Development of High Efficiency Core Materials for Vacuum Insulation Panels

by

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Abstract

Vacuum insulation panel (VIP) is one of the recent innovations that can enhance the energy efficiency of buildings with slim construction. VIPs in pristine condition offer six to ten times higher thermal insulating capacity compared to traditional insulations. The high thermal performance of VIPs is achieved by applying a vacuum to an open porous core material which is encapsulated by a multilayer envelope, providing high resistance to air and water vapor entry. However, the core vacuum level decreases over time, mainly due to the penetration of air and water vapor through the envelope and into the pore structure of the core. The thermal performances of various VIPs are differently sensitive to the decrease in core vacuum level, depending mainly on the mean effective pore size of the VIP-Core. Glass fiber board is widely used as a macroporous VIP-Core due to its low density, high porosity, high mechanical stability, all of which provide high thermal performance at high vacuum. Compared to precipitated silica-VIP, glass fiber-VIP is more sensitive to the decrease in core vacuum level due to its larger mean effective pore sizes. The challenge for VIP-designers is to cost-effectively reduce the thermal performance degradation of glass fiber-VIPs during the service life.

After developing an experimental setup for making VIPs and measuring their effective thermal conductivity, this study investigates the effect of two alterations on the thermal performance of a glass fiber board as the VIP-Core: 1) Hydraulic pressing of the VIP during evacuation; and 2) Addition of zeolite powder or diatomaceous earth powder to change the microstructure of glass fiber boards. The mean distance between fibers is reduced due to the pressing during evacuation. The mean effective pore size of the VIP-Core is reduced due to combined effects of pressing during evacuation and the addition of zeolite particles; and it is reduced further due to combined effects of pressing during evacuation and the addition of diatomaceous earth particles. Compared to the glass fiber board, the glass fiber-zeolite composite has on average 20% higher thermal performances at various vacuum levels. The glass fiber-diatomaceous earth composite has a comparable thermal performance with the precipitated silica, up to the vacuum level of P = 10^2Pa, in addition to have on average 30% higher thermal performance, at various vacuum levels, compared to the glass fiber board. This study concludes that the glass fiber- silica powder composite is a viable method for reducing the mean effective pore size of the VIP- Core.

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List of Abbreviations and Symbols

Abbreviations and Symbols	Definition	Unit
VIP	Vacuum Insulation Panel	-
HFM	Heat Flow Meter	-
GFB	Glass Fiber Board	-
ZE	Zeolite Powder	-
DE	Diatomaceous Earth Powder	-
GFB-DE	Glass Fiber-Diatomaceous Earth Powder Composite	-
GFB-ZE	Glass Fiber-Zeolite Powder Composite	-
PUR	Polyurethane Foam	-
D_M	Mean Distance between Fibers	(m)
d_M	Mean Fiber Diameter	(m)
d_{MP}	Mean Particle Size of Silica Powder	(m)
δ	Mean Effective Pore Size	(m)
δ_{GFBs}	Mean Effective Pore size of Glass Fiber boards	
δ_{GFB}	Mean Effective Pore size of the Glass Fiber board under Consideration	(m)
δ_{FS}	Mean Effective Pore Size of Fumed Silica	(m)
δ_{PS}	Mean Effective Pore Size of Precipitated Silica	(m)
$\delta_{GFB-Silica}$	Mean Effective Pore Size of Glass Fiber Powder Composite	(m)
δ_{PUR}	Mean Effective Pore Size of Polyurethane Foam	(m)
δ_{PF}	Mean Effective Pore Size of Phenolic Foam	(m)
Al	Aluminum	-
PE	Polyethylene	-
PET	Polyethylene Terephthalate	-
Fig	Figure	-
q''_S	Heat Flux via Solid Conduction	(W/m^2)
q''_R	Heat Flux via Radiation	(W/m^2)
q''_G	Heat Flux via Air inside Pore Structure of VIP-Core	(W/m^2)
q''_{fl}	Heat Flux through a Fiber Layer	(W/m^2)
$q''_{Coupling}$	Coupling Effect between different Heat Transfer Modes	(W/m^2)
q''_T	Total Heat Flux	(W/m^2)
λ_E	Effective Thermal Conductivity of VIP-Core	(W/m.K)

λ_S	Solid Thermal Conductivity of VIP-Core	(W/m.K)
λ_s	Thermal Conductivity of Core's Solid Skeleton Constituent Particles or Material	(W/m.K)
λ_{sf}	Thermal Conductivity of Each Glass Fiber	(W/m.K)
λ_{SGFB}	Solid Thermal Conductivity of Glass Fiber Board	(W/m.K)
λ_{SPS}	Solid Thermal Conductivity of Precipitated Silica	(W/m.K)
λ_R	Radiative Thermal Conductivity of VIP-Core	(W/m.K)
λ_{RGFB}	Radiative Thermal Conductivity of Glass Fiber Board	(W/m.K)
λ_{RPS}	Radiative Thermal Conductivity of Precipitated Silica	(W/m.K)
λ_G	Thermal Conductivity of Air inside Pore Structure of VIP-Core	(W/m.K)
λ_{GGFB}	Thermal Conductivity of Air inside Pore Structure of Glass Fiber Board	(W/m.K)
λ_{GPS}	Thermal Conductivity of Air inside Pore Structure of Precipitated Silica Board	(W/m.K)
λ_{GFS}	Thermal Conductivity of Air inside Pore Structure of Fumed Silica Board	(W/m.K)
$\lambda_{Coupling}$	Thermal Conductivity due Coupling Effect	(W/m.K)
$\lambda_{g,0}$	Thermal Conductivity of Free Air	(W/m.K)
$\lambda_{g,e}$	The effective Thermal Conductivity of Air inside the VIP-Core	(W/m.K)
λ_{Series}	Effective thermal Conductivity of VIP-Core in when Air and Solid Phase are in series with respect to the heat flow direction through the VIP-Core	(W/m.K)
$\lambda_{Parallel}$	Effective thermal Conductivity of VIP-Core in when Air and Solid Phase are in parallel with respect to the heat flow direction through the VIP-Core	(W/m.K)
I_{mean}	Mean Free Path between Air Molecules	(m)
Kn	Knudsen Number	-
K_B	Boltzmann constant (1.3807×10^{-23})	J/K
d_g	Diameter of Gas Molecules	(m)

d_{apt}	Apparent Density of VIP-Core	
β	Constant between 1.5 and 2.0, Depending on The Gas Type, the Core Material and the Temperature	-
P	Air Pressure inside the VIP-Core	Pa
T	Temperature	$K/^0C$
T_a	Average Temperature within VIP-Core	$K/^0C$
T_h	Temperature of Hot Side of VIP-Core	$K/^0C$
T_c	Temperature of Cold Side of VIP-Core	$K/^0C$
t_k	Thickness of VIP-Core	
FS	Fumed Silica	-
e_{SGFB}	Specific Extinction Coefficient of Glass Fiber Board	(m^2/Kg)
R_S	Thermal Resistance of the Solid Phase VIP-Core	$m^2.K/W$
R_G	Thermal Resistance of the Gas Phase VIP-Core	$m^2.K/W$
R_M	Thermal resistance of the micro structure marked in Fig. (8b)	$m^2.K/W$
ε	Porosity	(%) / -
ε_{se}	Porosity of the Part of Core in Series with the Heat Flow Direction	(%) / -
ε_{pr}	Porosity of the Part of Core in Parallel with the Heat Flow Direction	(%) / -
α	Part of Core in Parallel with the Heat Flow Direction	-
n_L	Number of Glass Fibers in Each Layer (of Unit Area)	-
$\mathcal{E}_w$	Emissivity of Wall	(W/m^2)
$\mathcal{E}_f$	Emissivity of Fiber	(W/m^2)
G	Constant, depending on Gas Type and Temperature	-

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Besides my advisors, I would like to express my gratitude to my parents for their lifetime support, constant love, and sacrifices. I could never have accomplished my MASc without their patience and encouragement.

Dedication

I dedicate this work and give special thanks to my lovely parents for their endless love, support, and encouragement. I will always appreciate all they have done.

Chapter 1: Introduction

The energy efficiency and carbon footprints of buildings are influenced greatly by the application of high performance insulation materials. Vacuum insulation panels (VIPs) are regarded as super insulation materials for buildings. VIPs are produced by evacuating an open porous core material which is encapsulated by a high air and water vapor barrier envelope. VIPs, in pristine condition, offer thermal performances of around six to ten times higher than traditional (i.e. fibrous or foam) thermal insulation materials[1]–[3]. Although VIPs have a potential for combining the reduction of heat loss in buildings with slim wall constructions, the mass application of VIPs in buildings is restricted by the cost factor and the uncertainty regarding the long-term performance of VIPs [4], [5]. The thermal performance of VIPs and the cost of their production are significantly affected by the hygrothermal (i.e. heat, air and moisture response) properties of the constituent core material. Precipitated silica, fumed silica and glass fiber boards are generally used as VIP-Cores[4]. The envelopes have high barrier properties, however, a high stress is permanently induced on the envelope by the air pressure difference between the core vacuum and the outside of VIP[5]. Consequently, air and water vapor penetrates into the pore structure of the core through micro leakages in the envelope and the core vacuum level decreases over time. All VIP-Cores are open porous, evacuation capable and at high vacuum, they all have high thermal performances[2], [6], [7]. However, the thermal performance of various VIPs are differently sensitive to the decrease in core vacuum level, depending mainly on the mean effective pore size of the VIP-Core [1], [8]. Precipitated silica (PS) and fumed silica (FS) have small mean effective pore sizes (δ_{PS} =1- 3μm and δ_{FS} =40-70nm), restricting the degradation of their thermal performances due to air penetration, and therefore they have superior service life. However, they are comparatively expensive[2]. On the other hand, the cost of production for glass fiber boards is comparable with traditional thermal insulations but the service life of glass fiber boards, available at this moment, is shorter (around 15 years)[2]. The rapid aging of glass fiber boards is attributed to their larger mean effective pore sizes (up to δ_{GFB} =300 μm), compared to precipitated silica and fumed silica [9]. This motivates research into the glass fiber- silica powder composite as a method for reducing the mean effective pore size of the glass fiber boards as VIP-Cores and therefore extending their service lifespan.

1.1 Thesis Outline

A brief framework of this thesis is provided in this section. The first introductory Chapter 1 is written to link the context of the thesis according to research progress. After reviewing the general concept of vacuum insulation panels (VIPs) as super insulating material, the most common VIP-Cores and the heat transfer theory in glass fiber boards as VIP-Cores, Chapter 2 shows that the thermal performance of VIPs deteriorates mainly depending on the mean effective pore size of the VIP-Core over time and the glass fiber-silica powder composite is a viable method for making high efficiency VIP-Cores. The mean distance between fibers (D_{MGFB}) and the mean particle size of silica powder (d_{MP}) are identified as the control parameters for making high efficiency glass fiber-silica powder composites.

Chapter 3 presents the experimental setup for measuring the effective thermal conductivity of VIPs at the core vacuum levels between 1 and 10^5Pa, and discusses the experimental results. Three VIP-Cores are considered:1) glass fiber board (GFB), 2) glass fiber- zeolite composite (GFB-ZE), and 3) glass fiber-diatomaceous earth composite (GFB-DE).The experiments with these materials are mainly aimed at investigating the effect of two alterations on the thermal performance of a glass fiber board (with the mean effective pore size (mean distance between fibers) of $\delta_{GFB} = D_{MGFB}$ =130 μm); as a VIP-Core: 1) Hydraulic pressing of the VIP during evacuation; and 2) Addition of zeolite powder (with the mean particle size of $d_{MPZE} = 2$ μm) or diatomaceous earth powder (with the mean particle size of d_{MPDE} =4μm) to change the microstructure of glass fiber boards.

Chapter 4 summarizes the main results and contributions of the present research work and suggests directions for possible future works.

1.2 Research Contributions

The presented research shows the development and fabrication procedure of glass fiber-silica powder composites as a viable method for making high efficiency VIP-Cores. This provides an alternative for the production of glass fiber boards with small mean fiber diameters in range of ($d_M = 0.1 - 1$ μm), which is constrained by the high cost of production. The mean effective pore sizes of glass fiber boards are reduced due to the addition of powder particles to the microstructure of the glass fiber board used for making the composite. The main contributions of this study are summarized as follows:

1. By reviewing heat transfer theory in glass fiber boards, this research identifies the mean fiber diameter (d_M), the mean distance between fibers (D_{MGFB}) and the mean particle size of silica powder (d_{MP}) as control parameters for making high efficiency glass fiber-silica powder composites.
2. The effects of three alterations on the thermal performance of the glass fiber board (GFB) as the VIP-Core: (1) Pressing during evacuation (2) Combination of pressing during evacuation and the addition of zeolite (ZE) particles, and (3) Combination of pressing during evacuation and the addition of diatomaceous earth (DE) particles are investigated. This study then presents glass fiber-

diatomaceous earth powder as an alternative core material which has a comparable thermal performance with precipitated silica up to the core vacuum level of (P=10^2 Pa).

3. This thesis suggests making high efficiency glass fiber-silica powder composites by using glass fiber boards with the mean distance between fibers up to ($\mathrm{D}_{\mathrm{MGFB}} = 130\ \mu m$) and a silica powder with the mean particle size of ($\mathrm{d}_{\mathrm{MP}} = 10\ \mu m$) . This glass fiber-silica powder composite has a comparable thermal performance with precipitated silica, up to the core vacuum level of (P= 10^4 Pa) and the ratio of $\frac{\mathrm{D}_{\mathrm{MGFB}}}{\mathrm{d}_{\mathrm{MP}}} \approx 10$.

