insulation properties of this new type core under various vacuum levels and pressing loads. GW and OFS are used as the specimen. Heat transfer models to estimate k_{cop} is introduced first and the measurement results using devices such as vacuum guarded hot plate (VGHP) and FT-IR are presented. Finally, characteristics of GW and OFS as the core are discussed in depth.

2. Heat transfer models

The GW sample has a density of 165 kg/m^3 and porosity of 0.92–0.94 when uncompressed. It was made by a Chinese company. The fiber roughly aligned in-plane (Fig. 1(a)) and the fiber diameter is diverse from several hundreds of nanometer to 2 μm (Fig 1(a)). The OFS sample was manufactured by OCI Co., Ltd. It has a density of 45 kg/m^3, porosity of 0.98 when uncompressed and particle diameter of 7–40 nm (Fig 1(b)). It has certain amount of opacifier, whose size and mass fractions are classified. Suffice it to mention that the absorption coefficient is roughly greater than 1 mm^{-1} and this research is intended to reveal the general behavior pattern of OFS.

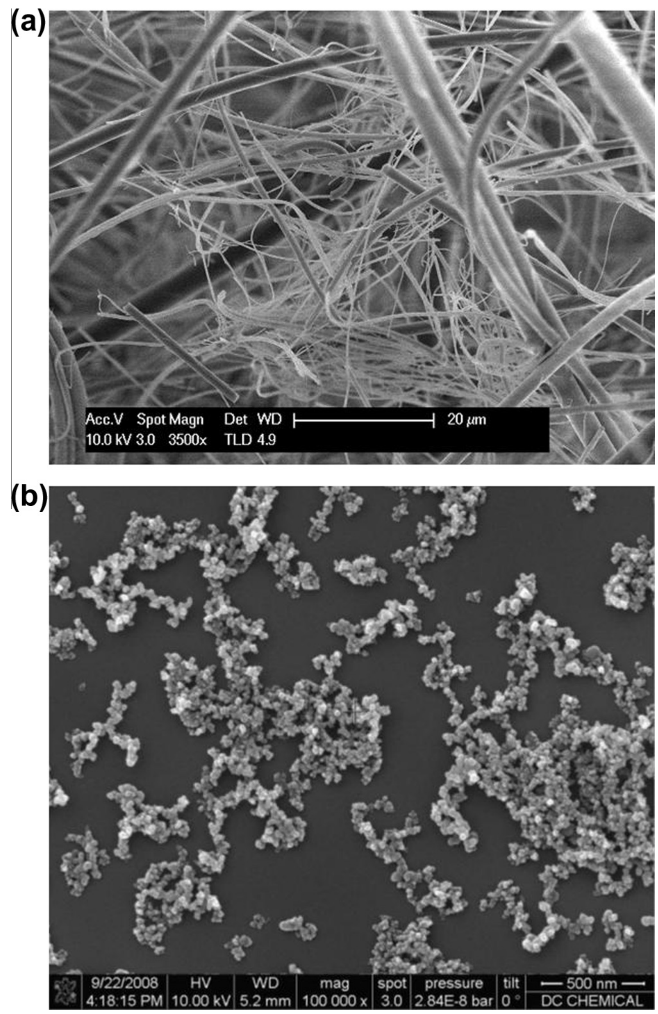

Fig. 1. SEM micrograph of (a) GW and (b) OFS sample (provided from OCI Co. Ltd.).

2.1. Solid conductivity

To predict the solid conductivity, we first review the model of Kwon et al. [14], who derived k_s of fiber and powder by approximating the porous structures. Fiber structure is idealized as beams stacked in staggered manner as shown in Fig. 2. Using this model, the solid conductivity of fiber $k_{s,fiber}$ in the vertical direction can be written as

$$k_{s,fiber}(\theta) = 16k_f\left[\left(\frac{\sqrt{2}\pi^4 E}{48P_{ext}(1-\Pi)^4(1-\nu^2)}\right)^{1/3} + \frac{\pi^2}{4(1-\Pi)^3\sin^2\theta}\right]^{-1}, \tag{2}$$

where k_f is the thermal conductivity of fiber at bulk state, P_{ext} is the pressing load, Π is porosity, E and ν are the Young's modulus and the Poisson's ratio, respectively and θ is the angle between lay-