

# Vacuum Insulation Panels (VIPs) for building construction industry - A review of the contemporary developments and future directions

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## Abstract

Demand for energy efficient buildings has increased drastically in recent years and this trend will continue in the future. Insulating building elements will play a key role in meeting this demand by reducing heat losses through the building fabric. Due to their higher thermal resistance, Vacuum Insulation Panels (VIPs) would be a more energy efficient alternative to conventional building insulation materials. Thus, efforts to develop VIPs with characteristics suitable for applications to new and existing buildings are underway. This paper provides a review of important contemporary developments towards producing VIPs using various materials such as glass fibre, foams, perlite and fibre/powder composites. The limitations of the materials currently used to fabricate VIPs have not been emphasized in detail in previous review papers published. Selection criteria, methods to measure important properties of VIPs and analytical and numerical models presented in the past have been detailed. Limitations of currently employed design tools along with potential future materials such as Nano/microcellular foams and  $\text{SiO}_x/\text{SiN}_x$  coatings for use in VIPs are also described.

**Keywords:** Vacuum Insulation Panel (VIP); Thermal insulation; Thermal conductivity; Payback period; Thermal bridging effect; Useful life time

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## 1. Introduction

In 2007, the UK government set a target to gradually improve the energy efficiency and carbon performance of buildings required via the Building Regulations 2006 Part L. The aim of this was to achieve a zero carbon emission level for new homes by 2016 [1]. This carbon reduction will initially be realised by a 25% improvement in the energy/carbon performance set in Building Regulations 2006 Part L achieving the Code for Sustainable Homes (CSH) level 3 by 2010; then secondly, in 2013, to a 44 % improvement achieving the CSH level 4; and ultimately in 2016, to zero carbon emissions achieving the CSH level 6 [2]. Further, the UK government intends to set zero carbon targets for new non domestic buildings by 2019 [3]. These standards are expected to assist the UK government significantly in reducing Carbon dioxide (CO<sub>2</sub>) emissions from buildings and achieving the 2050 target to reach net carbon emissions at least 80% lower than the 1990 baseline as set in the Climate Change Act 2008 [4]. Buildings account for almost half of the UK's total carbon emissions [5] and are directly related to energy consumption. In the first quarter of 2010 domestic and services sectors were responsible for 50% of total UK energy consumption [6]. A major portion of supplied space heating energy is lost through poorly insulated building fabric. Heat losses can be reduced by lowering the heat transfer coefficient (U-value) of building fabric by applying insulation. It is evident from Fig.1 that lowering the average U-value from the Building Regulation standard value (0.40 W m<sup>-2</sup> K<sup>-1</sup>) to that required by level 5 of the CSH standard will reduce the annual space heating demand and CO<sub>2</sub> emissions by 7.80 kWh m<sup>-2</sup> a<sup>-1</sup> and 1.56 kg CO<sub>2</sub> m<sup>-2</sup> a<sup>-1</sup> respectively. Average building U-value, energy savings and amount of CO<sub>2</sub> emission reduced were calculated using equation (1) and (2) and fuel emission factor of 0.20 [7,8,9].

$$U = \{(U_1 \times A_1) + (U_2 \times A_2) + (U_3 \times A_3) + (U_4 \times A_4)\} / \{(A_1 + A_2 + A_3 + A_4)\} \quad (1)$$

$$\text{Energy savings per annum (kWh m}^{-2}\text{)} = \text{HDD} \times U \times 24/1000 \times \eta \quad (2)$$

Where

A is the insulated area (m<sup>2</sup>)

U is the average U-value (W m<sup>-2</sup> K<sup>-1</sup>)

HDD is the heating degree day (°C day)

η is the efficiency of heating system

Subscripts 1, 2, 3 and 4 denotes building elements wall, floor, roof and window respectively

Conventional insulation materials such as expanded polystyrene (EPS) with a reported thermal conductivity ( $\lambda$ ) of  $0.035 \text{ W m}^{-1} \text{ K}^{-1}$  [10] requires a thickness of 4-5 times larger than Vacuum Insulation Panels (VIPs) ( $\lambda = 0.008 \text{ W m}^{-1} \text{ K}^{-1}$ ) to lower the average U-value of building to that required by the CSH.

It is shown in Fig.2 that conventional insulation materials such as rock wool and glass fibre require a large thickness to lower the U-value of a typical masonry cavity wall of a semi-detached UK dwelling (built between 1945 and 1964) from  $0.53 \text{ W m}^{-2} \text{ K}^{-1}$  to  $0.15 \text{ W m}^{-2} \text{ K}^{-1}$  as required by the PassivHaus standard [11]. This large thickness of insulation may not be feasible in existing and new buildings due to space and techno-economic constraints. VIPs with thermal resistance potentially 5-8 times higher than the conventional insulation [12] offer a solution to the problem. VIPs can be applied to buildings at various locations, for either external or internal surfaces, such as walls, roof, ground floor, window frames, and on hot water cylinders. However, the application of VIPs in buildings has two main barriers; high cost and uncertainty over useful life time. Recently, use of nano insulation materials and dynamic insulation materials were discussed by Jelle et al. [13]. However, these insulation materials are still at a conceptual stage and no real life or lab scale testing results have been reported yet.