Chapter 2: High efficiency core materials for vacuum insulation panels - A review

Abstract

The energy efficiency of built environment depends principally on the application and performance of thermal insulation. Vacuum insulation panels (VIPs) are particular super insulation materials for high energy efficient buildings. VIPs are produced as a rigid panel comprised of inner core board encapsulated by an outer high barrier envelope under evacuated conditions. VIPs in pristine condition have effective thermal conductivities on the order of (10^{-3} W/mK) which is 10 to 15% of the value for conventional insulation materials, such as glass wool and polyurethane foam. However, high stress is permanently induced on the envelope caused by the difference between atmospheric pressure and high core vacuum level (within envelope). This can result in micro leakages, leading to the decrease in the core vacuum level and consequently reducing the service life of VIPs. All VIP-Cores are open porous and therefore evacuation capable. However, the thermal performance of each VIP-Core can deteriorate significantly, mainly depending on its mean effective pore size. The challenge that VIP- designers face is to reduce the cost and increase the long term performance of VIPs. After reviewing a variety of VIP-Cores (glass fiber boards, silica powders and foams) and heat transfer theory in glass fiber boards, this study shows the need for making hybrid core materials by using glass fiber boards which have comparable thermal performances with precipitated silica and fumed silica. It investigates glass fiber-silica powder composites for making high efficiency VIP-Cores, in which, the mean effective pore size of the VIP-Core is reduced by the addition of silica powder particles to the pore structure of the glass fiber board. It is concluded that the thermal performance of glass fiber-silica powder composites depends greatly on the mean distance between fibers ($\mathrm{D_M}$) (and therefore on the mean fiber diameter ($\mathrm{d_M}$)) of the glass fiber board and the mean particle size of the silica powder ($\mathrm{d_P}$). The glass fiber-silica powder has a comparable thermal performance with precipitated silica up to the core vacuum level of (P = 10^4Pa) by using a glass fiber board with the mean fiber diameter of ($\mathrm{d_M} = 1 - 5\ \mu\mathrm{m}$) and therefore the mean distance between fibers of up to around ($\mathrm{D_M} = \delta_{\mathrm{GFB}} < 130\ \mu\mathrm{m}$) ;and a silica powder with the mean particle size of around ($\mathrm{d_P} = 10\ \mu\mathrm{m}$). The glass fiber-silica powder composite has the mean effective pore size of ($\delta_{\mathrm{GFB-Silica}} < 10\ \mu\mathrm{m}$). This study suggests further studies into characterizing the thermal performance of glass fiber-silica powder composites using the ratio($\frac{\mathrm{D_M}}{\mathrm{d_P}}$),where ($\mathrm{D_M}$) is the mean distance between fibers and ($\mathrm{d_{MP}}$) is the mean particle size of the silica powder used for making the composite.. This glass fiber-silica powder is made using a glass fiber board with the mean fiber diameter of ($\mathrm{d_M} = 0.1 - 1\ \mu\mathrm{m}$) , mean distance between fibers of around ($\mathrm{D_M} = \delta_{\mathrm{GFB}} =< 26\mu\mathrm{m}$) and silica powder with the mean particle size of around ($\mathrm{d_{MP}} = 260\ \mathrm{nm}$). The mean effective pore size of the VIP-Core is estimated to be reduced to ($\delta_{\mathrm{GFB-Silica}} < 100\ \mathrm{nm}$). The glass fiber-

silica powder composite is used to achieve a comparable thermal performance with fumed silica up the core vacuum level of (P = 10^4Pa).

1. Introduction

Space and water heating accounts for 80% and 53% of the total end-use energy for residential and commercial buildings in Canada, respectively [10]. Use of high performance thermal insulation is critical to save the substantial amount of space heating energy lost through the building's envelope. Vacuum insulation panels (VIPs) are particular super insulation materials which have a huge potential to help in reducing the carbon foot prints of buildings and in conforming to stringent energy standards such as building standard LEED by Canada Building Council. VIPs mainly consist of open porous core materials evacuated and encapsulated in multilayer air and water vapor barrier envelope [6][10]. VIPs in pristine condition have effective thermal conductivities on the order of (10^{-3} W/mK) which is 10 to 15% of the value for conventional insulation materials such as mineralized wood fiber, cellulose, glass wool and polyurethane foam. However, high stress is permanently induced on the envelope arising from the difference between atmospheric pressure and the extremely low core internal air pressure ($P < 1$ Pa). Such high stresses result in micro leakages, leading to the decrease in the core vacuum level and consequently leading to the deterioration of thermal performance of VIPs over time. The challenge that VIP designers must confront is to reduce the cost and to increase the long term performance of VIPs. The thermal performance and the cost of VIPs are critically dependent on the hygrothermal (i.e. heat, air and moisture response) properties of the VIP-Cores. The design of VIPs for building applications faces the challenge of maintaining the super insulating capacity of VIP-Cores over the operation time of 30-50 years. This necessitates high efficiency VIP-Cores that not only have a low effective thermal conductivity at high vacuum but also maintain a high fraction of their high thermal insulating performance as the core vacuum level decreases over time due to air and water vapor penetration through the envelope into the VIP-Core. Glass fiber boards and silica powders (fumed silica and precipitated silica) are commonly used as VIP-Cores. All VIP-Cores are open porous and therefore evacuation capable. The thermal performance of a VIP depends significantly on the pore structure of the VIP-Core and mainly on the mean effective pore size of the VIP-Core. Fumed silica and precipitated silica have superior service life as a required criterion for building applications. However, silica powders are comparatively expensive. In contrast, glass fiber boards have shorter service life of around 15 years since they are sensitive to the decrease in the core vacuum level. However, they offer lower cost of production as a required criterion for building's application. Therefore, designing high efficiency VIP-Cores is a priority for VIP-designers. This will allow VIP-Cores to be less sensitive to air ingress compared to glass fiber boards, without compromising the cost factor. By reviewing the heat transfer in glass fiber boards as a VIP-Core, this study is aimed at identifying controllable parameters for making high efficiency glass fiber-silica powder composites. The mean effective pore size of the VIP-Core is reduced due to the addition of silica powder particles to the pore structure of the glass fiber board used for making the composite. This study concludes that the thermal performance of glass fiber-silica powder composites depends mainly on the mean distance between fibers (D_M) and on the mean fiber diameter (d_M) of the glass fiber board as well as the mean particle size of the silica powder (d_{MP}). In order for the glass fiber-silica powder composite to have the mean effective pore size of up to ($\delta_{GFB-Silica} <$ $10\ \mu m$) and therefore comparable thermal performance with precipitated silica, up to the core vacuum level of (P = 10^4 Pa), this study suggests using a glass fiber board with the mean fiber diameter $d_M = 1 - 5\ \mu m$ and therefore mean distance between fibers of around ($D_M = \delta_{GFB} < 130\ \mu m$).The silica powder should have the mean particle size of around ($d_{MP} = 10\ \mu m$). Additionally, this study suggests further investigation into characterizing the thermal performance of glass fiber-silica powder composites with the relation between the mean distance between fibers (D_M) and the mean particle size of the silica powder (d_{MP}) which is quantified by the ratio of ($\frac{D_M}{d_{MP}}$). This will allow further studies aimed at making a composite which has the mean effective pore size of up to ($\delta_{GFB-Silica} < 100\ nm$) with thermal performance comparable to fumed silica, up to the core vacuum level of (P = 10^4 Pa). The composite is proposed to be made by using a glass fiber board with the mean fiber diameter of ($d_M = 0.1 - 1\ \mu m$); and therefore the mean distance between fibers of around ($D_M = \delta_{GFB} =< 26 \mu m$); and the silica powder with the mean particle size of around ($d_{MP} = 260\ nm$).

2. Vacuum insulation panel

Vacuum insulation panels (VIPs) are fabricated based on the similar principle used in thermoses or evacuated “DEWARs” invented by James Dewar in 1890[11], [12]. The thermos is composed of a porous honeycomb coated with glass and/or steel, impermeable to air and evacuated from the comb[12]. In these system, air convection is restricted by high vacuum (pressure below 1Pa) and radiative heat transfer is restricted using spherical or cylindrical reflecting walls. The walls are produced in spherical or cylindrical shape, so that the thermos-bottle has the mechanical strength to withstand the atmospheric pressure of 10^5 N.m^{-2} (10^5Pa)[5], [12].

2.1 VIP-Structure

VIPs are produced as a flat load-bearing core board encapsulated by a multilayer high barrier envelope under evacuated condition (P < 1Pa) [13]–[16]. The core material is open porous and therefore evacuation capable. Since VIPs are designed in the form of a panel, a material with high mechanical strength has to be inserted into the envelope as the core. Otherwise, the VIP would not withstand the external load caused by atmospheric pressure[2]–[5], [7], [8], [12], [16]–[18]. Fig. (2.1) shows schematically the construction of a Vacuum Insulation Panel(VIP) [5].

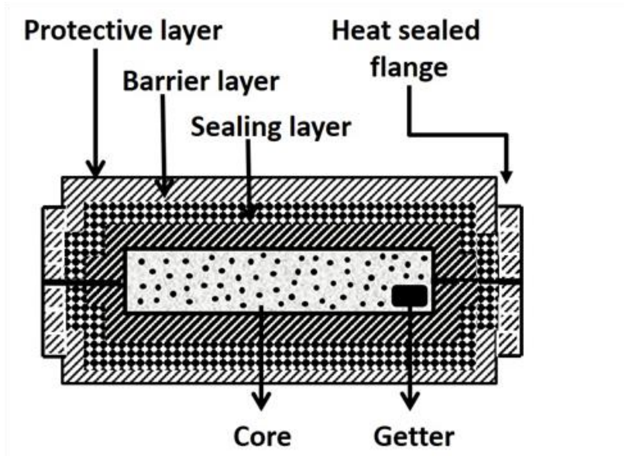

Fig 2.1: Components: Vacuum insulation panel [2], [5]

Silica powders, glass fiber boards, phenolic foam and polyurethane foam are generally used as VIP-Cores. The envelope consists of thin laminated metal foils and special high-barrier metallized laminates. These laminates are made mainly from several layers of Al-coated polyethylene (PE) or polyethylene terephthalate (PET). The highest grade barrier properties are essential for the envelope to fulfill the requirements of long-term application in buildings. An efficient envelope is one which provides high barrier against air and water vapor (H_2O) penetration, with thermal bridging across the VIP also restricted. An inefficient envelope surrounding the evacuated core forms a thermal bridge between both sides of the panel especially at its edges and corners. The thermal performance of a VIP is largely influenced by thermal bridging effect, especially for metal-based barrier foils(Al-foil). Although a sustainable high vacuum is achieved with laminated aluminum foils (with thickness of around 10 µm or more), the heat transfer rate (W/m^2) through the edge of a laminated metal foil envelope rises drastically because of thermal bridge effect [5], [19]. This leads to even higher heat transfer rate through the envelope than the heat transfer rate through the core material. Polymer films have higher vapor transmission rates for oxygen and nitrogen compared to metalized films. A multilayer approach is suggested to design an efficient envelope which fulfills various requirements for building applications. In recent VIP- Design the opposing prerequisites of low gas permeation and low thermal heat transfer is optimized by three-fold metallized polymer films with thickness of 30-100 nm for each metallization[5]. As seen in Fig. (1) [5], in multilayered approach, the envelope is primarily consisted of three layers: a protective layer, a barrier layer and a sealing layer. Polyethylene terephthalate (PET) is mostly used as the protective layer (the outer most layer) by which the VIP is protected from “environmental and handing stresses”[20]. Al-coated Polyethylene (PE) is most used as the intermediate barrier layer against air and water vapor. The laminated layers are heated between two hot bars under pressure to form the sealing layer which is the inner most layer. The permeation rate through the envelope varies depending on the environments’ temperature and humidity[2], [5], [19]. During the service life of a VIP, the core vacuum level decreases gradually by either gases and water vapor penetratong from outside through the envelope into the core pores or by outgassing from inside of the core or envelope material. Air penetration diminishes the thermal resistivity of the open porous cores. A suitable getter or desiccant is placed inside the VIP-Core, absorbing gases and water vapors. Although getters and desiccants extend the service life of VIP, they are not required for all VIP-Cores. Silica powder cores acts themselves as desiccants, but for glass fiber boards and foams a small amount of silica gel is required as desiccant. Highly porous materials such as synthetic zeolites are used as getters. Opacifiers are added to VIP-Cores to reduce the radiative heat loss through the core. Silicon carbide (SiC), carbon black, titanium dioxide (TiO2) and iron dioxide (Fe3O4) are generally used as opacifiers [2], [5].

VIPs, in pristine condition, generally have R-values per inch 6 to 10 times greater compared to conventional insulation materials. Fig 2.2 illustrates the comparison for the thermal resistivity of a Glass fiber –VIP against the common insulation materials [21].

