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Low cost composites for vacuum insulation core material

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A B S T R A C T

Vacuum insulation technology provides unprecedented performance and its applications have expanded, particularly in the form of vacuum insulation panels (VIP). One of the challenges of using VIP include greater cost compared to traditional insulation because fumed silica is commonly used as the core material. The demand for low cost material with comparable service life to fumed silica constantly grows. Diatomaceous earth (DE) and glass bubbles (GB) represent alternative materials that have potential for cost effective VIP applications. The pore size distribution of the DE was determined quantitatively by mercury porosimetry and nitrogen sorption. The majority of pores in DE are ranged around 1 μm. The average pore size of GB was estimated to be 50 μm via scanning electron microscopy. Subsequently, the relationship between pore size and gaseous thermal conductivity was established using the Kaganer relation. Thermal conductivity measurements were made using the transient plane source technique, which produces higher values compared to steady state methods such as guarded hot plate. Therein, fumed silica was used as a baseline for all measurements performed in this study. DE composites showed very promising results, with its thermal conductivity only 26% higher than pure fumed silica below 10^4 Pa.

1. Introduction

The advent of vacuum insulation occurred more than a 100 years ago and it was then widely used in cryogenic containers known as Dewars, named after the founder of this technology [1]. Dewars utilized steel and glass barriers to enclose a hollow evacuated region because of the structural strength required to withstand pressure difference. Vacuum insulation has since made significant progress, its applications expanded to various sectors including building, transportation and appliances in the form of vacuum insulation panels (VIP). Thermal conductivity as low as 4 mW/m.K at the center of the panel have been reported, approximately 10 times lower compared to traditional insulation materials such as expanded polystyrene, which have thermal conductivity values ranging from 30 to 40 mW/m.K [2,3]. VIPs consist of a porous core material that withstands compression due to pressure difference and a barrier laminate, which provides the vacuum seal for the underlying core material. At high vacuum, heat flow is limited to the porous solid, which entails very large interfacial thermal resistance and hence, resulting in a low thermal conductivity. The introduction of a core material permits the application of thin metallized polymer foils for barrier laminate. However, VIPs have a limited service life because vacuum is lost over a period of time as air permeates through the thin metallized polymer foil. The rate of vacuum degradation in the panel dictates its lifetime and this is especially critical for building applications, which typically require efficient insulation for an extended period of time (30–50 years). Rate of vacuum degradation can be reduced by changing the type of barrier laminate used [4], however the sensitivity of thermal conductivity to air intake depends on the core material.

Silica aerogels are by far the best materials for vacuum insulation [5]. However the cost of production of aerogels are far too high and they lack the mechanical strength for VIPs applications [6]. Fumed silica (FS) instead became a popular core material used for VIPs because it is similar to silica aerogel in terms of insulating ability. Although less expensive than silica aerogel, fumed silica is still a costly material (at ≈$4/kg) [7]. This creates a challenge for the widespread application of VIPs in appliance and large scale structures due to its cost relative to traditional insulation materials. Thus, alternative core materials were introduced into the market. Glass fiber, for example, are now commonly used for VIPs because of its lower cost compared to fumed silica [8]. Glass fibers have low thermal conductivity (~30 mW/m.K) even at atmospheric pressure and have been reported to show slight improvement in terms of

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insulating ability compared to fumed silica at very low gas pressures (<10 Pa). However, its effectiveness quickly deteriorates when gas pressure in the panel increases above 100 Pa [1]. This behavior is highly unfavorable for VIP applications that require long service life e.g. building insulation. Polyurethane and polystyrene foams have similar shortcoming at gas pressures above 100 Pa [9,10]. Polymeric materials are further complicated by outgassing issues when placed under a vacuum [11]. To the best of our knowledge, there are two other naturally occurring materials that have been studied as potential VIP core material. Pumice is a highly porous volcanic rock that contain pores averaging at 3.4–40 μm [8,12]. Similarly, perlite is also a type of highly porous volcanic rock but it has a wider range of pores from 0.01 to 100 μm [7,13]. Both powders were mixed with other constituents to form composites and tested for their thermal conduction properties under varying gas pressures. Since these powders are both naturally occurring and require very little processing, they serve to be low cost alternatives. Caps et al. pioneered the use of composite core materials with the use of opacifiers to reduce radiation contribution of heat transfer [14,15]. In the present study, composites containing diatomaceous earth (DE) and glass bubbles (GB) are considered for VIP core materials. DE comprises of skeletal remains (frustules) of microscopic plants that are closely related to the brown algae [16]. GB are soda–lime–borosilicate glass that is processed into hollow spheres by 3 M [17].