## **2. Vacuum Insulation Panel (VIP) - Components and materials**

A VIP can be described as an evacuated open porous material placed inside a multilayer envelope as shown in Fig.3. The main components of a VIP are inner core, barrier envelope and getters & desiccants. The envelope could either consist of thick metal sheets or multilayer barrier of metalized polymeric layers to provide protection against environmental and handling stresses. A suitable getter or a desiccant is inserted inside the VIP core to adsorb gases and water vapours which might penetrate into a VIP through envelope barrier. In the case of conventional non-vacuum insulation materials convection in material pores causes the dominant heat transfer across such materials, whereas in VIP this mode of heat transfer is suppressed by creating a vacuum inside the core material. VIPs can either be classified as (i) sheet based VIPs and (ii) film based VIPs [14]. These are also called static VIPs because the vacuum can only be created at the time of manufacturing and cannot be created again over their useful life time. Sheet based VIPs use metal sheet envelope which exhibit better load bearing capacity and resistant to mechanical damages, but suffer from heavier weight and a greater thermal bridging effect [15,16]. On the other hand, thinner, ( $100\text{-}150 \times 10^{-6} \text{ m}$ ), and lighter multilayered metalized polymer film envelopes are easily punctured during handling.

### **2.1. VIP core**

The core, fabricated from porous material of suitable pore size, is the inner part of a VIP as shown in Fig.3. Its function is to maintain the vacuum below a minimum critical level and to physically support the VIP envelope. Gaseous heat transfer is suppressed within the core using small size porous materials such as open porous foams, powders and fibres.

#### **2.1.1. Foams**

Open cell foams such as polyurethane (PUR) and expanded polystyrene (EPS) with pore sizes in the range of  $30\text{-}250 \times 10^{-6} \text{ m}$  can be used as a core in VIPs. These foams have low thermal conductivity in evacuated conditions due to their low density ( $60\text{-}100 \text{ Kg m}^{-3}$ ) and small pore size of foam materials. However, a low gas pressure,  $\leq 1 \times 10^{-4} \text{ bar}$ , is required to achieve a reasonable thermal resistance in the case of foams, used as VIP core material. Kwon et al. [17] calculated the value for the total thermal conductivity of polyurethane foam of pore size

100  $\mu\text{m}$  as  $0.0078 \text{ W m}^{-1} \text{ K}^{-1}$  at  $1 \times 10^{-4}$  bar. However, such a low pressure is not feasible to maintain over the useful life time of the VIP, which is expected to be 100 years or longer for building applications. For foams with a density of  $70 \text{ kg m}^{-3}$  the radiative and solid conductivity at 300 K was reported as  $0.0027 \text{ W m}^{-1} \text{ K}^{-1}$  and  $0.003\text{-}0.007 \text{ W m}^{-1} \text{ K}^{-1}$  respectively [17], with a combined solid and radiative conductivity in the range of  $0.0057\text{-}0.0097 \text{ W m}^{-1} \text{ K}^{-1}$ , a value higher than the normally accepted design thermal conductivity value for a VIP core of  $0.004 \text{ W m}^{-1} \text{ K}^{-1}$ . Clearly it would be difficult to achieve this lower thermal conductivity value using foams in VIPs even with zero gaseous conductivity. Commercially available PUR foam ( $\text{£}6.03 \text{ m}^{-2}$ ) is capable of providing higher thermal resistance compared to other insulation materials such as glass fibre ( $\text{£}2.39 \text{ m}^{-2}$ ) and EPS ( $\text{£}2.39 \text{ m}^{-2}$ ) for the same insulation thickness [18]. However, PUR foam has higher fire toxicity due to the release of mainly carbon monoxide (CO), hydrogen cyanide (HCN) and other harmful emissions [19]. Thermal conductivity of foams can be reduced further by reducing the size of pores. Recently, rubber blended polypropylene and polyethylene nano/microcellular foam (average cell diameter  $(0.5\text{-}2 \times 10^{-6} \text{ m})$ ) has been developed by  $\text{CO}_2$  pressure quench method [20]. Nano/microcellular foams with improvised structural arrangement, though currently in the development phase, are potential candidates for VIP core materials in the medium term.

### 2.1.2. Powders

Currently fumed or pyrogenic silica, silica aerogels and expanded perlite individually or in a mixture form are employed in VIP cores. Fumed silica is commonly used due to its ability to yield a low thermal conductivity  $0.003\text{-}0.006 \text{ W m}^{-1} \text{ K}^{-1}$  whilst requiring a pressure in the range of  $20\text{-}100 \times 10^{-3}$  bar [21] owing to a favourable pore size of  $300 \times 10^{-9} \text{ m}$  and a specific surface area in the range of  $5\text{-}60 \times 10^{-2} \text{ m}^2 \text{ Kg}^{-1}$ . Its density is approximately  $150\text{-}200 \text{ Kg m}^{-3}$ . Fumed silica was first developed by Degussa AG (currently Evonik Industries) in Germany in 1942 [22]. Due to its low density, high specific surface area and low thermal conductivity fumed silica is a suitable core material for VIPs to achieve the accepted core thermal conductivity design value of  $0.004 \text{ W m}^{-1} \text{ K}^{-1}$ .

Silica aerogels, first developed by Kistler in 1931 using sodium silicate [23], are nano porous materials with pore size of approximately 20 nm and a density in the range of 3 to  $350 \text{ kg m}^{-3}$ . In general, aerogels are made by two steps (i) wet gel formation by acidic condensation or sol-gel process (ii) drying of wet gel by using supercritical or ambient drying to produce silica aerogel [24]. A low density and a smaller pore size ( $1\text{-}100 \times 10^{-9} \text{ m}$ ) render silica aerogel a thermal conductivity of (approximately  $0.001\text{-}0.003 \text{ W m}^{-1} \text{ K}^{-1}$  in evacuated and opacified conditions depending on temperature) and can even achieve a value of  $0.004 \text{ W m}^{-1} \text{ K}^{-1}$  at 50 mbar or less making it suitable for VIP applications [25]. Another advantage of Silica aerogel is that it is also considered as non reactive and non flammable. However, due to its high cost it has not been widely used in VIPs for building applications.