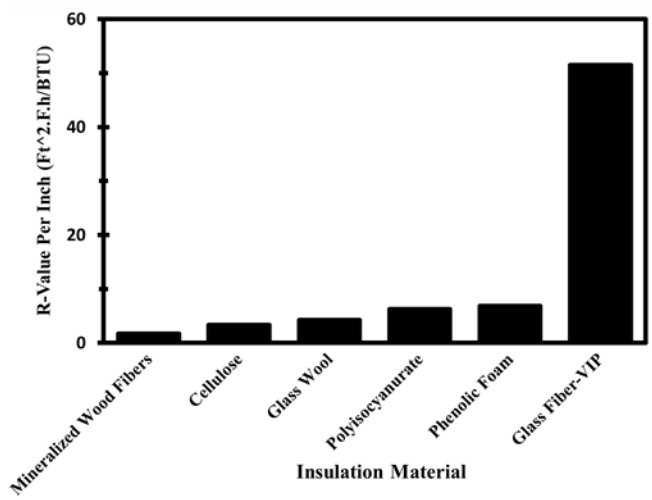

Fig 2.2: Thermal resistivity of Glass Fiber-VIP compared against several common insulation materials The supremacy of VIPs is rooted in its effective thickness when used as insulation material for building

Three mechanisms of heat transfer are to be restricted by the VIP-Core. Conduction is the transfer of heat through the physical contact of constituent particles of the VIP-Core. Energy is transferred from more energetic particles to the particles with less energy through conduction. The air convection in the core is comprised of two heat transfer mechanisms. Random air molecular motion transfers heat between air molecules and between air molecules and constituent particles (diffusion). Further bulk or macroscopic motion of the air molecules inside the core transfers heat through the core pores (advection) [22]. The effective thermal conductivity of air inside the core depends on how well both mechanisms simultaneously lead to air convection. Thermal radiation is the emitted thermal energy by matter at nonzero temperature. Regardless of the form of core, radiation takes place due to changes in the electron configurations of the constituent atoms or molecules. Unlike conduction and convection which require the presence of a material medium, radiation does not. The radiative energy is transported by electromagnetic waves (or alternatively viewed as photons), which is the underlying reason that radiation takes place most efficiently in vacuum[22]. Therefore, the heat flux through a porous core material involves three different heat transfer modes: 1) Heat transfer $q_S^{"}$ (W/m^2) via conduction within solid skeleton of the VIP-Core, 2) Heat transfer $q_R^{"}$ (W/m^2) via radiation, 3) Heat transfer $q_G^{"}$(W/m^2) via air inside pore structure of the VIP-Core. The total heat flux $q_T^{"}$ (W/m^2) is approximated by the sum of three heat fluxes (Eq. (2.1)), in which a simplistic approach of thermal resistance in parallel is assumed, all heat transfer mechanisms are assumed to be taking place independently[11].

$$q_T^{"} = q_S^{"} + q_R^{"} + q_G^{"}(+ \mathrm{q}_{\mathrm{Coupling}}^{"}) \qquad \text{Eq. (2.1)}$$

$\mathrm{q}_{\mathrm{Coupling}}^{"}$ (W/m^2) denotes the coupling effect which has to be considered for VIP-Cores with incoherent internal structures such as silica powders and glass fiber boards. The microstructure of glass fiber boards is incoherent since it is composed of fibers which have different diameters and are randomly distributed in different directions. This implies that for silica powders and fibers due to complex interaction between three heat transfer mechanisms, the total heat transfer is larger than the sum of three heat transfer mechanisms. The coupling effect is more evident at high core internal air pressures [4]. The model on the coupling term is known, but because of its complexity, this term is neglected in most literature and research [8]. The heat transfer rate through a VIP-Core is quantified by the core material's effective thermal conductivity λ_E (W/m.K) according to the thermal gradient. In a standard approach, λ_E is assumed to represent a sum of single values which describe on their own one of the pre heat transfer mechanisms. All heat transfer mechanisms are simultaneously taking place in the VIP- Core. The sum of all mechanisms is experimentally measured during steady state condition by a Heat Flow Meter [5] or a Vacuum Guarded Hot Plate [1]. (Eq. (2.2))[1], [23], [24].

$$q_T = \lambda_E . A . \frac{\mathrm{dT}}{dt_k} \qquad \text{Eq.(2.2)}$$

, q_T denotes the total heat transfer (W) through the core, λ_E is the effective thermal conductivity of the VIP-Core (W/m.K), A is surface area (m^2), dT (K) is the temperature difference over the VIP- Core and dt_k (m) is the thickness of the VIP-Core (m)[25][4]". Dividing both sides of the Eq.(2.1) with $\frac{dT}{dt_k}$, yields[10]

$$\lambda_E = \lambda_S + \lambda_R + \lambda_G + \lambda_{Coupling} \qquad \text{Eq.(2.3)}$$

Where λ_S denotes the conduction within the core's solid skeleton and is the solid thermal conductivity of the core , λ_R describes the radiation between core internal pore surfaces and is radiative thermal conductivity of the VIP-Core , λ_G describes the heat transfer through air inside the VIP-Core and is thermal conductivity of air inside the VIP-Core and $\lambda_{Coupling}$ denotes the coupling effect. In general, the conduction and air convection are linearly proportional to the temperature difference across the VIP-Core, as the two dominant heat transfer modes. Consequently, VIP-Cores exhibit a linear relationship between the effective thermal conductivity and temperature [26].

2.2 Core materials for VIP

VIP-Cores are open porous, meaning they have different mean effective pore sizes. Since a part of the internal structure of VIP-Cores are pores, they have low densities. At high vacuum (P <1 Pa), the effect of air can be neglected for all VIP-Cores, since there is a small number of air molecules in the pore structure of the VIP-Cores and the heat conduct by the air inside the VIP-Core (λ_G) is negligible. This is because air convection is highly restricted and the effective thermal conductivity of the VIP-Core is mostly comprised of its solid thermal conductivity(λ_S) and its radiative thermal conductivity(λ_R). The vacuum level decreases over time by either penetrating air and water vapor into the pore structure of the core or by outgassing from inside of the core and the envelope material [3], [4], [18], [19]. As vacuum level decreases, λ_G is estimated analytically by Knudsen relation (Eq.(2.4)), [4]

$$\lambda_G = \frac{\lambda_{g,0}}{1 + 2\beta Kn} \qquad \text{Eq.(2.4)}$$

$$Kn = \frac{I_{mean}}{\delta} \text{ and } I_{mean} = \frac{K_B T}{\sqrt{2\pi d_g^2 P}} \qquad \text{Eq.(2.5)}$$

,Where $\lambda_{g,0} = 26\ \mathrm{mW/m.K}$ is the thermal conductivity of free air. As expressed in Eq. (2.5), Kn (Knudsen number) is the ratio between the mean free path (I_{mean}) of gas molecules and the mean effective pore size (δ), K_B is the Boltzmann constant (1.3807×10^{-23} (J/K)), d_g is the diameter of the gas molecules and β is a constant between 1.5 and 2.0, depending on the gas type, the core material and the temperature. P is the pressure of air inside the VIP-Core. Kwon et al. (2009)[19] employed the following correlation (Eq. (6)) to estimate the thermal conductivity of air inside the VIP-Core , at T= 25 ^{0}C and by using β=0.016/P.

$$\lambda_G = \frac{\lambda_{g,o}}{1 + \frac{0.032}{P\delta}} \qquad \text{Eq.(2.6)}$$

This expression shows that as the vacuum level decreases between (P =1-10^5 Pa), λ_G increases differently for various VIPs depending on the mean effective pore size of the VIP-Core (δ) [2]–[5], [8], [17], [18]. For larger mean effective pore sizes, a higher vacuum level is required to maintain λ_G at a negligible level. Glass fiber board, fumed silica, silica aerogel, precipitated silica, phenolic foam and polyurethane foam are generally used as VIP-Cores.

2.2.1 Glass fiber board

Glass fiber board is used as VIP-Core for building and high temperature applications due to its low density, high thermal stability (>1000°C)[27] and high acoustic insulations properties[27]. Glass fiber is produced by marble melt process or flame attenuation process. The product of the former is named as chopped strand glass fiber board, while the product of the latter is flame attenuated glass fiber wool[28] . Kwon et al. (2009)[19] reported a density of 250 (Kg/m^3), fiber diameters of between 0.5-0.7 μm, the radiative thermal conductivity (λ_{RGFB}) of 0.7 (mW/mK) [19]and the solid thermal conductivity (λ_{SGFB}) of approximately 2.1 (mW/mK) at 300 K[19] for the glass fiber board used as VIP-Core. Collectively this results in the effective thermal conductivity (λ_{EGFB}) of 2.8 (mW/mK) at high vacuum. However, a high vacuum level (P = 1Pa) is required to maintain the thermal conductivity of air inside the glass fiber board (λ_{GGFB}) at the negligible level [11]. Although glass fiber boards have a lower initial effective thermal conductivity compared to fumed silica, but they are very sensitive to the decrease in the core vacuum level (core internal air pressure). This sensitivity comes from their large pore sizes compared to fumed silica (FS). As the core internal air pressure exceeds (P = 10^2Pa), the effective thermal conductivity of glass fiber boards (λ_{EGFB}) increases exponentially with the decrease in the core vacuum level. Getters/desiccants are required by Glass fiber-VIPs to continuously adsorb gases/ moisture which penetrate through envelope into the VIP-Core over time. Glass fiber- VIPs have a maximum service life of 15 years. However, such short service life is not suitable for building applications[29].

Chan et al. (2019) [30] used Glass fiber-VIPs in retrofitting an existing wall of a commercial building in Whitehorse, Yukon, Canada. They evaluated the field performance data from continuous in situ monitoring of their installation (2011–2018) in order to assess the long-term performance of glass fiber- VIPs in an extreme cold climate[31], [32]. They reported that all VIPs installed in 2011 remain functional after 8 years. The effectiveness of glass fiber-VIPs was decreasing linearly at an average rate of 0.9% per annum. However, the aging rate of Glass fiber-VIPs increases exponentially as core air pressure exceeds P = 10^2 Pa.

2.2.2 Fumed Silica

Evonik industries developed a hydrothermal process for making fumed silica (FS) in the early 1940ies. FS is the synthetic amorphous form of silicon dioxide. It is produced by pyrolysis of silicon tetrachloride in an oxyhydrogen flame (Eq. (2.7)[33].

$SiCl_4 + 2H_2 + O_2 \rightarrow SiO_2 + 4\ HCl$ Eq.(2.7)[33])

The molten particles of silicon dioxide fuse together to form chain-like silica aggregates. Upon cooling, these aggregates tend to form much larger agglomerates. The overall morphology of the fumed silica powder depends on both the structure of the primary particles and the states of aggregation and agglomeration. FS is normally mixed with opacifers (reducing radiation) and fibers (improving structural stability). The fumed silica composite is then pressed into boards and laminated by multilayer envelope for making a FS-VIP[13].FS is nontoxic and has a bulk density of 160-200 (Kg/m^3) [13][34], porosity of (ε_{FS} = 90-95%) [35].Simmler et al. performed compression test on two samples of fumed silica with the size of (60mm X 50mm X 20mm) and found that fumed silica fulfilled the requirement in building applications[36]. Kim and Song (2013) reported that at high core vacuum levels ($P \leq 10$ Pa), the opacified FS-VIPs has the effective thermal conductivity of (λ_{EFS} = 2.5-3.6 (mW/mK)) [37] . They reported that the effective thermal conductivity (λ_{EFS}) of opacified FS is increased by 3 (mW/mK) from λ_{EFS} =3 (mW/m.K) to λ_{EFS} = 6 (mW/m.K) after decreasing the core vacuum level from around ($P = 10^3$ Pa) to ($P = 10^4$Pa) [37]. Small pore size(δ_{FS} =40-70nm[17]), high porosity, low density and high specific surface area of (50-600(m2/g))[18]or(263.5 (m2/g))[17] are some of properties of FS. Kalneas and Jelle (2014) stated that other advantages for FS are recyclability and incombustibility[13]. If the envelope is perforated, FS has the effective thermal conductivity of $\lambda_{EFS} =$ 20 (mW/m.K) which is lower than the thermal conductivity of free air ($\lambda_{g,0} =$ 26 (mW/m.K) . However, the major drawbacks of FS are its high cost and low radiative heat resistivity. Kim and Song (2013) [38]estimated the specific transport extinction coefficient (e_s)of fumed silica and glass wool by using Rossland approximation modeling. Fumed silica has the e_{SFS} = 23 (m^2/Kg) [37] while glass fiber has the e_{SGFB} = 52 (m^2/Kg)[37].The low e_S excludes FS from materials which are considered to have low radiative thermal conductivity. These two downsides of fumed silica have been motivating some new studies for making hybrid core materials (HCMs). These HCMs are made of FS mixed with other filling materials.

Silica aerogel (SA) is another silica based VIP-Core. Silica aerogels are nano porous materials with mean effective pore size of around (δ_{SA} = 20 nm) [39] and a density in the range of 3 to 350(kg/m^3) [39]. In 1931, Kistler produced silica aerogel for the first time sing sodium silicate [39]. In general, aerogels are made by two steps[40]: (1) Wet gel formation by acidic condensation (sol-gel process) by using sulphuric acid or phosphoric acid and (2) Drying of wet gel by supercritical (or ambient) drying to produce silica aerogel. Potter (1993)[40] reported that opacified silica aerogel has the mean effective pore sizes of ($\delta_{SA} =$ 1-100nm[40]) and the effective thermal conductivity of between (λ_{ESA} =1-3 (mW/m.K)) [40] and depending on the temperature . Baetens (2011)[41] reported that the effective thermal conductivity of silica aerogel is slightly increased to (λ_{ESA} = 4 (mW/mK)) [41], at the core vacuum level of (P= 10^3 Pa)[21]. Silica aerogel is non-reactive and non-flammable. However, due to its high cost it is not widely used as VIP-Core in buildings. Silica aerogel (SA) is optically transparent and therefore has comparatively high radiative thermal conductivity. Other drawback of Silica aerogel is rooted in its extreme brittleness which make it difficult to handle [40], [41]. This can be improved by preparing composites of silica aerogels with other mechanically stable materials.The silica aerogel can be mixed with expanded perlite to make a low cost mechanically stable composite [5], [41].

2.2.3 Foam

Foams are also used as a VIP-Core. Foams are classified into two types: closed and open-cell structure foams. Concerning ease of evacuation as an essential property of cores, only open-cell structure foams such as polyurethane or phenolic foam are used as VIP-Cores. Foams-VIPs are mostly used in refrigerators, where shorter service life is required. Low cost, low density, low effective thermal conductivity at high vacuum, relative small pore sizes, and "ease of production"[19] are some properties which are reported for foams by various research works. Kim et al.(2012) [38] reported the mean effective pore size of δ_{PF}= 260 µm , density of 25(kg/m^3) and ignition temperature of 595 ^{0}C for Phenolic foam. In case of fire, little smoke and toxic gases are expected during combustion of phenolic foam. Generally phenolic foam has "great properties regarding flame, smoke and toxicity (FST)" [38] [42] . However, low mechanical strength is the downside of phenolic foams and improving it has been the objective of many researches [43] . As reported by Jae-Sung Kwon (2009)[19], the polyurethane foam (PUR) has a mean effective pore size of ($\delta_{PUR} =$ 100µm) and has effective thermal conductivity of λ_{EPUR} =7.8 (mW/m.K), at the core vacuum level of (P = 10Pa). As reported by Frick. et. al. (2006)[3], phenolic foam has mean effective pore size of ($\delta_{PF} =$ 260 µm) and effective thermal conductivity of around ($\lambda_{EPF} =$ 5 mW/mK), at a vacuum level of (P = 1Pa) [11]. However, a maximum value of 4 (mW/mK) is normally adopted for the effective thermal conductivity of VIP-Cores at high vacuum.[44]. Such a low thermal conductivity value is apparently difficult to realize in Foam-VIPs. Another drawback of foams is their sensitivity to the decrease in the core vacuum level to (P> 1 Pa). Such high vacuum level is hard to preserve over the service life of the VIP.