The aim of the present work is to introduce DE and GB for VIP applications in comparison with glass fibers and fumed silica. The thermal conductivity of DE and GB in vacuum were investigated by Fricke et al. and Allen et al., however, composites of these materials have not been investigated [1,18]. Thus, mixtures of these materials will be characterized for their vacuum insulating performance in relation to pore structure. Specific processing requirements, addition of opacifying agents and getters for these composites are important considerations for large scale VIP manufacturing. However, these subjects are beyond the scope of this paper. The present study focuses on the potential of these composites as long life-time VIP core materials relative to fumed silica and glass fiber.

2. Experimental

Thermal conductivity measurements were made using a Thermal Constants Analyzer (Hot Disk TPS 1500) coupled with a 6.4 mm Kapton sensor (C5501). This instrument employs the transient plane source (TPS) technique, which as its name implies measure temperature as a function of time. By contrast, standard methods such as the guarded hot plate typically require steady state conditions whereby temperature distribution in the sample is independent of time. The relationship between temperature change (ΔT), time, and thermal conductivity (Λ) for the transient plane source technique is given by Eq. (1) [19].

$$\Delta T(\tau) = P_0\left(\pi^{3/2}\alpha\Lambda\right)^{-1} D_s(\tau) \qquad (1)$$

P_0 represents the heating power supplied into the sensor, α is the sensor radius, τ is a dimensionless time variable and $D_s(\tau)$ is a time dependent function. Thermal conductivity is extrapolated from the slope when ΔT is plotted with $D_s(\tau)$. The sample compartment of the instrument was incorporated with a bell jar vacuum chamber, which enabled measurements in controlled atmospheres and gas pressures. A schematic of the setup is shown in Fig. 1.

Micromeritics ASAP 2010 was used for nitrogen gas adsorption measurements. Specific surface area was calculated using the BET method while pore size distributions were calculated by BJH and t-plot methods. However, the BJH and t-plot methods are limited to meso- and micro-pores. Therefore, larger pores were evaluated quantitatively by mercury porosimetry (Poremaster-60). In addition, pore size was also assessed qualitatively using transmission electron microscopy (FEI Technai G2 F20) and scanning electron microscopy (JEOL JSM-6060LV). Perkin Elmer Frontier FT-MIR spectrometer was used to determine the IR transparency of the samples in the attenuated total reflectance (ATR) mode.

3. Materials

3.1. Characterization

Diatomaceous earth (DE), also known as Diatomite, consist of skeletal remains (frustules) of diatoms, a common algae that is found in both salt and fresh water. The frustules are mainly comprised of amorphous silica and typically contain small amounts of lime, alumina, iron and structural water [20]. The exact composition of the frustules vary depending on the source. However, amorphous silica remains as the main constituent in all cases. The range of values for the composition of DE is given in Table 1. The DE used in this study is supplied by Perma-Guard™ (PG) and Ames flower shop (EMO).

The structure of DE as shown in Fig. 2(a–c) is evidently very porous, which explains its low bulk density of 0.38 g/cm^3. The light

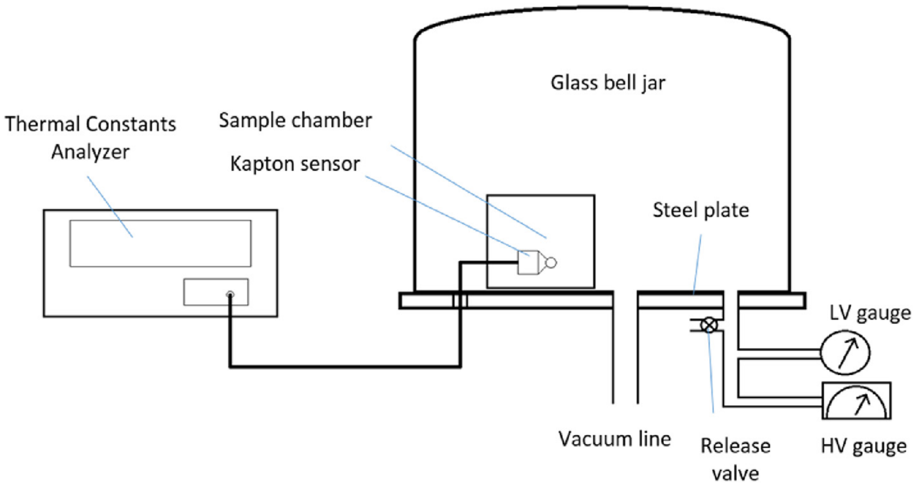

Fig. 1. Schematic of experimental setup for measuring thermal conductivity under controlled gas pressure conditions.