Expanded perlite, was found to be less effective than silica aerogel and fumed silica requiring a low pressure below 0.1 mbar to achieve the desired design centre of panel thermal conductivity value [26]. Expanded perlite can be used in combination with fumed silica in different mass ratios and such a mixture can be optimized to achieve a low thermal conductivity at a comparatively high pressure for a specified useful life of the VIP. However, it is not expected to achieve typical design centre of panel value at reasonable pressure.

### 2.1.3. Glass fibre

Glass fibre can also be used as the core of a VIP for high temperature applications due to its low density and high thermal stability ( $>1000^\circ\text{C}$ ). Kwon et al. [17] reported a radiative

conductivity of  $0.0007 \text{ W m}^{-1} \text{ K}^{-1}$  and a solid conductivity of approximately  $0.0021 \text{ W m}^{-1} \text{ K}^{-1}$  for glass fibre (density of  $250 \text{ kg m}^{-3}$  and a fibre diameter of  $0.5\text{-}0.7 \times 10^{-6} \text{ m}$ ) at  $300 \text{ K}$ . Collectively this results in a thermal conductivity of  $0.0028 \text{ W m}^{-1} \text{ K}^{-1}$  requiring a suppression of the gaseous conductivity within  $0.0012 \text{ W m}^{-1} \text{ K}^{-1}$  to achieve a VIP core thermal conductivity of  $0.004 \text{ W m}^{-1} \text{ K}^{-1}$ . A pressure of approximately  $0.01 \times 10^{-3} \text{ bar}$  was required to suppress the gaseous thermal conductivity to a negligible level [27]. Kwon et al. [17] also reported a theoretical total thermal conductivity value of  $0.0036 \text{ W m}^{-1} \text{ K}^{-1}$  for a glass fibre core at  $0.1 \times 10^{-3} \text{ bar}$ . Araki et al. [28] investigated the performance of glass fibre based VIPs for insulating hot water cylinders. Glass fibre based VIPs are a good candidate for domestic ovens, furnaces, concentrated solar power plants and fuel cell power plants.

#### 2.1.4. Fibre/powder composites

Mukhopadhyaya et al. [29] proposed the use of composites of glass and mineral oxide fibre with pumice and zeolite powder as VIP core material. Thermal conductivity of these materials was found to be comparable to precipitated silica and nanogels for a pressure range of  $0.25\text{-}100 \times 10^{-3} \text{ bar}$ . A lower embedded energy of such composites compared to that of silica based materials is expected to improve life cycle rating of VIP as they require. Low cost alternatives, such as, wood fibre composite with pumice powder [29], are also being considered, though their real time effectiveness in VIPs has not been reported yet.

## 2.2. VIP envelope

The envelope not only protects the VIP from air and water transmission but also provides mechanical strength to withstand atmospheric pressure and handling stresses during transportation and installation. Performance of the envelope depends upon its barrier properties and capability to resist thermal bridging across the edges. Envelope materials are expected to have a water vapour transmission rate (WVTR) of approximately  $0.0001 \text{ g m}^{-2} \text{ d}^{-1}$  and oxygen transmission rate (OTR) of  $0.001 \text{ cm}^3 \text{ m}^{-2} \text{ d}^{-1}$  to yield a useful life time of approximately 30-50 years for building applications [30]. However, the range of useful life time 30 to 50 years is wide and for building applications life time of 100 years needs to be considered and specified more precisely to build the confidence in manufacturers and users. A combination of polymers and thin metalized films or metal foils is currently employed to produce VIP envelope [30,31]. Generally, permeance of multilayer film envelope of a VIP depends on temperature, relative humidity and size of panel [32]. Barrier properties of envelope films can be improved by reducing the number and size of defects in the barrier layer [30]. A typical VIP envelope with three metalized films was reported to have a WVTR and an OTR of  $0.003\text{-}0.005 \text{ g m}^{-2} \text{ d}^{-1}$  and  $0.001\text{-}0.002 \text{ cm}^3 \text{ m}^{-2} \text{ d}^{-1}$  respectively at  $23^\circ\text{C}$  and  $50\% \text{ RH}$  [30]. For a two-layered metallised envelope panel estimated useful life time is 16 to 38 years depending upon panel size and climatic conditions [33]. Baetens et al. [34] calculated that aluminium foil can keep the thermal conductivity of core minimum as compared to multilayered metalized films. Clearly, a significant improvement in barrier properties is needed to achieve a useful life time of 100 years or longer for a VIP for building applications. Higher barrier properties of aluminium foil envelope compared to a metalized polymeric envelope are evident. However, an aluminium foil envelope suffers from a higher thermal bridging effect. Linear thermal transmittance values of  $0.01 \text{ W m}^{-1} \text{ K}^{-1}$  for a metalized film envelope and  $0.07 \text{ W m}^{-1} \text{ K}^{-1}$  for an aluminium foil envelope were reported [35].

### 2.2.1. Structure of envelope

A typical VIP envelope consists of three material layers; (i) outer protective layer (ii) barrier layer (iii) inner sealing layer, each serving a distinct function. These layers are joined together as shown in Fig.3 and Fig.4 to form an envelope by using a suitable adhesive such as polyurethane. Kwon et al. [36] proposed a double envelope with an additional porous core

material sandwiched between the inner envelope and outer envelope to reduce the gas permeation through the envelope as shown in Fig.5. However, this may increase the thickness and cost of VIP and any increase in pressure in outer core will also contribute towards degradation of VIP performance.