2.2.4 Why focus on making hybrid core materials by using glass fiber boards?

Fig. (3) shows the comparison for the thermal performance of a glass fiber board (GFB) against the thermal performance of precipitated silica (PS) and fumed silica (FS) at the core vacuum levels (core internal air pressures) of between P =1-10^5Pa. At high vacuum (P = 1 Pa), the effective thermal conductivity (λ_E) of all VIP-Cores (glass fiber board, precipitated silica and fumed silica) is mostly comprised of solid and radiative thermal conductivity ($\lambda_S + \lambda_R$) and the thermal conductivity of air inside the pore structure of core (λ_G) is negligible. As the core vacuum level decreases, λ_G and therefore, λ_E of all VIP-Cores is increased by growing air convection inside the core. Following Eq. (6), λ_G is increased differently for each VIP-Core (glass fiber board, precipitated silica or fumed silica) depending on the mean effective pore size. At high vacuum level (P = 1Pa), the GFB has the effective thermal conductivity of 2.3 mW/m.K ($\lambda_{EGFB} = 2.3\ \mathrm{mW/m.K}$) which is lower than the value reported by Kwon et al. (2009) for the sum of ($\lambda_{SGFB} + \lambda_{RGFB}$) for a glass fiber board. It indicates that at P = 1Pa, λ_{GGFB} is at the negligible level (0- 0.3 mW/m.K). λ_{EGFB} is increased by 0.5 mW/m.K to 2.8 mW/m.K at p = 10 Pa, indicating that λ_{GGFB} is increased by 0.5 mW/m.K , compared to p = 1Pa. Consequently, at p = 10Pa, λ_{GGFB} is estimated as (0.5- 0.8 mW/mK) . Following Eq. (6), the mean effective pore size is estimated as around ($\delta_{GFB} = 60 - 100\ \mu m$) for the GFB. At high vacuum (P = 1-10 Pa), the effective thermal conductivity of precipitated silica stays constant at ($\lambda_{EPS} = 3.1$ mw/mK) which is mostly comprised of ($\lambda_{SPS} + \lambda_{RPS}$) . λ_{EPS} is increased by 0.3 mW/m.K to 3.4 mW/m.K at p = 10^2 Pa while λ_{EPS} is increased by 1.2 to 4.3 mW /mK at P = 6. 10^2 Pa indicating that λ_{GPS} is increased by 0.9 mW/m.K , compared to p = 10^2 Pa. Consequently, at 6. 10^2 Pa, λ_{GPS} is estimated as 1.2 mW/mK . Following Eq. (6), the mean effective pore size is estimated as around ($\delta_{PS} = 2 - 3\mu m$) for the precipitated silica (PS). This is the underlying reason that λ_{GPS} is at negligible level (< 0.3 mW/m.K) at p = 10^2Pa and is at low level (< 1 mW/m.K) up to P = 10^3Pa. Fumed silica is a nano porous material with the mean effective pore sizes in range of (δ_{FS} = 40-70nm)[19]). As seen in Fig 2.3, the effective thermal conductivity of fumed silica (λ_{EFS}) is increased by 0.3 mW.m.K by decreasing the core vacuum level from P =1 Pa to P = 10^3 Pa. This indicates that λ_{GFS} is restricted to the negligible level up to the core vacuum level of (P=10 Pa)

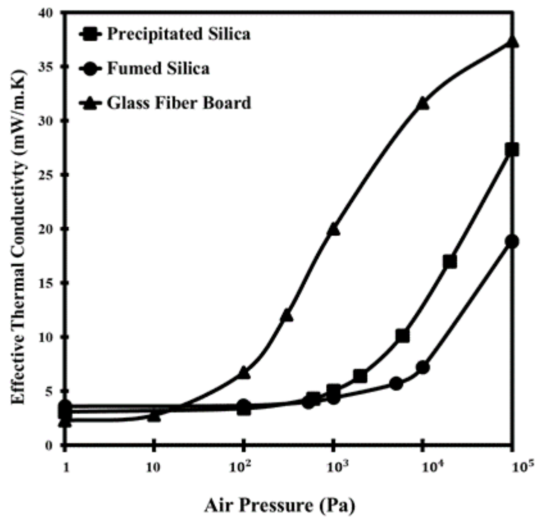

Fig 2.3: The thermal performance of a glass fiber board compared with precipitated silica and fumed silica[1]

Although Glass fiber-VIP has the lowest effective thermal conductivity at high vacuum level of (P =1 Pa) among three VIP-Cores, it is sensitive to the decrease in the core vacuum level due to air and water vapor penetration through the envelope into the core (λ_{GGFB} increases exponentially by decreasing the core vacuum level to P>10^2 Pa). At high vacuum precipitated silica- VIP and Fumed Silica – VIP have higher effective thermal conductivities. However, they are considerably less sensitive to a decrease in the core vacuum level, since they have lower mean effective pore sizes ($\delta_{\text{PS}} = 2 - 3\mu\text{m}$ and δ_{FS} = 40-70nm) compared to Glass fiber –VIP ($\delta_{\text{GFB}} = 60 - 100\ \mu\text{m}$). Glass fiber boards and silica powders have incoherent structures and contradictory properties, at high core vacuum, and at low core vacuum levels. This suggests making glass fiber –silica powder composite to cost effectively reduce the mean effective pore size of glass fiber board, so that the air convection is more restricted and the VIP-Core is less sensitive to the decrease in the core vacuum level. The mean effective pore size of the VIP-Core is reduced due to the addition of silica powders to the pore structure of the glass fiber board as silica powders settle between the fibers.

Before discussing the glass fiber-silica powder composite as a method for making high efficiency VIP-Cores, we need to investigate heat transfer theory in glass fiber boards as open porous materials. Appropriate theoretical assumptions are essential for estimating the contribution of each heat transfer mechanism to the total heat flux through the glass fiber board. On one hand, the complicated evaluation of three heat transfer mechanisms is simplified benefiting from the appropriate assumptions. On the other hand, the evaluation is generalized for various open porous cores. In the following sections, the treatment of solid and air phases is further developed for glass fiber boards which results in more complex equations with fewer unknown parameters[45].

3. Heat transfer theory in glass fiber boards

Bankvall[45] developed a theory to estimate different heat transfer modes in VIP-Cores as open porous materials. VIP-Cores are treated as the combination of a solid phase and air phase. Using this theory, the effective thermal conductivity of the VIP-Core is correlated to the individual thermal conductivities of solid phase and air phase. Here, two extreme cases are considered for analytical purposes. Fig 2.4[45] shows the first case in which air and solid phases are in series with respect to the heat flow through the core. Fig 2.5[45] shows the second case in which two phases are parallel to the heat flow through the core. R_S and R_G denote the thermal resistance for solid phase and air phase, respectively[45].

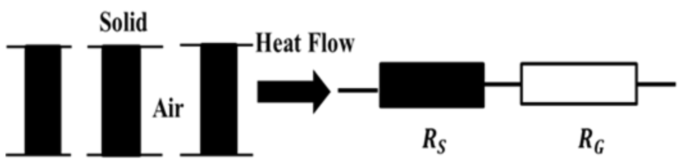

Fig 2.4: Air and solid phase are in series with respect to the heat flow direction through the VIP-Core[42]

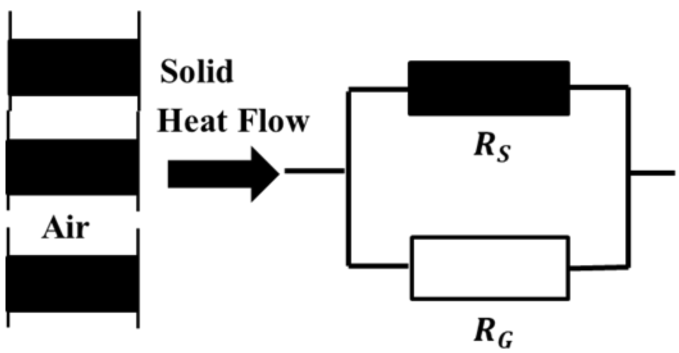

Fig 2.5: Air and solid phase are in parallel with respect to the heat flow direction through the VIP-Core [42]

For series and parallel cases as the extreme cases, the effective thermal conductivity of the core is expressed in Eq. (2.8)[45] and Eq. (2.9)[45], respectively,

$$\lambda_{\text{Series}} = \frac{\lambda_{g,e}\lambda_s}{\lambda_g.(1-\varepsilon) + \lambda_s.\varepsilon} \qquad \text{Eq.(2.8)}$$

$$\lambda_{\text{Parallel}} = \lambda_s.(1-\varepsilon) + \lambda_{g,e}.\varepsilon \qquad \text{Eq.(2.9)}$$

, in which λ_{Series} and $\lambda_{Parallel}$ are the effective thermal conductivity of core in series and parallel case, ε denotes the porosity of open porous core, λ_s is the thermal conductivity of core's solid skeleton constituent particles or material (fibers in case of glass fiber boards) and $\lambda_{g,e}$ is the thermal conductivity of air inside the VIP-Core corresponding to the core vacuum level and the mean effective pore size . At atmospheric pressure, $\lambda_{g,e}$ is replaced by $\lambda_{g,0}$ = 26 (mW/m.K)., In reality, the core has t effective thermal conductivity in the range between λ_{Series} and $\lambda_{Parallel}$. Fig. 2.6 [45] shows the unit volume of the open porous core, as schematically illustrated in Fig. 2.7 [45], as a combination (in parallel) of the extreme cases.

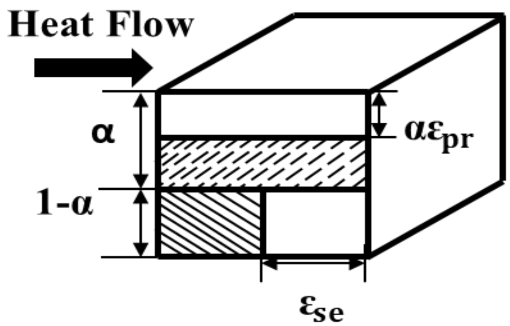

Fig 2.6: Unit volume of the open porous core (schematic illustration of Bankvall's model for estimating the effective thermal conductivity of the open porous cores). [45]

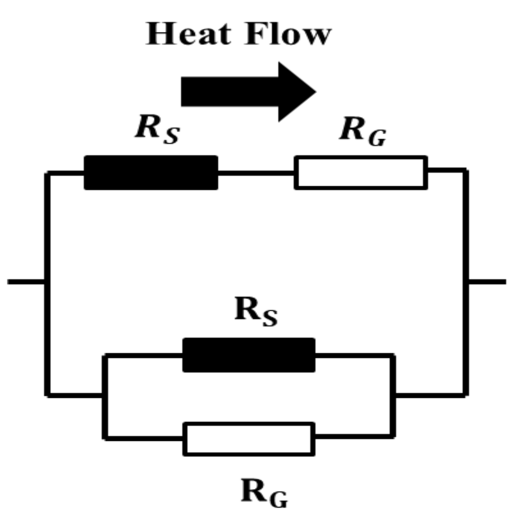

Fig 2.7: Combination of two extreme cases[42]

The effective thermal conductivity of the VIP-Core is expressed in Eq. (2.10)[45],

$$\lambda_E = \alpha.(\varepsilon_{pr}.\lambda_{g,e} + (1-\varepsilon_{pr}).\lambda_s) + (1-\alpha)\frac{\lambda_s.\lambda_{g,e}}{\varepsilon_{se}.\lambda_s + (1-\varepsilon_{se}).\lambda_{g,e}} \quad \text{Eq.(2.10)}$$

Here, α denotes the part of core in parallel with the heat flow direction, while (1-α) denotes the part of core in series with the heat flow direction. ε_{se} and ε_{pr} are porosities of the part of core in series and in parallel with the heat flow direction. The porosity of the core (ε) is expressed in Eq. (2.11)[45]. α is in range of (0.95-0.99[45]) for glass fiber boards with ε_{pr} in range of (0.99-1[45]) and ε_{se} is in range of (0.11-0.38[45]).

$$\varepsilon = (1-\alpha).\ \varepsilon_{se} + \alpha\ .\ \varepsilon_{pr} \quad \text{Eq.(2.11)}$$

Consequently, the effective thermal conductivity of open porous cores depends upon two independent parameters. The first one is an arbitrary pairing of ε_{se} and ε_{pr} and the second is α. As seen in Fig. (6), the $\alpha.(1-\varepsilon_{pr}).\lambda_s$ in Eq.(2.10) signifies the part of thermal conductivity which is due direct heat conduction via the solid skeleton of the VIP-Core (fibers in case of glass fiber-VIP, powder particles in case of silica powders) . This part entail a small part of the effective thermal conductivity of VIP-Cores since, core materials have high porosities. At high vacuum, this mechanism and thermal radiation are two heat transfer mechanisms governing the heat transfer through the VIP-Core. The conduction in the solid phase of the core is expressed in the Eq. (2.12)[45]. The effect of air convection inside the open porous core is estimated using Eq. (2.13) [41].C

$$\lambda_S = \alpha.(1-\varepsilon_{pr}).\lambda_s \quad \text{Eq.(2.12)}$$

$$\lambda_G = \alpha.\varepsilon_{pr}.\lambda_{g,e} + (1-\alpha).\frac{\lambda_s\lambda_{g,e}}{\varepsilon_{se}\lambda_s + (1-\varepsilon_{se}).\lambda_{g,e}} \quad \text{Eq.(2.13)}$$

λ_S is the solid thermal conductivity of core, while λ_s is the thermal conductivity of the core constituting particles (thermal conductivity of each individual fiber in case of glass fiber boards). λ_G is the effective thermal conductivity of air inside the pore structure of the VIP-Core. At atmospheric pressure, $\lambda_{g,e}$ is replaced by $\lambda_{g,0}$ = 26 (mW/m.K). After exploring the general aspects related to the heat transfer modeling in the VIP-Cores as open porous materials, the analytical models for glass fiber boards are described to estimate the various heat transfer mechanisms in glass fiber boards.

