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Experimental investigations into thermal transport phenomena in vacuum insulation panels (VIPs) using fumed silica cores

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ABSTRACT

This paper reports the experimental and theoretical evaluation of various heat exchange phenomena that occur in a vacuum insulation panel (VIP). Fumed silica and a range of IR-opacifiers were mixed in different proportions to identify the best composition that yields minimum thermal conductivity value at ambient and evacuated conditions. Three variants of carbon black (CB) and one each of silicon carbide (SiC) and titania (TiO_2) were employed as opacifiers. Of all tested, CB was found to be the best opacifier based on the detailed experimental FTIR investigations performed whereby specific extinction was measured for each composition. To demonstrate the performance of the optimised samples of core materials developed four VIPs were manufactured which achieved a significantly low overall VIP thermal conductivity of <4 mW m^{-1} K^{-1} (R-value > 36.03 ft^2 °F h/BTU in.) measured using guarded hot plate apparatus. With these thermal conductivity values the samples perform much better than most state of the art commercially offered VIPs.

1. Introduction

Vacuum Insulation Panels (VIPs) consist of evacuated core materials specially developed to minimise heat transfer through conduction and radiation by using microporous materials combined with a small proportion of opacifiers. Presently, fumed silica (SiO_2), is preferred for VIP core due to its preferably small scale pore size distribution, which allows it to maintain a lower overall thermal conductivity at sufficiently high core gas pressure of about 10–100 mbar. Pure fumed silica acts like a desiccant with high water adsorption capability, its moisture content at saturation state being approximately 0.04 kg/kg at a relative humidity of 60% [1]. By having a microporous structure with a high porosity, fumed silica exhibits a very low solid and gaseous thermal conductivity [2]. Fumed silica based VIPs could achieve thermal conductivities varying between 0.003 W m^{-1} K^{-1} and 0.006 W m^{-1} K^{-1} at an internal pressure of 1–100 mbar and a panel density of 150–225 kg/m^3 [3]. This characteristic alone enables fumed silica VIP cores to be used as superinsulation for applications that require longer service life of >50 years with an assured low thermal conductivity.

However, heat transfer phenomena in VIPs, owing to complexity, are not fully understood yet. Current research into VIPs is limited to the characterisation of existing VIP products [4,5] with only a few reporting newer material developments [6–8]. Although, use of opacifiers to reduce the radiative thermal conductivity of VIPs has been historically studied [9–11] but no specific optimum core compositions have yet been established. An accurate understanding and quantitative evaluation of the effect of type and amount of opacifier is critical to develop low cost, high performance durable VIPs. This paper reports the experimental and theoretical evaluation of solid, gaseous and radiative modes of heat exchange that simultaneously occur in a VIP. A range of infrared-opacifiers, such as carbon black (CB), silicon carbide (SiC) and titania (TiO_2), were studied in varying proportions in fumed silica to experimentally assess their comparative effectiveness in reducing the radiative thermal conductivity. The overall aim was to identify the optimum fumed silica based core composite composition that yields minimum overall thermal conductivity value at ambient and evacuated conditions. For this purpose four VIPs were manufactured employing the core composites developed and their overall thermal conductivity measured using guarded hot plate apparatus. Gaseous and solid thermal conductivities were theoretically calculated employing well established correlations mentioned in Section 2.

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Table 1
Relevant physical properties of the materials employed.

Material	Identifying characteristics
AEROSIL® 300	300 m^2/g (BET surface area)
CB1	15–25 m^2/g (BET surface area)
CB2	150 m^2/g (BET surface area)
CB3	<15 m^2/g (BET surface area)
TiO_2	1.5 μm (mean particle size)
SiC	5.8 μm (mean particle size)

2. Experimental and analytical procedure

2.1. Materials

The fumed silica AEROSIL® 300 from EVONIK Industries AG was kept constant for all samples, reported here; three types of commercially available carbon black opacifiers, (CB1, CB2 and CB3); SiC and TiO_2 opacifier were employed. Relevant physical properties of various materials employed have been listed in Table 1. The particle size shown in Table 1 was measured by Laser Scattering Particle Size Distribution Analyser, HORIBA LA-920. These materials were mixed in different mass proportions to achieve a range of VIP core material samples. The special process technology has been developed to guarantee a homogeneous mixture. The specific composition of each tested sample can be seen in Table 2. To increase the mechanical strength of the core mixtures 5% mass content glass fibre was added to all samples except samples 6, which had 3% of the glass fibre. Glass fibre employed for this purpose had an average diameter of 9 μm and a length of 6 mm.