#### 2.2.2. Protective Layer

It is the outer most layer of the envelope as shown in Fig.3, which protects the VIP from environmental and handling stresses and also acts as a substrate for barrier layer. Currently, polyethylene terephthalate (PET) is used as protective layer due to its low cost and better barrier properties. Use of other materials for envelope is being investigated, for example Araki et al. [28] investigated Nylon 6 (Polyamide) as a protective layer in VIP envelope for high temperature application such as heat pumps and water storage tanks due to its high melting point (225°C). A drawback of Nylon 6 is its high cost.

#### 2.2.3. Barrier Layer

The middle layer (Fig.3) which acts as a barrier against air and water vapour transmission is known as the barrier layer. It is either an aluminium foil or metalized layers of polymers in which aluminium is attached to polymeric substrate. The number of barrier layers in a VIP envelope varies from one to three; though a three layer structure is widely used due to its better barrier properties against air and water vapour transmission. Currently polypropylene (PP) and polyethylene terephthalate (PET) are being used as substrates [37]. Araki et al. [28] investigated the use of metalized layer of ethylene vinyl alcohol copolymer (EVOH) and metallised layer of PET in VIP envelope and found that WVTR and OTR index for this type of envelope were high as compared to the envelope with aluminium foil. Teniers [38] reported the better barrier properties of metalized layer of EVOH. However, due to the presence of high thermal conductivity metal in such barrier layers the thermal bridging effect on edges of VIP becomes dominant. Thermal bridging effect can be reduced by replacing the metalized barrier layer with silicon oxides ( $\text{SiO}_x$ ) and silicon nitride ( $\text{SiN}_x$ ) coatings. Barrier properties and mechanical properties of these materials are comparable to the metalized barrier layer [39,40,41,42,43]. Use of  $\text{SiO}_x$  and  $\text{SiN}_x$  coated PET in barrier layers for VIPs has not been reported to date. Nevertheless, these materials have great potential for VIP applications and required further investigation. Electrospun Methyltriethoxysilane (MTES) nanofiber fabric [44] is also a potential candidate for the barrier layer due to its high thermal stability and super hydrophobicity.

#### 2.2.4. Sealing Layer

The sealing layer is the inner most layer in a multilayered VIP envelope (Fig.3). This layer seals the core material in the envelope. Imperfections in sealing seams generally contribute approximately 30% total gas permeation. Heat sealing is a commonly used process to join the laminates. In sealing process the film surfaces are heated between two hot bars under pressure. This creates a bond between two polymer layers due to diffusion. For achieving a better seal, the temperature and time allowed for sealing are very important factors. At a specific initiation temperature, the seal begins to form and its strength increases till a certain maximum value is achieved [45]. Conventionally Low Density Polyethylene (LDPE) and High Density Polyethylene (HDPE) have been used in VIPs as a sealing layer [37]. Malsene et al. [45] experimentally found no significant difference between the seal strength of these materials and concluded that a sealing layer material should be chosen on the basis of its air and water vapour permeability. Araki et al. [28] reported the use of other materials such as polybutylene (PBT) and high retort-cast polypropylene (HR-CPP) as sealing layers for high temperature applications.

### 2.3. Getters, desiccants and opacifiers

Getters and desiccants are placed inside the core to extend the useful life time of a VIP by continuously adsorbing water vapours (desiccants) and gases (getters) which may get into it over its useful life time through either permeation from the outside environment or via out gassing of core and envelope materials or both. In the case of silica core VIPs, core itself acts as a desiccant but for other core materials a small amount of silica gel desiccant is required. Araki et al. [28] used synthetic zeolites getters to adsorb gases for a glass fibre core. Opacifiers are used to reduce the radiative conductivity of the core material by making it opaque to infrared radiation. Silicon carbide (SiC) is the most commonly used opacifier in fumed silica core. Other opacifiers such as carbon black, titanium dioxide (TiO<sub>2</sub>) and iron oxide (Fe<sub>3</sub>O<sub>4</sub>) are also being used.

### 2.4 Manufacturing of VIPs

Main steps involved in the manufacturing of a VIP are shown in Fig.6. Heat sealing of the envelope could either be a three sided seal or a four sided seal. Three sided seal has the advantage of reduced gas permeation through the seal flanges compared to four-sided seal [36].

### 2.5 VIP economic analysis

Fig.7 compares the payback period predicted for VIP and EPS when used as building insulation under different scenarios of interventions detailed in Table 1. For the purpose of calculations typical U-values for existing UK buildings; wall 0.51 W m<sup>-2</sup> K<sup>-1</sup>, roof 0.25 W m<sup>-2</sup> K<sup>-1</sup>, floor 0.18 W m<sup>-2</sup> K<sup>-1</sup> and window 1.4 W m<sup>-2</sup> K<sup>-1</sup> were assumed [46]. Payback period, an indication of the time required to recover the cost of insulation, is defined as the ratio of cost of insulation to the annual savings in heating cost as shown in equation (3). Annual heating cost (C<sub>A</sub>) was calculated using the equation (4) [47]. Main parameters used in payback period calculation are detailed in Table1.

$$PBP = C_{ins}/(C_{A,exis} - C_{A,imp}) \quad (3)$$

$$C_A = (86400 \times HDD \times C_f \times U \times PWF)/(H_V \times \eta) \quad (4)$$

$$PWF = N / (1 + i) \quad (5)$$

where

PBP is the Payback period (year)

C<sub>ins</sub> is the cost of insulation (£)

C<sub>A,exis</sub> is the annual heating cost with existing U-value (£ per annum)

C<sub>A,imp</sub> is the annual heating cost with improved U-value (£ per annum)

C<sub>f</sub> is the cost of fuel (£ m<sup>-3</sup>)

H<sub>V</sub> is the heating value of fuel (J m<sup>-3</sup>)

η is the efficiency of heating system

PWF is the present worth factor as shown in equation (5) if interest rate (i) is equal to inflation rate.