3.1 Solid thermal conductivity of glass fiber boards

The solid thermal conductivity of glass fiber board (λ_{SGFB}) is influenced first by the direct heat conduction passing through fibers and second the interaction between the air molecules and glass fibers[45]. Fig (8) schematically illustrates the pore structure of the glass fiber board. As seen in Fig. (8a and 8c) the fibers are assumed to be randomly oriented in parallel layers at right angle to the heat flow direction. However, o certain other assumptions about the pore structure of glass fiber are required for theoretically estimating the solid thermal conductivity. $n_L$is the number of glass fibers in each layer (of unit area) which is estimated (Eq. (2.14))by using the mean fiber diameter (d_M) [45]. D_M is the mean distance between two fibers which is estimated by Eq. (2.15)[45],

$$n_L = \frac{4(1-\varepsilon)}{\Pi.d_M} \qquad \text{Eq.(2.14)}$$

$$D_M = \frac{\Pi.d_M}{4(1-\varepsilon)} \qquad \text{Eq.(2.15)}$$

Here, the glass fiber board is assumed to consist of uniformly and symmetrically arranged fibers (Fig. (8a)). Fig. (8b) shows the point of contact of two fibers (a cylinder with plane ends which is connected to two hemispheres) [45]. At the point of contact, the heat is transferred through direct contact between the fibers and the binder surrounding the fibers.

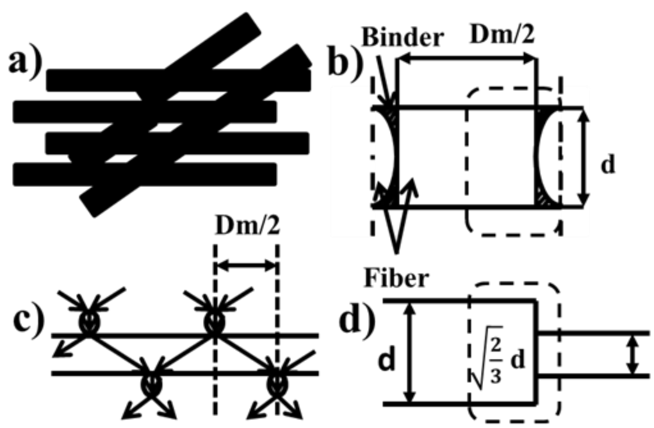

Fig 2.8: Solid conduction in a glass fiber board[42]

Bankval [45] assumed the part that is marked in Fig. 2.8b [45] to be thermally equivalent to Fig. 2.8d[45]. In other words, in Fig.(8d) a cylinder with the same volume is replacing the hemisphere of Fig. 2.8b and the influence of the binder is neglected, since the thermal conductivity of binder is usually 10 times less than the fibers[45]. The thermal resistance of the marked micro structural unit (R_M) is estimated by Eq. (2.16)[45], consequently the total heat flux (W/m^2) through a fiber layer (q''_{fl}) is estimated by Eq. (2.17)[45],

$$R_M = \frac{(3+\frac{D_M}{d_f})}{\Pi.\lambda_{sf}.d_f} \qquad \text{Eq. (2.16)}$$

$$q''_{fl} = 2\frac{n_L^2}{R_m}\Delta T \quad \text{Eq. (2.17)}$$

, ΔT is the temperature difference between two sides of the fiber layer. The equivalent solid thermal conductivity of the glass fiber board (λ_{SGFB}) is estimated by using Eq. (2.18)[45] or Eq. (2.19)[45].

$$\lambda_{SGFB} = 2\frac{n_L^2.d_M}{R_M} \quad \text{Eq. (2.18)}$$

$$\lambda_{SGFB} = \frac{32(1-\varepsilon)^2.\lambda_{sf}}{\Pi\left(3+\frac{\Pi}{4(1-\varepsilon)}\right)} \quad \text{Eq. (2.19)}$$

Here, ε is the effective porosity of the GF-board and λ_{sf} is the thermal conductivity of each glass fiber. Fig 2.9 illustrate the variation of λ_{SGFB} upon increasing porosity (Eq. (19)[45]). As seen in Fig 2.9 for high porosity glass fiber boards, the equivalent solid thermal conductivity is less than 1 (mW/m.K) and can be neglected for evaluation of the effective thermal conductivity of the glass fiber boards[45]. D_M depends on the mean fiber diameter (d_M) while, both are controllable parameters for the solid thermal conductivity of glass fiber boards (λ_{SGFB}).

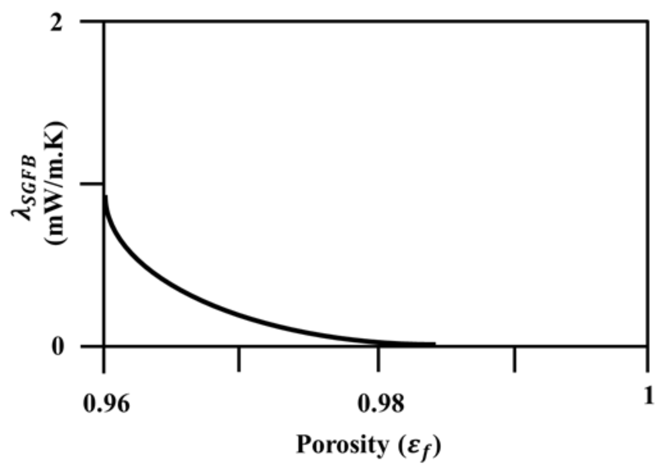

Fig 2.9: Solid thermal conductivity of glass fiber boards vs. porosity of the board [42]

3.2 Radiative thermal conductivity of glass fiber boards

Rosseland approximation (Eq.(2.20)[46]) is the most used modeling for estimating the radiative thermal conductivity of VIP-Cores. Whereby, key parameters in are the average temperature within the VIP-Core (T_a) and the mean transport extinction coefficient E(T). As expressed in Eq. (2.22), the specific transport extinction coefficient (e(T)) which depends on apparent density (d_{apt}) of the core and mean transport specific extinction (E(T)) [46]. T_a (K) is expressed in Eq. (2.21)[46], T_h and T_c are the temperatures of hot side and cold side of the VIP-Core, respectively.

$$\lambda_R = \frac{16}{3}\frac{\sigma n^2 T^3}{E(T)} \quad \text{Eq.(2.20)}$$

$$T_a = \sqrt[3]{(T_h^2 + T_c^2)(T_h + T_c)/4} \quad \text{Eq.(2.21)}$$

$$e\,(T) = \frac{E(T)}{d_{apt}} \quad \text{Eq.(2.22)}$$

The value of Stefan- Boltzmann constant (σ) is 5.67×10^{-8} (W/ m^2K^4). n is the mean index for refraction which varies for different VIP-Cores (e.g. around 1 for silica)[46]. T_h is the temperature of hot side of VIP-Core and T_c is the temperature of cold side of VIP-Core. d_{apt} is the apparent density of the VIP-Core. For glass fiber boards, some theoretical assumptions are required for estimating the radiative thermal conductivity. First, it is assumed that the glass fiber board consists of disoriented fibers at right angle to the direction of heat transfer. As schematically illustrated in Fig 2.10 [45], t_k is the thickness of the glass fiber board, D_M is the mean distance between two fibers and T_0 and T_n are temperatures of the wall on the cold side and hot side of the board, respectively.

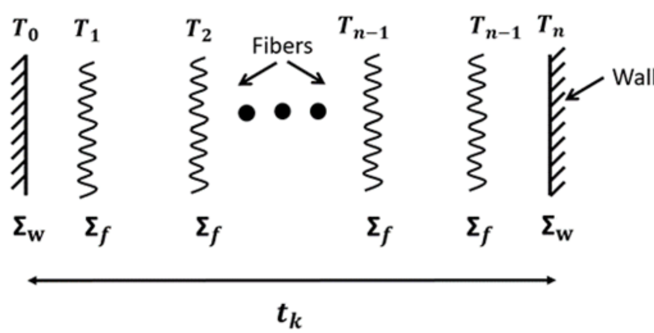

Fig 2.10: Thermal radiation model in a glass fiber core [42]

Secondly, it is assumed that the fibers and the walls on both sides of the board "behave as grey, non-transparent bodies" with emissivity of ε_w(W/m^2) and ε_f (W/m^2) . Under these assumptions, the radiation is estimated by Eq. (2.23) for the glass fiber board [45],

$$q_R^{"} = \frac{\sigma_s(T_0^4 - T_1^4)}{\frac{1}{\varepsilon_w}+\frac{1}{\varepsilon_f}-1} = \frac{\sigma_s(T_1^4 - T_2^4)}{\frac{2}{\varepsilon_f}-1} = \ldots\ldots.= \frac{\sigma_s(T_{n-2}^4 - T_{n-1}^4)}{\frac{2}{\varepsilon_f}-1} = \frac{\sigma_s(T_{n-1}^4 - T_n^4)}{\frac{1}{\varepsilon_w}+\frac{1}{\varepsilon_f}-1} \quad \text{Eq.(2.23)}$$

$$2q_R^{"} = \frac{\sigma_s}{\frac{1}{\varepsilon_w}+\frac{1}{\varepsilon_f}-1} . (T_0^4 - T_1^4 + T_{n-1}^4 - T_n^4) \quad \text{Eq.(2.24)}$$

$$(n-2)q_R^{"} = \frac{\sigma_s}{\frac{2}{\varepsilon_f}-1} \sum_1^{n-2} (T_i^4 - T_{i+1}^4) = \frac{\sigma_s}{\frac{2}{\varepsilon_f}-1} (T_1^4 - T_{n-1}^4) \quad \text{Eq.(2.25)}$$

$$q_R^{"} = \frac{\sigma_s(T_0^4 - T_n^4)}{(n-1)(\frac{2}{\varepsilon_f}-1+\frac{1}{n-1}(\frac{2}{\varepsilon_w}-1))} \quad \text{Eq.(2.26)}$$

Here, σ_s= 5.7. 10^{-8} W/m^{2}K^4 is the Stefan-Boltzmann constant. The addition of the first and the last expression in Eq. (2.23) leads to the equation which is more simplified (Eq. (2.24)[45]) and the addition of the rest expressions gives the Eq. (25)[45]. The elimination of $(T_1^4 - T_{n-1}^4)$ from Eq. (2.25) leads to Eq. (2.26)[45] by which the radiation is estimated by using temperatures of the wall on the cold side (T_c) and the hot side of the glass fiber board (T_h). If n – 1 = t_K /D_M is inserted, for the moderate temperature differences compared to the absolute temperature, the radiative thermal conductivity of the glass fiber core (λ_{RGFB}) is estimated by Eq. (2.27)[45],

$$\lambda_{RGFB} = \frac{4\sigma_s . D_M . T_a^3}{(\frac{D_M}{t_k} . (\frac{2}{\varepsilon_w}-1)+(\frac{1}{\text{в}}))} \quad \text{Eq.(2.27)}$$

$$\text{в} = \frac{\varepsilon_f}{2-\varepsilon_f} = \text{f}(\text{T}, d_M, \varepsilon_f) \quad \text{Eq.(2.28)}$$

,where T_a is the average temperature within the glass fiber board. The radiational properties of fibers and fiber layers are described by the factor β(Eq. (2.28))[45], в depends on temperature (T), the mean fiber diameter (d_M) and porosity (ε). As seen in Eq. (2.27)[45], the radiative thermal conductivity of glass fiber board varies upon the mean distance between fibers (D_M) , the mean fiber diameter (d_M) , the thickness of glass fiber board (t_K), and the emittance (ε_w) of the boundary surfaces. However, for a thickness sufficiently large compared to the mean fiber diameter and sufficiently black boundary surfaces, the radiative thermal conductivity (λ_{RGFB}) is estimated using Eq. (2.29)[45],

$$\lambda_{RGF} = 4\sigma_s . D_M . \beta . T_a^3 \quad \text{Eq.(2.29)}$$

$$D_M = \frac{\Pi}{4} \frac{d_M}{1-\varepsilon_f} \quad \text{Eq.(2.30)}$$

D_M is the mean distance between fibers which is interpreted as the mean free path for photons and then expressed in Eq. (2.30). D_M is identified as the controllable parameter for the radiative thermal conductivity of glass fiber boards (λ_{RGF}).

3.3 Thermal conductivity of air inside glass fiber boards

Bankvall [45] employed the following correlation (Eq. (2.31)) to estimate the thermal conductivity of air inside glass fiber boards,

$$\lambda_{GFGB} = \lambda_{g,o}.\frac{PD_M}{PD_m + G.T} \qquad \text{Eq.(2.31)}$$

P is the pressure of air inside the glass fiber board and G is a constant, depending on the gas type (air in case of VIP). For air, G = 2.332. 10^5 . Here, D_M is the mean effective pore size of glass fiber boards and therefore, a controllable parameter for the thermal conductivity of air inside the glass fiber board(λ_{GGFB}).