2.2. Characterisation

The overall thermal conductivity (k) of a VIP with an evacuated core is the sum of four distinct heat transfer mechanisms and is expressed by the following equation:

$$k = k_S + k_G + k_R + k_{\text{coup}} \quad (1)$$

where k_S is the solid thermal conductivity; k_G the gaseous thermal conductivity; k_R the radiative thermal conductivity and k_{coup} the coupling effect.

2.2.1. Specific extinction coefficient

Radiative conductivity, k_R, describes the amount of heat exchanged across the core board by electromagnetic radiation. For a VIP core at low vacuum, thermal (infrared) radiation contributes to a significant amount of heat transferred across it. Opacifiers, which have a higher refractive index, are added to core materials to reduce radiative conductivity due to additional absorption, scattering and reflection phenomena they cause [9,10]. This is especially necessary for core materials such as fumed silica which has nearly zero inherent resistance to infrared radiative exchange through it at short IR-wavelength. However, opacifier could, in some cases, cause a concomitant increase in the solid conductivity and the coupling effect. Opacifiers, such as SiC and TiO_2, being denser than core materials, such as fumed silica, also make the core heavier. It is crucial to have an optimised amount of opacifier in the core mixture. Alam et al. [6] have recently proposed a low cost alternative to fumed silica composite based core material with a radiative thermal conductivity of less than 0.001 W m^{-1} K^{-1} at 300 K.

Specific extinction coefficient (e^*), a function of temperature, determines the infrared (IR) extinction performance of opacifiers in the samples such that a higher value of the specific extinction results in a lower thermal radiative conductivity.

The specific extinction coefficient was calculated using the following equation [12]:

$$e^* = -\frac{\ln(\tau)}{L\rho} \quad (2)$$

where τ is the infrared transmittance of the samples, measured at different infrared wavelengths 2.5–25 μm by the use of a Fourier Transform Infrared Spectrometer (Perkin Elmer Spectrum One, FT-IR Spectrometer). It was calculated as a ratio of the incident IR intensity on the sample and the transmitted IR intensity.

L is the equivalent thickness of experimental powder sample in the potassium bromide (KBr) pellet, which was calculated using the following equation:

$$L = \frac{WP}{\rho A} \quad (3)$$

where W is the total mass of the KBr pellet (kg); P is the mass percentage of the powder sample in the KBr pellet (%); ρ is the density of the monolithic sample (kg m^{-3}); A is the cross-sectional area of the pellet (m^2).

The values of specific extinction coefficient, e^*, were calculated with an accuracy of 10%. Subsequently, the specific extinction coefficient (e^*) was used in Eq. (4) to calculate the Rosseland mean extinction coefficient, $E(T)$ [13].

$$E(T) = e^*\rho \quad (4)$$

The IR transmittances (τ) of all the samples were measured using Perkin Elmer Spectrum One FT-IR Spectrometer over a spectral wavelength range of 2.5–22.5 μm at room temperature held at 20 °C, see Fig. 1. To acquire each spectrum for every sample 100 scans were performed. Due to difficulty in obtaining an optically thin film from powders, KBr method was used [14,15]. FT-IR scanning resulted in the transmittance as a function of wavelength for each sample, as shown in Fig. 1. Specific extinction was calculated and is shown in Fig. 2. It is evident that the opacifiers have different effects on transmittance or extinction coefficient at different wavelengths and designers should choose the one that achieves the highest extinction coefficient at a specific wavelength range of interest. CB1 (sample 2) was found to have the highest average extinction coefficient for the same mass proportion over the overall range of wavelength, 2.5–22.5 μm, considered, as shown in Fig. 3.

As expected, an increase in the mass% proportion of the opacifiers resulted into higher extinction coefficients. It can be seen in Fig. 4, that a 40% mass proportion of CB1 yielded an overall highest extinction coefficient over the range of 10% to 40%.

Table 2
Sample composition and specific mass ratios of composites employed using AEROSIL® 300 as the main core material.

Sample	Opacifier identifier	Opacifier mass concentration (%)	Glass fibre mass concentration (%)
1	CB1	10	5
2	CB1	20	5
3	CB1	30	5
4	CB3	20	5
5	CB2	20	5
6	CB3	10	3
7	TiO_2	20	5
8	TiO_2	30	5
9	CB1	40	5
10	SiC	20	5
11	SiC	30	5
12	SiC	40	5
13	CB1	35	5
14	TiO_2	10	5