N is the life time of insulation (years)

In scenario 1 VIP and EPS with a thickness of 10 mm and 48.3 mm respectively were considered for insulating the building, the average U-value was calculated as 0.40 W m<sup>-2</sup> K<sup>-1</sup>. In scenario 2 VIP and EPS with a thickness of 25 mm and 113 mm respectively were assumed, resulting in a average U-value of 0.31 W m<sup>-2</sup> K<sup>-1</sup>. Payback periods of VIP predicted

for scenarios 1 and 2 are too long compared to those calculated for EPS. In scenario 3 a payback period of VIP and EPS insulation just sufficient to achieve a building average U-value of  $0.27 \text{ W m}^{-2} \text{ K}^{-1}$  were predicted. It was found that the payback period of VIP was 10 times longer than that for EPS. Scenario 4 compared the payback period of insulation required to achieve an average building U-value of  $0.24 \text{ W m}^{-2} \text{ K}^{-1}$ . EPS had a payback period 8 years shorter than VIP although EPS required a prohibitively large thickness of 256 mm. Such a thick insulation layer cannot be employed to insulate the wall and floor area of most of the existing buildings. The main reason for the longer payback period of VIP insulation in all scenarios is its high initial cost, which must be reduced significantly if VIP is to provide a cost effective alternative to conventional insulation materials. In the case of existing commercial buildings, especially those which cannot be insulated on the outer surfaces such as listed buildings [48], VIP is an attractive alternative to conventional insulation materials as the facade of the building will not be modified as much. In Scenarios 4, VIP was found to achieve a considerably shorter payback period when the economic value of the potential space savings due to thinner VIP was considered in all the scenarios, in scenario 4 it was even shorter than EPS. For calculating the economic value of space saved, an average rent of commercial buildings situated in London was assumed as  $\text{£ } 40 \text{ ft}^{-2}$  [49].

### 3. Heat transfer phenomena in a VIP

With the VIP maintained at a pressure lower than a certain value, sufficient to suppress the convective heat transfer, the remaining modes of heat transfer include solid conduction, radiation and gaseous conduction. Total thermal conductivity of a VIP core can be expressed as [50]

$$\lambda_c = \lambda_s + \lambda_R + \lambda_G + \lambda_{cv} + \lambda_{coup} \quad (6)$$

where

$\lambda_s$  is the solid thermal conductivity ( $\text{W m}^{-1} \text{ K}^{-1}$ )

$\lambda_R$  is the radiative thermal conductivity ( $\text{W m}^{-1} \text{ K}^{-1}$ )

$\lambda_G$  is the gaseous thermal conductivity ( $\text{W m}^{-1} \text{ K}^{-1}$ )

$\lambda_{cv}$  is the gaseous convection within pores ( $\text{W m}^{-1} \text{ K}^{-1}$ )

$\lambda_{coup}$  is the thermal conductivity due to the coupling effect ( $\text{W m}^{-1} \text{ K}^{-1}$ )

The thermal conductivity  $\lambda_c$  of VIP core can be reduced by suppressing the thermal conductivity terms shown in the right hand side of equation (6) to minimum and is expected to be in the range of  $0.004 \text{ W m}^{-1} \text{ K}^{-1}$  [31,50]. In equation (6)  $\lambda_{coup}$  represents coupling effect which becomes evident at higher pressures for powders and fibre materials due to interaction between them in the VIP core.

#### 3.1. Solid conduction

Solid conduction occurs through the skeleton of core material whereby the heat is transferred through the physical contact of the constituent particles of the core material. Its magnitude depends upon material structure, density and external pressure on the core. The following correlation was proposed for the variation of solid conductivity with density of the core material [50].

$$\lambda_s = \rho^\alpha \quad (7)$$



where  $\rho$  is the density ( $\text{kg m}^{-3}$ ) and the index  $\alpha$  has a value of unity for foams and ranges over 1.5 to 2 for nano materials. It is clear from equation (7) that the materials with a low density will yield a smaller solid conductivity.

### 3.2. Radiation

Radiative heat transfer in the form of electromagnetic waves requires no medium and is a significant mode of transferring heat in vacuum conditions. It can be calculated by using equation (8) [50].

$$\lambda_R = (16n^2\sigma T_r^3)/(3E(T_r)) \quad (8)$$

where

$n$  is the mean index of refraction

$\sigma$  is the Stefan-Boltzmann constant ( $5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$ )

$T_r$  is the average temperature within the insulation material (K)

$E$  is the extinction coefficient of the insulating material ( $\text{m}^{-1}$ )

Radiative heat transfer can be reduced by adding opacifier to the core material. Caps and Fricke [19] reported that at room temperature thermal conductivity of pure silica is higher by 0.002-0.003  $\text{Wm}^{-1} \text{ K}^{-1}$  than that of silicon carbide opacified precipitated silica.

### 3.3. Gaseous thermal conduction

Heat transfer occurs through convection and conduction processes in gases. Its intensity depends on the ratio of mean free path of gas molecules and the pore size of the material i.e., Knudsen Number. Kaganer [51] proposed the following correlation equation (9) to estimate the gas conductivity,  $\lambda_G$ , as a function of Knudsen Number.

$$\lambda_G = \lambda_0 / (1 + 2\beta \text{Kn}) \quad (9)$$

where

$\lambda_0$  is the thermal conductivity of air at atmospheric pressure ( $\text{W m}^{-1} \text{ K}^{-1}$ )

$\beta$  is the coefficient which depends on accommodation coefficient and the adiabatic coefficient of the gas