3.4 Effective thermal conductivity of glass fiber boards

Bankvall's modeling (Eq. (32)[45]) estimates the effective thermal conductivity of a glass fiber board (λ_{EGFB}) as open porous material by adding he solid thermal conductivity, thermal conductivity of air inside the glass fiber board and the radiative thermal conductivity. In result, the effective thermal conductivity of the glass fiber board (λ_{EGFB}) is estimated using the Banksvall's modeling (Eq. (2.32)[45]).

$$\lambda_{EGFB} = \alpha.\left(1 - \varepsilon_{pr}\right).\lambda_{sf} + \alpha.\varepsilon_{pr}.\lambda_{ge} + (1 - \alpha).\frac{\lambda_{sf}\lambda_{ge}}{\varepsilon_{se}\lambda_{sf} + (1-\varepsilon_{se}).\lambda_{ge}} \qquad \text{Eq.(2.32)}$$

Here, it is derived that the porosity ratio ($\frac{\varepsilon_{pr}}{\varepsilon_{se}}$) is a controllable parameter to make high efficiency glass fiber boards or hybrid core materials made by using glass fiber boards. Reducing ε_{pr} has opposing effects on the solid thermal conductivity of the core and the thermal conductivity of the air inside the glass fiber board. Smaller ε_{pr} results in higher solid thermal conductivity ($\alpha.\left(1 - \varepsilon_{pr}\right).\lambda_{sf}$) and lower thermal conductivity of air inside the glass fiber board ($\alpha.\varepsilon_{pr}.\lambda_{ge} + (1 - \alpha).\frac{\lambda_s\lambda_{ge}}{\varepsilon_{se}\lambda_s + (1-\varepsilon_{se}).\lambda_{ge}}$). Smaller ε_{pr} means the advection mechanism (the effect of air inside the glass fiber board)is more restricted due to smaller pores in parallel with the air molecules and the heat flow. In contrast, the conduction through the solid skeleton of the VIP-Core is enhanced due to more mass of solid skeleton in parallel with air molecules and the heat flow. Increasing ε_{se}, reduces the diffusion mechanism (the effect of air inside the glass fiber board). Bigger ε_{se} means, the diffusion mechanism is more restricted due to less mass of solid skeleton being in series with the air molecules and therefore, less interaction between solid skeleton molecules and air molecules. As the porosity ratio $\left(\frac{\varepsilon_{pr}}{\varepsilon_{se}}\right)$ decreases, the effect of air inside the glass fiber board-which is quantified as thermal conductivity of air (λ_G)- is reduced. As $\varepsilon_{pr} \longrightarrow 1$ and $\varepsilon_{se} \longrightarrow 0$, the thermal conductivity of air (λ_{GGFB}) is maximized (Eq. (2.33) [45]) and contrastingly as $\varepsilon_{pr} \longrightarrow 0$ and $\varepsilon_{se} \longrightarrow 1$, the thermal conductivity of air (λ_{GGF}) is minimized, as expressed in Eq. (2.34)[45],

$$\lambda_{GGFBmax} = \alpha . \lambda_{ge} + (1 - \alpha)\, \lambda_{sf} \qquad \text{Eq.(2.33)}$$

$$\lambda_{GGFBmin} = (1 - \alpha)\lambda_{ge} \qquad \text{Eq.(2.34)}$$

On the other hand, Bankvall's modeling (Eq. 2.35[45]) estimates the effective thermal conductivity of a glass fiber board (λ_{EGFB}) by using the effective porosity (ε_f) and the mean distance between two fibers (D_M)). The effective thermal conductivity of glass fiber board (λ_{EGFB}) is estimated (Eq. 2.35 [45]), by adding the solid thermal conductivity of the glass fiber board (λ_{SGFB}), the thermal conductivity of air inside the glass fiber board (λ_{GGFB})and the radiative thermal conductivity of the glass fiber board (λ_{RGFB}).

$$\lambda_{EGFB} = \frac{32(1-\varepsilon_f)^2 . \lambda_{sf}}{\Pi\, (3 + \frac{\Pi}{4(1-\varepsilon_f)})} + \lambda_{g,o} . \frac{PD_M}{PD_M + G.T} + 4\sigma_s . D_M . \beta . T_a^3 \qquad \text{Eq.(2.35)}$$

,from which, it is derived that the mean distance between fibers (D_M) is a controllable parameter to make high efficiency glass fiber boards or high efficiency hybrid core materials by using glass fiber boards. According to Bankvall's modeling , smaller (D_M), has a reducing effect on the thermal conductivity of the air inside the glass fiber board (λ_{GFGB}) and the radiative thermal conductivity of the glass fiber board (λ_{RFGB}). By reducing D_M , the ε_{pr} of the glass fiber board is decreased, whereby, the air advection is more restricted for the same core vacuum level and the thermal performance of the glass fiber board is enhanced.

The mean distance between fibers (D_M) varies for different glass fiber boards, depending on the mean fiber diameter (d_M). The mean fiber diameters of ($d_{M1} = 0.1\ \mu m, d_{M2} = 1\ \mu m, d_{M3} = 5\ \mu m, d_{m4} = 10\ \mu m$) and the porosities of ($\varepsilon > 0.9$) are generally reported for Glass fiber- VIPs in literature. Following Eq. (30) and assuming a porosity of ($\varepsilon_f = 0.95$), the mean distance between fibers (D_M) is estimated for the four glass fiber board with $d_{M1} = 0.1\ \mu m, d_{M2} = 1\ \mu m, d_{M3} = 5\ \mu m, d_{m4} = 10\ \mu m$ (Table 2.1).

Table 2.1: The comparison of mean distance between fibers for four glass fiber boards with different mean fiber diameters

	Porosity (ε)	Mean Fiber Diameter (d_M (μm))	Mean Distance between Fibers (D_M (μm))
Glass fiber board (1)	0.95	0.1	2.6
Glass fiber board (2)	0.95	1	26
Glass fiber board (3)	0.95	5	130
Glass fiber board (4)	0.95	10	260

The mean distance between fibers (D_M) and the mean fiber diameter (d_M) have significant effect on the thermal performance of Glass fiber-VIPs at the core vacuum levels (P > 10 Pa). $d_{M1} = 0.1$ μm is preferred for lower λ_{GGFB} at the core vacuum levels (P > 10 Pa). However, the cost of production increases significantly for the glass fiber board with lower mean fiber diameters ($d_{M1} = 0.1$ μm and $d_{M2} = 1$ μm. Glass fiber-Silica powder composite is a cost effective method for reducing the mean effective pore size of the glass fiber boards as VIP-Cores. The effectiveness of this method depends mainly on the mean particle size of the silica powder (d_P) and therefore the relation between the mean distance between fibers D_M and the mean particle size of silica powder (d_P) which is quantified as the ratio of $\frac{D_M}{d_P}$

.

4. Glass Fiber-Silica powder composite

Mukhopadhyaya et al. (2009)[1] developed the glass fiber-silica powder composite as a method for producing high efficiency hybrid core materials. Where, a VIP-Core is made by using a glass fiberboard and pumice powder. They used a glass fiber board with the density of 104 kg/ m^3[47]. The distances between fibers (pore sizes) are reported to be up to around 400 μm Consequently, the mean effective pore size of the glass fiber board is estimated to be around ($D_M = \delta_{GFB} = 100 - 200$ μm). First, they cut the glass fiber board into the layers with the thickness of 3.5 mm. They distributed pumice powder (in layers of 3.5 mm thickness) on each glass fiber layer (each layer with the thickness of 3.5 mm), then they sandwiched the different layers together[1], as shown in Fig 2.11. They produced a glass fiber- pumice composite with the thickness of 2.5 cm and a density of 320 Kg/m3. They investigated exclusively the thermal behavior of the glass fiber board and reported that the effective thermal conductivity of the glass fiber board is increased by 80% at the core vacuum level of (P = 10^4 Pa), compared to the core vacuum level of (P = 1 Pa)[1]. The glass fiber board has the effective thermal conductivity of around 7mW/m.K at high vacuum level of (P=1 Pa) and the effective thermal conductivity of 34 mW/m.K [1]at the core vacuum level of (P $= 10^4$ Pa). The glass fiber board shows a similar change in the effective thermal conductivity to the glass fiber board investigated (as seen in Fig (3)) by other researchers (Heinemann et al. (1999)[15]; Stimmler et al. (2005)[18]), although it has a higher sum of solid and radiative thermal conductivities (higher effective thermal conductivity at high vacuum levels (P<1 Pa). Due to the comparatively large mean effective pore size ($D_M = \delta_{GFB} = 100 - 200\ \mu m$), the thermal conductivity of air inside the glass fiber board ((λ_{GGFB})) rises rapidly with the decrease in the core vacuum level. In contrast, the glass fiber-pumice composite has a similar thermal performance to precipitated silica up to the core vacuum level of(P= 10^4 Pa). This leads to the mean effective pore size of the VIP-Core is reduced due to the addition of pumice powder particles with the mean size of ($d_{MP} = 10\ \mu m$) to the pore structure of the glass fiber board. The pores with the mean sizes of ($D_M = \delta_{GFB} = 100 - 200\ \mu m$) are significantly filled with the pumice particles with the mean size of ($d_{MP} = 10\ \mu m$) . The glass fiber-powder composite has an effective thermal conductivity of around 14 mW/m.K [1]at the vacuum level of (P = 10^4 Pa) which is only around 2mW/m.K higher than the effective thermal conductivity of precipitated silica at the same core vacuum level. Since the mean effective pore size of the glass fiber board used by Mukhopadhyaya et al. (2009)[1] is around ($D_M = \delta_{GFB} = 100 - 200\ \mu m$), following Table 2.1, the mean fiber diameter is estimated to be around ($d_{M1} = 5 - 10\ \mu m$). In other words Mukhopadhyaya et al. (2009)[1] made a glass fiber silica-powder composite with the $\frac{D_M}{d_{MP}}$ of around 10 by using a glass fiber board with the mean fiber diameter ($d_{M1} = 5 - 10\ \mu m$) and the mean distance between fibers of ($D_M = \delta_{GFB} = 100 - 200\ \mu m$; and a silica powder with the mean particle size of ($d_{MP} = 10\ \mu m$) . Whereby, the glass fiber- silica powder composite has the mean effective pore size of ($\delta_{GFB-Silica} < 10\ \mu m$) and therefore comparable thermal performance with precipitated silica up to the core vacuum level of (P = 10^4 Pa.

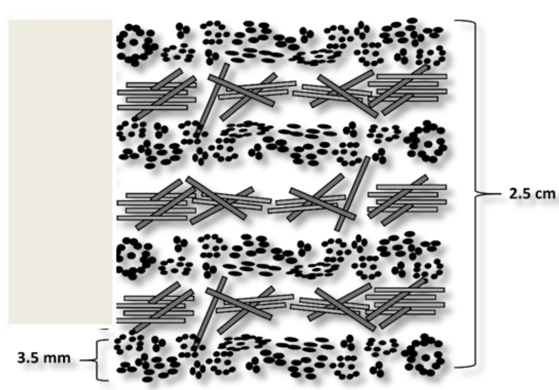

Fig 2.11: Glass fiber-pumice powder composite (as a high efficiency hybrid core material)

5. Discussion

Glass fiber-VIP, Precipitated Silica-VIP and Fumed Silica-VIP offer high thermal performance at the high core vacuum level of (P =1 Pa), at which, there is a small quantity of air molecules inside the VIP-Core and

λ_G is at the negligible level for all VIP-Cores. During the service life of a VIP, the core vacuum level decreases gradually by either penetrating gases and water vapor through envelope into the VIP-Core or by outgassing from inside of the core or envelope material. Glass fiber boards have generally the mean effective pore sizes up to ($D_M = \delta_{GFB} = 300\ \mu m$), while precipitated silica has the mean effective pore size of around ($\delta_{PS} = 1 - 3\ \mu m$) and fumed silica has mean effective pore size of ($\delta_{FS} = 40 - 70$ nm). Due to larger mean effective pore sizes, the thermal performance of glass fiber-VIP deteriorate exponentially and considerably rapidly compared to Precipitated Silica- VIP and Fumed Silica- VIP, when the core internal air pressure exceeds ($P > 10^2$ Pa). Alternative to the production of glass fiber boards with small mean fiber diameters in range of ($d_M = 0.1 - 1\ \mu m$), which is constrained by the high cost of production, glass fiber-silica powder composite is a method aimed at reducing the mean effective pore size of the VIP-Core by using a glass fiber board ($D_M = \delta_{GFB} < 300\ \mu m$) and a silica powder with the mean particle size of (d_P).

Fig 2.12 illustrates the 3D variation of the dimensionless ratio of solid and gas phase thermal conducitvites ($\frac{\lambda_G}{\lambda_S}$) for a glass fiber board as the VIP-Core due to the change in dimensionless ratios related to the pore structure. These are ($\frac{1-\alpha}{\alpha}$), representing the part of core's solid skeleton in series with the heat flow to the part of core's solid skeleton in parallel with the heat flow and ($\frac{\varepsilon_{pr}}{\varepsilon_{se}}$), representing the porosity of the part in parallel to the porosity of the part in series with respect to the heat flow direction . The solid thermal conductivity of the glass fiber board is estimated as ($\lambda_{SGFB} = 2.1$ mW/m.K) for the purpose of drawing the diagram (Fig. (12)) which is the λ_{SGFB} reported by Kwon et al. [17] for the glass fiber board with a density of 250 (kg/m3). The pore structure characteristics ε_{pr}, ε_{se} and α ,vary between 0.01-0.99 with increments of 0.01 and depending on the mean fiber diameter (d_M) and therefore mean distance between fibers ($D_M = \delta_{GFB} < 300\ \mu m$) in case of pure glass fiber boards and additionally on the mean particle size (d_{MP}) of the silica powder in case of glass fiber-silica powder composites. Consequently, ($\frac{\lambda_G}{\lambda_S}$) of the VIP-Core varies between 8.25- 81.15 upon varying ($\frac{1-\alpha}{\alpha}$) and ($\frac{\varepsilon_{pr}}{\varepsilon_{se}}$) between around 0-2 and 0-4, respectively.