$\text{Kn}$  is the Knudsen number which is equal to the ratio of molecular mean free path length ( $l$ ) to the pore size diameter ( $\Phi$ ) as shown in equation (10)

$$\text{Kn} = l/\Phi = (k_B T)/(\sqrt{2} \pi d^2 p \Phi) \quad (10)$$

where

$k_B$  is the Boltzmann's constant ( $1.38 \times 10^{-23} \text{ J K}^{-1}$ )

$T$  is the thermodynamic temperature (K)

$d$  is the diameter of gas molecule (m)

$p$  is the gas pressure (Pa)

Kwon et al. [17] employed the following correlation, equation (11), to estimate the gaseous thermal conductivity of air at 25 °C using  $\beta = 0.0016/P$ .

$$\lambda_G = \lambda_0 / ((1 + (0.0032/P\Phi))) \quad (11)$$

where

P is the pressure (Pa)

$\Phi$  is the pore width of the porous insulation material (m)

By using equation (11) the calculated values of gaseous thermal conductivity of air for different pore sizes are shown as a function of pressure in Fig.8. It can be seen that materials with pore size in the nanometric range have negligible gaseous thermal conductivity even at atmospheric pressure. It is clear from Fig.8 that with increasing pore size comparatively lower pressure is required to suppress gaseous thermal conductivity.

#### 4. Measurement of basic properties of VIPs

Gas pressure rise inside a VIP core is an important criterion to predict its service life. Pressure increase can be due to addition of gases from one or more of these sources (i) residual gases present inside VIP after manufacturing (ii) out gassing of materials present in envelope and core (iii) permeation through barrier envelope and seal flange [36,52]. Pressure measurement in a VIP is a challenging process as the core is sealed inside an outer envelope. Table 2 details different techniques employed to measure pressure inside a VIP, Water vapour transmission and thermal conductivity.

#### 5. Aging of VIP

##### 5.1. Useful life time prediction of VIP

Useful life time of a VIP is the time period in which total VIP thermal conductivity (i.e. centre of panel thermal conductivity) exceeds a certain limiting value [59,60]. The variation in gas and water vapour pressure inside the core material determines the change in thermal conductivity of the VIP core. This rate of change of thermal conductivity is employed to predict the useful life time of a VIP [30]. The moisture transmission through a VIP core can be attributed to the Knudsen diffusion and surface diffusion [61]. Knudsen diffusion is molecule-wall collision due to the larger mean free path of the molecules as compared to the pore size and surface diffusion is the movement of molecules along the pore wall [62].

Simmler and Brunner [35] predicted the useful life time for a VIP with silica core and metalized envelope for constant environmental conditions using equation (12) and suggested the preliminary thermal design values of change in core thermal conductivity for useful life time of 25 years for silica VIP  $0.006 \text{ W m}^{-1} \text{ K}^{-1}$  for aluminium foil and  $0.008 \text{ W m}^{-1} \text{ K}^{-1}$  for metalized polymeric envelope due to air and water infiltration for at least 20 mm thick and 250 mm wide panel.

$$\frac{\partial \lambda_c}{\partial t} = \frac{\partial \lambda_c}{\partial P} \frac{\partial P}{\partial t} (T, \varphi) + \frac{\partial \lambda_c}{\partial u} \frac{\partial u}{\partial t} (T, \varphi) \quad (12)$$

where

$\lambda_c$  is the core thermal conductivity ( $\text{W m}^{-1} \text{ K}^{-1}$ )

u is the moisture content (% mass)

T is the temperature (K)

$\varphi$  is the relative humidity (%)

Schwab et al. [33] presented a correlation (13) for predicting thermal conductivity as a function of time for a fumed silica kernel VIP. In correlation (13) initial thermal conductivity was limited to only solid and radiative conductivity and thermal conductivity due to increase

in gas pressure and water content over time was added to calculate the time dependent thermal conductivity,  $\lambda(t)$ .

$$\lambda(t) = \lambda_{evac} + \frac{\lambda_{free\ gas}}{1 + (p_{1/2,gas}/p_{gas}(t))} + b.Xw(t) \quad (13)$$

where

$\lambda_{evac}$  is the thermal conductivity (in evacuated conditions) ( $W\ m^{-1}\ K^{-1}$ )

$\lambda_{free\ gas}$  is the thermal conductivity of the free and still gas ( $W\ m^{-1}\ K^{-1}$ )

$p_{1/2,gas}$  is the pressure at which the gaseous thermal conductivity equals one half of  $\lambda_{free\ gas}$  (Pa)

$p_{gas}$  is the gas pressure (Pa)

$b$  is the sorption isotherm constant

$Xw$  is the water content (% mass)

At 10°C thermal conductivity increased by 0.0005  $W\ m^{-1}\ K^{-1}$  per mass % of adsorbed water and a 30 mbar increase in gas pressure led to a rise of 0.001  $W\ m^{-1}\ K^{-1}$  in thermal conductivity [30]. Tenpierik et al. [59,63] based on the equation (12) proposed an analytical model equation for estimating changes in thermal conductivity over time and useful life time for a VIP with silica core and aluminium foil envelope. This equation (14) includes the rate of change of thermal conductivity due to gas and water vapours as separate terms.

$$\Delta\lambda_c(t) \approx \frac{\partial\lambda_c}{\partial p_g} p_{g,e} \left(1 - e^{-\frac{t-t_{get}}{t_g}}\right) + \frac{\partial\lambda_c}{\partial p_{wv}} p_{wv,e} \left(1 - e^{-\frac{t-t_{des}}{t_w}}\right) + \frac{\partial\lambda_c}{\partial u} \frac{du}{d\phi} \phi_e \left(1 - e^{-\frac{t-t_{des}}{t_w}}\right) \quad (14)$$

where

$p_g$  is the pore gas pressure (Pa)

$p_{g,e}$  is the atmospheric gas pressure (Pa)

$p_{wv,e}$  is the partial water vapour pressure outside the VIP (Pa)

$t$  is the time (s)

$t_{get}$  is the time shift due to a getter (s)

$t_{des}$  is the time shift due to a desiccant (s)

$t_g$  is the time constant for gas pressure increase (s)

$t_w$  is the time constant for water content increase (s)

$\phi_e$  is the relative humidity of the air outside the VIP (%)

For compressed fumed silica a simplified model, (15), was used to approximate rapid estimation of useful life time by assuming nil extension of VIP life using getter and desiccant [59, 63].

$$T_{sl} \approx a e^{b(\lambda_{lim} - \lambda_0 - \lambda_w)}. d_p. \left(\frac{l_p}{s_p}\right)^c. \frac{T_0}{T} e^{E_a/R\left(\frac{1}{T} - \frac{1}{T_0}\right)} \quad (15)$$

where

$a$  ( $s m^{-(1+c)}$ ),  $b$  ( $m K W^{-1}$ ) and  $c$  are regression parameter

$E_a$  is the activation energy for permeation through the barrier envelope ( $J mol^{-1}$ )

$R$  is the universal gas constant ( $J mol^{-1} K^{-1}$ )

$l_p$  is the perimeter length of VIP (m)

$s_p$  is the surface area of VIP ( $m^2$ )

$\lambda_w$  is the thermal conductivity of liquid water and water vapour at equilibrium ( $W m^{-1} K^{-1}$ )

$\lambda_0$  is the thermal conductivity of air at atmospheric pressure ( $W m^{-1} K^{-1}$ )

This approximating model is limited to VIP thickness in the range of 0.01-0.05 m, temperature in the range of 268-318 K, perimeter length to surface area ratio in the range of 2-12  $m^{-1}$  and a constant relative humidity of 50%. However, for building applications constantly changing environmental conditions require a model that is able to predict VIP useful life time under real life transient conditions. Recently, Beck et al. [61] proposed a dynamic simulation model for a silica VIP core under dynamic hygrothermal conditions and was able to simultaneously calculate the moisture transmission and temperature profile of the VIP core. Wegger et al. [64] performed accelerated aging testing of VIPs to evaluate the effect of various factors such as temperature, moisture and pressure on thermal performance. The results of the aging tests showed acceptable agreement with that of the accompanying theoretical analysis. A parametric regime for accelerated aging tests of VIPs in laboratories was also proposed.

## 5.2. Thermal bridging effect

It is customary to express the performance of VIPs in terms of either the centre of panel or effective thermal conductivity with later incorporating the effect of thermal bridges around the edges. These thermal bridges appear at three levels for VIP application; (i) VIP level (ii) building components level (iii) facade level [65]. Thermal bridges or linear thermal transmittance at VIP level occurs at edges due to the difference in thermal conductivity of evacuated core and surrounding envelope materials. The linear thermal transmittance depends upon the panel thickness, length of perimeter and surface area. Effective thermal conductivity of a VIP can be calculated by adding linear thermal transmittance to centre of panel thermal conductivity as described in equation (16) [30,66].

$$\lambda_{eff} = \lambda_{cop} + \Psi_{VIP\ edge} \cdot d_p \cdot l_p / s_p \quad (16)$$

where

$\lambda_{cop}$  is the centre of panel thermal conductivity ( $W m^{-1} K^{-1}$ )

$\Psi_{VIP\ edge}$  the is linear thermal transmittance ( $W m^{-1} K^{-1}$ )

$\lambda_{eff}$  is the effective thermal conductivity ( $W m^{-1} K^{-1}$ )

$d_p$  is the thickness of VIP (m)

Wakili et al. [66] employed a two-dimensional numerical simulation tool TRISCO to predict the effective thermal conductivity and reported measurements using a guarded hot box.

Values of linear thermal transmittance calculated by Wakili et al. [66] for a square-shaped VIP of size 1  $m^2$  are shown in Fig.9. It can be seen that linear thermal transmittance values are higher for a VIP with an aluminium foil (8 $\mu$ m) envelope as compared to the aluminium

coated polymeric foil envelopes. Linear thermal transmittance values for a VIP, 10-40 mm thick, lie in the range of 0.008-0.010 W m<sup>-1</sup> K<sup>-1</sup> for envelopes consisting of three 12 μm metalized PET layers, while for a 6 μm aluminium foil it varied between 0.022 and 0.040 W m<sup>-1</sup> K<sup>-1</sup> [67]. Simmler and Brunner [35] calculated the safe design values for linear thermal transmittance to be 0.007 W m<sup>-1</sup> K<sup>-1</sup> and 0.01 W m<sup>-1</sup> K<sup>-1</sup> respectively for an aluminium foil and a metallised envelope. Clearly an aluminium foil envelope is not suitable for use in VIP envelope.

Thorsell and Kallebrink [68] proposed the serpentine edge design to minimise the linear thermal transmittance at VIP edges. For the stainless steel envelope with 17 serpentes of 20 mm depth the linear thermal transmittance was reported as 0.0096 W m<sup>-1</sup> K<sup>-1</sup> compared to 0.028 W m<sup>-1</sup> K<sup>-1</sup> for a straight steel edge. These values were calculated by using simulation tool Femlab. However, these linear thermal transmittance values were still larger as compared to the values obtained by the Wakili et al. [66] for the metallised and aluminium foil envelopes. Schwab et al. [69] reported similar results and recommended that a minimum panel size of 1 m<sup>2</sup> for aluminium foil VIP.