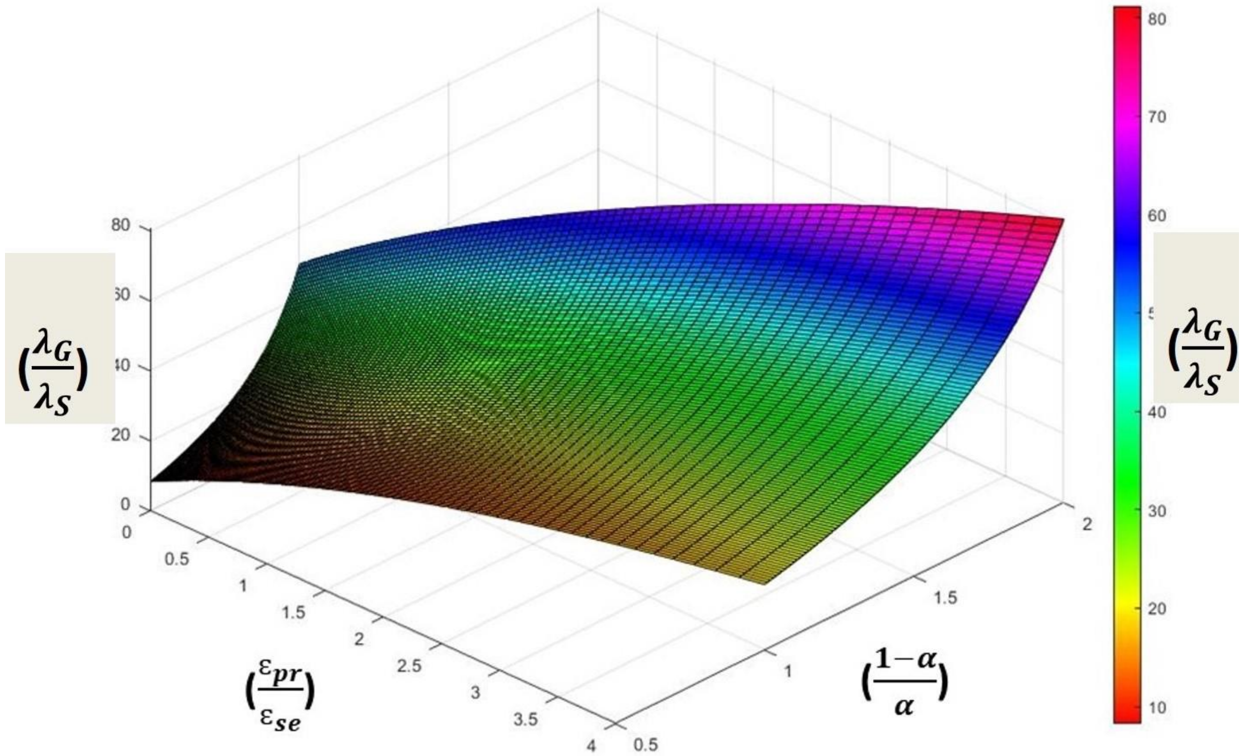

Fig 2.12: 3D variation of the three dimensionless ratios of $(\frac{1-\alpha}{\alpha})$, $(\frac{\varepsilon_{pr}}{\varepsilon_{se}})$ and $(\frac{\lambda_G}{\lambda_S})$ for a glass fiber board as open porous core

As seen in Fig (12), the thermal conductivity of air inside the VIP- Core (λ_G) , is between 8 - 80 times greater than the solid thermal conductivity of the VIP-Core (λ_S) for a VIP-Core (in this case, a glass fiber board) with ($\lambda_{SGFB} = 2.1$ mW/m.K)) . On one hand, by evacuating air molecules , λ_G of VIP-Cores (a large portion of their effective thermal conductivity) is almost eliminated. VIPs have the least effective thickness among all insulation materials which are used in Canada. On the other hand, by reducing the mean effective pore size (δ) and therefore the porosity ratio $(\frac{\varepsilon_{pr}}{\varepsilon_{se}})$ of the VIP-Core, the ratio of $(\frac{\lambda_G}{\lambda_S})$ is reduced, whereby the VIP-Core is less sensitive to the decrease in the core vacuum level. Fig. 2.13 illustrates schematically the working principle of glass fiber- silica powder composites as the approach for making high efficiency hybrid core materials. The mean effective pore size (δ) and the porosity ratio $(\frac{\varepsilon_{pr}}{\varepsilon_{se}})$ of the VIP-Core are reduced due to the addition of powder particles to the pore structure of the glass fiber board.

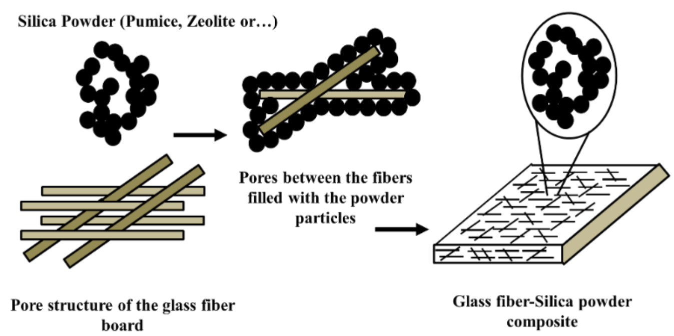

Fig 2.13: The working principle of glass fiber-silica powder composite

This study suggests making a glass fiber-silica powder composite (GFB-Silica) by using a glass fiber board with the mean fiber diameter ($d_M = 1 - 5\mu m$) and the mean effective pore size (the mean distance between fibers) of up to ($\mathrm{D_M} = \delta_{\mathrm{GFB}} = 130\mu\mathrm{m}$)\ and silica powder with the mean particle size of ($\mathrm{d_P} = 10\ \mu m$). The powder particles with diameters in the range ($d_M < d_P < D_M$) mostly intensifies the reduction of ε_{pr}, as they placed themselves between fibers from different layers, while the powder particles with diameters in the range smaller than the mean fiber diameter of glass fiber board ($d_P < d_M$) mostly intensifies the increase of ε_{se}, as they placed themselves between fibers on the same layer of the glass fiber board. By means of which, the mean effective pore size of the VIP-Core is reduced to around ($\delta_{\mathrm{GFB-Silica}} = 10\ \mu\mathrm{m}$). The ratio of ($\frac{\mathrm{D_M}}{\mathrm{d}_{MP}}$ = 10) is between the mean distance between fibers ($\mathrm{D_M}$) and the mean particle size of the silica powder ($\mathrm{d_{MP}}$) ; and the glass fiber –silica powder composite is estimated to have the comparable thermal performance with precipitated silica up to the core vacuum level of (P = 10^4 Pa). This suggestion is in accordance with the mean pore size of around (($\mathrm{D_M} = \delta_{\mathrm{GFB}} = 100 - 200\ \mu\mathrm{m}$) and the mean particle size of pumice powder ($\mathrm{d_{MP}} = 10\ \mu\mathrm{m}$) used by Mukhopadhyaya et al. (2009)[1] for making the glass fiber-pumice powder composite. Further studies are required into characterizing the thermal performance of the glass fiber-silica powder composite with the mean fiber diameter ($\mathrm{d_M}$), the mean distance between fibers ($\mathrm{D_M}$) and the mean particle size of silica powder ($\mathrm{d_{MP}}$). In order for the glass fiber-silica powder composite to have comparable thermal performance with fumed silica up to the core vacuum level of (P = 10^4 Pa), this paper suggests the mean fiber diameter ($\mathrm{d_M} = 0.1 - 1\ \mu\mathrm{m}$) and therefore the mean distance between fibers of up to ($\mathrm{D_M} = \delta_{\mathrm{GFB}} =< 26\mu\mathrm{m}$) for the glass fiber board (following Table 2.1 and the mean particle size of ($\mathrm{d_{MP}} = 260\ \mathrm{nm}$) for the silica powder. By means of which, the mean effective pore size of the VIP-Core is estimated to be reduced to ($\delta_{\mathrm{GFB-Silica}} < 100\ \mathrm{nm}$). In case of a glass fiber-silica powder composite with a ratio of $\frac{\mathrm{D_M}}{\mathrm{d}_{MP}}$ considerably larger than 10, this study suggests hydraulic pressing of the VIP-Core during evacuation. Whereby, the mean effective pore size (δ_{GFB} or $\delta_{\mathrm{GFB-Silica}}$), the porosity ratio

($\frac{\varepsilon_{pr}}{\varepsilon_{se}}$) and the ratio of $\frac{D_M}{d_{MP}}$ of the VIP-Core are reduced, meanwhile powder particle are forced into the pore structure of the glass fiber board.

6. Conclusions

VIPs offer a super insulating capacity and the least effective thickness among all insulation materials for building's application, since by evacuating the air inside the pore structure of VIP-Core, a large portion of its effective thermal conductivity is almost eliminated. However, the core vacuum level decreases gradually over the service life of VIPs (30-50 years for building's application). Glass fiber boards, precipitated silica and fumed silica are mostly used as VIP-Cores. All VIP-Cores are open porous and evacuation capable and have super insulating capacity at high vacuum. Meanwhile, the thermal performance of Glass fiber- VIPs deteriorates exponentially and considerably more rapidly compared to Fumed Silica-VIPs and Precipitated Silica-VIPs, as the core internal air pressure exceeds the level of (P = 10^2 Pa). Glass fiber-VIPs are sensitive to the air intake due to their larger mean effective pore sizes(up to ($D_M = \delta_{GFB} = 300$ µm)), compared to fumed silica (δ_{FS} = 40-70nm) and precipitated silica ($\delta_{PS} = 2 - 3$µm). However, fumed silica and precipitated silica are expensive, challenging their large scale application in buildings. Glass Fiber-Silica powder composite is a viable method for cost effectively making high efficiency VIP-Cores which are less sensitive to the air intake, compared to the glass fiber board used for making the composite. The thermal performance of the glass fiber –silica powder composite depends mainly on the mean distance between fibers (D_M)and therefore on the mean fiber diameter (d_M) of the glass fiber board and the mean particle size of the silica powder (d_{MP}). Hence, the mean fiber dimeter (d_M) and the mean particle size of silica powder (d_{MP}) are relatively flexible options considering the economy of production and various applications. The glass fiber silica-powder composite has the mean effective pore size of around ($\delta_{GFB-Silica} = 10$ µm) by using a glass fiber board with the mean fiber diameter ($d_{M1} = 5 - 10$ µm) and the mean distance between fibers of ($D_M = \delta_{GFB} = 130 - 260$ µm)); and a silica powder with the mean particle size of ($d_{MP} = 10$ µm). This yields a glass fiber-silica powder composite with the ratio of around ($\frac{D_M}{d_{MP}} = 10$) and the comparable thermal performance with precipitated silica up to a core vacuum level of (P = 10^4 Pa). Further studies are required for characterizing the thermal performance of glass fiber-silica powder composite with the ratio of $\frac{D_M}{d_{MP}}$ between the mean distance between fibers (D_M) and the mean particle size of the silica powder (d_{MP}), where, the mean effective pore size of around ($\delta_{GFB-Silica} <$ 100 nm)is purposed by using a glass fiber board with the mean fiber diameter of ($d_M = 0.1 - 1$ µm) and therefore the mean distance between fibers of around ($D_M = \delta_{GFB} =< 26$µm); and the silica powder with the particle size of around ($d_{MP} = 260$ nm). The glass fiber silica powder composite is estimated to have the comparable thermal performance with fumed silica up to the core vacuum level of (P = 10^4 Pa).

Chapter 3: Development of Hybrid VIP core materials: Glass Fiber-Silica powder composites

This Chapter of this manuscript-style thesis uses a number of equations from Chapter 2 for ease of reading.

Abstract

Vacuum insulation panels (VIPs) are one of the recent innovations for combining the increase of energy efficiency in buildings with slim construction. VIPs in pristine condition offer six to ten times higher thermal insulating capacities compared to traditional insulations. The high thermal performance of VIPs is achieved by applying a vacuum to an open porous core material which is encapsulated by a multilayer envelope, providing a high barrier to air and water vapor entry. However, the core vacuum level decreases over time, mainly due to the penetration of air and water vapor through the envelope and into the pore structure of the core. The thermal performances of various VIPs are differently sensitive to the decrease in core vacuum level, depending mainly on the mean effective pore size of the VIP-Core. Glass fiber board is widely used as a macro porous VIP-Core due to its low density, high porosity, high mechanical stability, all of which provide high thermal performance at high vacuum. Compared to Precipitated silica-VIP (with the mean effective pore size of (δ_{PS} =1- 3μm)), Glass fiber -VIP is more sensitive to the decrease in core vacuum level due to its larger mean effective pore size (δ_{GFB} =100-300 μm). The challenge for VIP-designers is to cost effectively reduce the degradation of thermal performance during the service life of glass fiber-VIPs. After developing an experimental set up for making VIPs and measuring their effective thermal conductivity, this study investigates the effect of two alterations on the thermal performance of a glass fiber board (with the mean effective pore size (mean distance between fibers) of (δ_{GFB} = D_{MGFB} =130 μm)) as the VIP-Core: 1) Hydraulic pressing of the VIP during evacuation; and 2) Addition of zeolite powder (with mean particle size of d_{MPZE} = 2 μm) or diatomaceous earth powder (with mean particle size of d_{MPDE} =4μm) to change the microstructure of glass fiber boards. The mean distance between fibers (D_{MGFB})is reduced from 130μm to 75 μm by pressing during evacuation. The mean effective pore size of the VIP-Core is reduced to 61 μm due to combined effects of pressing during evacuation and the addition of zeolite particles; and it is reduced to 21 μm due to combined effects of pressing during evacuation and the addition of diatomaceous earth particles. Compared to the glass fiber board, the glass fiber-zeolite composite has on average 20% higher thermal performance (20% lower effective thermal conductivities) at various vacuum levels (P = 1-10^5Pa). The glass fiber-diatomaceous earth composite has a comparable thermal performance with the precipitated silica, up to the vacuum level of (P = 10^2Pa), in addition to having on average, 30% higher thermal performance, at various vacuum levels (P = 1-10^5Pa), compared to the glass fiber board. This study concludes that the glass fiber- silica powder composite is a viable method for reducing the mean effective pore size of the VIP- Core. Here, the thermal performance

of the VIP-Core depends mainly on the relation between the mean distance between fibers (D_{MGFB}) and the mean particle size of the silica powder (d_{MP}). Whereby, the ratio of ($\frac{D_{MGFB}}{d_{MP}} = 10$) is suggested for making high efficiency glass fiber-silica powder composites.

1. Introduction

The energy efficiency and carbon footprints of buildings can be greatly improved by the application of high-performance thermal insulation materials. Vacuum insulation panels (VIPs) are regarded as super insulation materials for buildings. VIPs are produced by evacuating an open porous core material which is encapsulated by a very effective air and water vapor barrier envelope. VIPs, in pristine condition, offer thermal performances of about six to ten times higher than traditional (i.e. fibrous or foam) thermal insulation materials [1]–[3]. Although VIPs have the potential for combining the reduction of heat loss in buildings with slim wall constructions, the mass application of VIPs in buildings is restricted by the cost factor and the uncertainty regarding the long-term performance of VIPs[4], [5]. The thermal performance of VIPs and the cost of production are significantly affected by the hygrothermal properties of the constituent core material. Fumed silica, precipitated silica and glass fiber boards are generally used as VIP-Cores[4]. The envelopes have high vapour and air barrier properties, however, a high stress is permanently induced on the envelope by the air pressure difference between the vacuumed core and the atmosphere outside of VIP [5]. Consequently, air and water vapor penetrates into the pore structure of the core through diffusion or micro leakages in the envelope, and the core vacuum level decreases over time. All VIP-Cores are open porous, i.e. can be evacuated to high vacuum level, and they all have high thermal performances [2], [6], [7]. However, the thermal performance of various VIPs have different sensitivity to the decrease in vacuum level, depending mainly on the mean effective pore size of the VIP-Core [1], [8]. Precipitated silica (PS) and fumed silica (FS) have small mean effective pore sizes (δ_{PS} =1- 3µm and δ_{FS} =40-70nm), restricting the degradation of their thermal performance due to air penetration; and therefore they have superior service life. However, they are comparatively expensive [2]. On the other hand, the cost of production for glass fiber VIP-core is comparable with traditional thermal insulations but the service life of VIP constructed with glass fiber core, available at this moment, is shorter (around 15 years) [2]. The rapid aging of VIP with glass fiber core is attributed to larger mean effective pore sizes (δ_{GFB} =100-300 µm) of the glass fiber core, compared to precipitated or fumed silica. [9]. This motivates further research into the glass fiber- silica powder composite as an alternative for reducing the mean effective pore size of the VIP-Core and therefore extending the service lifespan.