Tenpierik et al. [63,70] and Tenpierik and Cauberg [71] assuming steady state boundary conditions, no lateral heat transfer between adjacent VIPs and zero thermal conductivity of core presented an analytical model to calculate thermal bridges due to VIP envelope. The results of model for non zero core thermal conductivity were validated against the predictions obtained from a commercially available software, TRISCO. Linear thermal transmittance was found to be a complex function of laminate thickness, laminate thermal conductivity, panel thickness and core thermal conductivity. The difference in results of the model and that obtained by TRISCO simulations was much larger for metalized VIP panel with core thermal conductivity 0.002 Wm<sup>-1</sup>K<sup>-1</sup> and a panel thickness of 20 mm. The results of linear thermal transmittance obtained by simulations for 0.004 W m<sup>-1</sup> K<sup>-1</sup> core thermal conductivity with aluminium foil, stainless steel foil and metalized film envelope are shown in Fig.10. It is evident from Fig.10 that metalized film results into a smaller thermal bridge effect than in the case of aluminium foil and stainless steel envelope. Linear thermal transmittance due to metalized films, though smaller than aluminium foil and stainless steel, still has a value in the range of 0.001-0.004 W m<sup>-1</sup> K<sup>-1</sup> depending upon the thickness of panel and core thermal conductivity. Results of both model and simulations show that materials with higher thermal conductivity in the VIP envelope generated larger thermal bridging effect. Clearly, it is imperative to use low thermal conductivity materials in the VIP envelope to reduce the thermal bridging effect. Thin films of SiO<sub>x</sub> and SiN<sub>x</sub> coated on a polymer substrate can be used to reduce this thermal bridging effect, which is expected to enhance the thermal performance of VIPs.

VIPs often consist of two protecting facings on both sides of the panels linked with a spacer. Schwab et al. [69] estimated the linear thermal transmittance values of expanded polystyrene covered VIPs with aluminium foil and aluminium coated envelopes and found that the presence of expanded polystyrene facing reduced the thermal bridging losses. Nussbaumer et al. [72] also observed the reduced thermal bridging effect when expanded polystyrene was used as a facing in building components. Tenpierik et al. [73] and Quenard and Sallee [65] calculated thermal bridging effect of facing and spacers and found that aluminium and stainless steel facing caused larger values of linear thermal transmittance as compared to polyester facing. Same trend was observed for spacers made up of aluminium as compared to thermoplastic spacer. EPS strips along the perimeter of an encapsulated VIP were reported to cause an additional thermal bridging effect depending upon their thicknesses [74]. To reduce this thermal bridging effect, designers should either completely remove EPS strip or minimise the thickness of perimeter insulator or use a better insulator for perimeter.

## 6. Conclusions and future directions

VIP is a high performance thermal insulation, with a large potential to reduce the CO<sub>2</sub> foot prints of buildings (1.56 kg CO<sub>2</sub> m<sup>-2</sup> a<sup>-1</sup>) and in conforming to stringent energy standards whilst using minimal existing space. The adoption of VIPs is presently constrained by their limitations namely, susceptibility to damage during installation and development, uncertain useful life time, thermal bridging and high cost. Presently, research is limited to only a few materials which are being used in core and envelope of VIPs and test results available to date are limited to a narrow range of climatic conditions. Thus, new materials, concepts and computer models experimentally validated under realistic climatic conditions are required. The aim of such activities should be to enhance the properties of VIP and reduce their cost making them more attractive to manufacturers, consumers and the construction industry.

VIP envelope consisting of PET multiple sheets coated with SiO<sub>x</sub> and/or SiN<sub>x</sub> have a good potential to replace the conventional aluminium and metalized PET films. Silicon coatings are expected to improve the thermal and barrier performance of the VIP envelope. Research needs to be focussed on developing a barrier material which will achieve an OTR of <10<sup>-3</sup> cm<sup>3</sup> m<sup>-2</sup> d<sup>-1</sup> at 23°C, 50% RH, and a WVTR of < 10<sup>-4</sup> g m<sup>-2</sup> d<sup>-1</sup> at 32°C, 90% RH which is expected to yield a useful life time of 50 years or more for VIPs. These coatings are also expected to reduce the thermal bridging effect and improve thermal resistance. A comprehensive computer model able to resolve the coupled complex heat and mass (gas and water vapour) exchange phenomena that occur in a VIP system would be a useful tool for researchers to predict VIP performance parameters, thermal conductivity, WVTR and OTR, over a prolonged duration subject to realistic ambient conditions of temperature and humidity. Such a model would assist in identifying the optimum configurations of VIP envelope specifying the type and thicknesses of coatings required for varying thickness of the substrate.

One criticism that the fumed silica core material faces is its high market prices (leading to a higher VIP cost). There is a definite scope of cost reduction for VIP core materials by preparing fumed silica-perlite composite, though this might result into some thermal resistance being sacrificed. Optimal proportions for these two materials in the core yielding the lowest possible thermal conductivity need to be ascertained. Open-celled polystyrene modified by employing a suitable filler material is also being seen as a potential core material due to low out gassing properties. The challenge here is to optimise the type, amount and distribution of filler material in the composite to achieve and maintain a suitable vacuum level inside the core to result in design thermal conductivity values with intended useful life of 100 years or more.

There is a need of identifying newer adhesive materials, which have a low thermal conductivity and are chemically and physically stable under vacuum conditions and least outgas. Among various components in the surrounding air, water vapour has the highest transmission rate and it permeates about 30,000 times faster than oxygen and nitrogen and is therefore one of the major contributor to increasing pressure along with oxygen and nitrogen. It is felt that a new class of super hydrophobic sealants and sealing processes is required to overcome the problem of permeation of water vapours through the seal areas.

Finally, it is utmost important to employ the knowledge generated in the laboratories to manufacture example VIPs with experimentally validated test results under realistic climatic conditions to earn the confidence of the builders, architects and building managers and owners.

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