After developing an experimental setup for measuring the effective thermal conductivity of VIP-core at the vacuum levels between 1 and 10^5Pa, this research is mainly aimed to investigate the effect of two alterations on the thermal performance of glass fiber as VIP-Core: (1) Hydraulic pressing of the VIP-core during evacuation, and (2) Addition of zeolite powder or diatomaceous earth powder to change the microstructure of glass fiber core. After developing an experimental setup for measuring the effective thermal conductivity of VIP-core at the vacuum levels between 1 and 10^5 Pa, this research is mainly aimed at investigating the effect of two alterations on the thermal performance of glass fiber as VIP-Core: (1) Hydraulic pressing of the VIP-core during evacuation, and (2) Addition of zeolite powder or diatomaceous earth powder to change the microstructure of glass fiber core.

2. Vacuum insulation panel- the concept

Vacuum insulation panels (VIPs) are produced with a core material board encapsulated by a multilayer high air and water vapor barrier envelope and evacuated to near zero pressure level (P= 1Pa). The core is an open porous material and therefore could be evacuated. Since, the VIP-Core is usually produced in the form of flat panel, and it must have high mechanical strength to withstand the air pressure differential (i.e. difference in pressure between internal vacuum and atmospheric pressure (P = 10^5Pa)) [2], [4], [5], [8]. Glass fiber, fumed silica, precipitated silica are mostly used as VIP-Cores. [1], [2], [19], [48]. The envelope is generally made of multiple layers of aluminum coated polyethylene (PE)) or polyethylene terephthalate (PET), acting as protective layer, barrier layer and sealing layer. Fig. 3.1 schematically illustrates the structure of a VIP [2], [5]. The VIP-Core is protected from ‘environmental and handling stresses’ by the protective layer (polyethylene terephthalate (PET)) which is the outer most layer. The middle layer (Al-coated polyethylene(PE)) is an effective air and water vapor barrier. The inner most layer is the sealing layer and is formed by heating of laminated layers between two hot bars under pressure[2], [5]. Fig. 3.2 shows a VIP with fumed silica core.

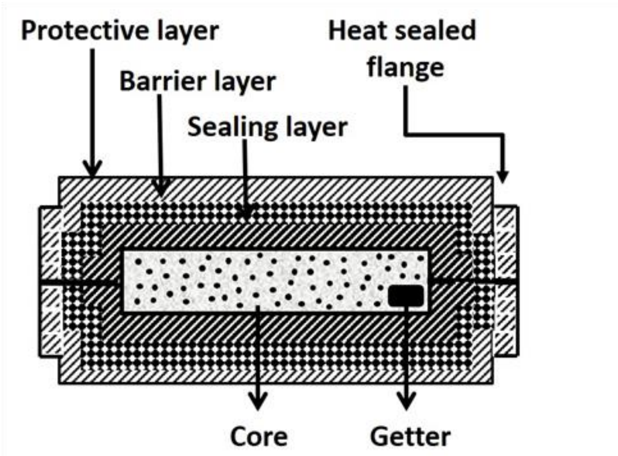

Fig 3.1: The construction of a VIP[2],[5]

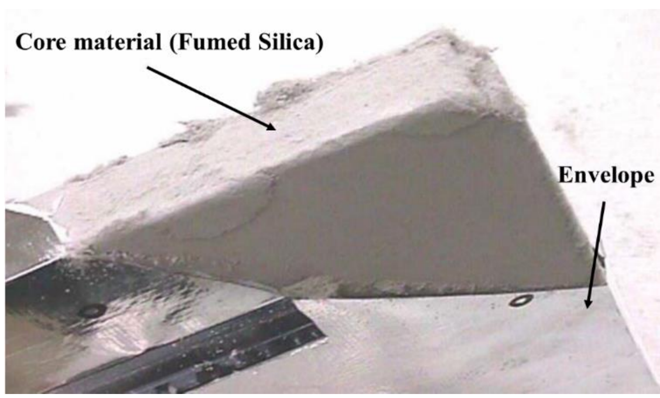

Fig 3.2: Fumed silica-VIP[1]

The effective thermal conductivity of VIPs has one-sixth to one tenth the value of conventional insulations used for building envelope applications. However, VIP designers are confronting three major challenges: (1) high cost of production, (2) effect of thermal bridging through the envelope, and (3) degradation of thermal performance over time [2], [9]. Although, the envelope of VIP has the highest grade barrier properties which are required for buildings' application, air and water vapor penetrate gradually from outside through envelope into the pore structure of the core, and, consequently, the core vacuum level decreases. The effective thermal conductivity of a VIP is greatly effected by the hygrothermal properties of the VIP-Core. The effective thermal conductivity (λ_E) of a VIP is comprised of three distinct thermal conductivities (corresponding to each mechanism of heat transfer) and the fourth coupling term (Eq. (3.1))[2]–[5], [8], [17], [18].

$$\lambda_E = \lambda_S + \lambda_G + \lambda_R + \lambda_{coup} \qquad \text{Eq. (3.1)}$$

λ_S is the solid thermal conductivity of the VIP-Core, denoting the conduction via solid skeleton of the core. λ_G is thermal conductivity of air inside the VIP-Core, denoting the heat transfer by air diffusion and convection mechanisms. λ_R is the radiative thermal conductivity of the VIP-Core, denoting the heat transfer across the VIP-Core by electromagnetic radiation mechanism. In general, conduction and air convection are linearly proportional to the temperature across the VIP-Core, as two dominant heat transfer modes. Consequently, VIP-Cores exhibit a linear relationship between the effective thermal conductivity and the temperature across the VIP-Core[26]. λ_{coup} denotes the second order coupling effects between the main mechanisms of heat transfer. Coupling effect (relevant for fibrous and powder core materials) is complex and is mostly considered to be negligible in the theoretical estimations for the effective thermal conductivity of VIP-Cores. In a standard approach, λ_E is measured by means of one-dimensional integral form of Fourier's law during steady state condition(Eq. (3.2))[25],

$$\lambda_E = \frac{q''_T t_k}{\Delta T} \qquad \text{Eq.(3.2)}$$

Where, λ_E is the effective thermal conductivity of the VIP (W/m.K), q''_T is the total heat flux (W/m^2), ΔT (K) is the temperature difference across the VIP, and t_k (m) is the thickness of the VIP (m). The guarded hot plate (GHP)[25] or the heat flow meter (HFM)[49] test apparatus is used to measure the effective thermal conductivity of VIPs. One of the significant challenges with VIPs is to perform the measurement of effective thermal conductivities during steady state condition for various core vacuum levels (P = 1-10^{5}Pa)[25].

VIP-Cores are open porous. They have different mean effective pore sizes. At high vacuum (the core vacuum level of P =1 Pa), the effect of air can be neglected for all VIP-Cores, since there is a small number of air molecules in the pore structure of the VIP-Cores, the thermal conductivity of the air inside the VIP-Core (λ_G) is very low. The effective thermal conductivity of the core is then close to the sum of its solid thermal conductivity(λ_S) and its radiative thermal conductivity(λ_R). The core vacuum level decreases over time due to penetration of air and water vapor into the pore structure of the core or by outgassing from inside of the core and envelope material. As the core vacuum level decreases, λ_G is estimated analytically by Knudsen relation (Eq.(3.3)), [4]:

$$\lambda_G = \frac{\lambda_{g,0}}{1 + 2\beta K_n} \qquad \text{Eq.(3.3)}$$

$$\mathrm{Kn} = \frac{\mathrm{I_{mean}}}{\delta} \text{ and } \mathrm{I_{mean}} = \frac{\mathrm{K_B T}}{\sqrt{2\pi d_g^2 P}} \qquad \text{Eq.(3.4)}$$

Here, $\lambda_{g,0}$ is thermal conductivity of free gas and is 26 mW/m.K for free air at P= 1 atm and T= 300K. As expressed in Eq. (3.4), Kn (Knudsen number) is the ratio between the mean free path I_{mean} of gas molecules and the mean effective pore size δ, K_B is the Boltzmann constant (1.3807× 10^{-23} J/K), d_g is the diameter of the gas molecules and β is a constant between 1.5 and 2.0, depending on the gas type, core material and temperature. P is the pressure of air inside the VIP-Core. Kwon et al. (2009) employed the following correlation (Eq. (3.5)) to estimate the thermal conductivity of air inside the core at T= 25 ^{0}C by using β=0.016/P.

$$\lambda_G = \frac{\lambda_{g,o}}{1 + \frac{0.032}{P\delta}} \qquad \text{Eq.(3.5)}$$

Using Eq. (3.5), we find that as the core vacuum level decreases (P increases from between 1to10^5 Pa), λ_G increases differently for each VIP-Core depending on the mean effective pore size [2]–[5], [8], [17], [18]. For larger effective pore sizes, a higher core vacuum level is required to maintain λ_G at the negligible level. Fumed silica is a nano porous material with the mean effective pore sizes in range of (δ_{FS} =40-70nm)[19]). λ_G of Fumed silica- VIP is restricted to the negligible level up to the core vacuum level of (P= 10^3 Pa). Glass fiber boards are macro porous materials with the mean effective pore sizes generally in range of δ_{GFBs}=100 µm-300µm. Consequently, the core vacuum level of (P = 1Pa) is required to restrict λ_G of Glass fiber- VIP at the negligible level [1], [19], [45]. Glass fibers boards are made by using two forms of glass fibers: (1) Chopped strand glass fiber boards produced by marble melt process and (2) Flame attenuated glass fiber wool produced by flame attenuation process [28]. Glass fiber boards have low densities, superior chemical and thermal stability (>1000 ^{0}C) outstanding acoustic insulation properties and excellent molding properties [28]. At high vacuum and at T= 300K (26.85 ^{0}C), Kwon et. al [19] reported the effective thermal conductivity (λ_{EGFB}) of 2.8 mW/m.K for a glass fiber board which is estimated by the sum of the solid thermal conductivity (λ_{SGFB} = 2.1 (mW/mK)) and the radiative thermal conductivity (λ_{RGFB} =0.7 mW/mK)[19]. Fig 3.3 shows a chopped strand glass fiber board which is used as a VIP-Core.

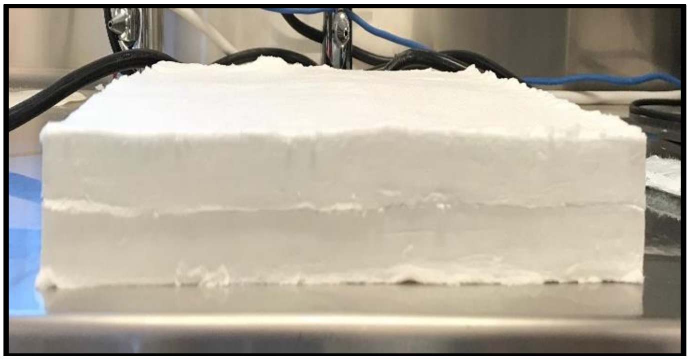

Fig 3.3: Glass fiber board as a VIP-Core

Compared to Precipitated Silica-VIPs and Fumed Silica-VIPs , glass fiber-VIPs have lower cost, and at high vacuum (P < 50 Pa), the effective thermal conductivity of glass fiber boards ($\lambda_S + \lambda_R$) is the lowest among all VIP-Cores. However, glass fiber boards have larger mean effective pore sizes (δ_{GFBs}= 100-300 µm) compared to fumed silica (δ_{FS} =40-70 nm [19]) and precipitated silica (δ_{PS} =1-3µm [1]) [2], [6], [10] [18]. λ_G and therefore λ_E of Glass fiber-VIPs increase exponentially as the core vacuum levels decreases over the critical value of (P = 10^2 Pa). In the case of VIP perforation (P = 10^5 Pa), the effective thermal conductivity of glass fiber boards (around λ_{EGFB} = 37 mW/mK) [1] is considerably higher than the effective thermal conductivity of fumed silica-VIP (around λ_{EFS} = 20 mW/mK) [1]. Consequently, the thermal performance of the glass fiber–VIPs is sensitive to the pressure increase (i.e. gradual loss and glass fiber-VIPs have maximum service life of 15 years (short service life for building's application) [39]. The glass fiber-silica powder composite is employed for making hybrid core materials which are less sensitive to the air ingress (i.e. increased pore pressure), compared to the glass fiber board (used for making the composite). The mean effective pore size of the VIP-Core is reduced as silica powders settle between the fibers.

This study aims to investigate the change in the mean effective pore size diameter in glass fiber-zeolite powder and glass fiber-diatomaceous earth powder composites. The control parameters which are relevant for the evaluation of the heat transfer in glass fiber boards have been identified. This allows with appropriate assumptions; the effective thermal conductivity of glass fiber boards be estimated.

2.1 Heat transfer theory in glass fiber boards

Bankvall [45] developed an analytical model for the estimation of the heat transfer in a glass fiber board as VIP-Core and introduced three distinct heat transfer mechanisms: the solid thermal conductivity (λ_{SGF}), the thermal conductivity of air inside the pore structure (λ_{GGF}), and the radiative thermal conductivity of the glass fiber board (λ_{RGF}). Banksvall's model estimates the effective thermal conductivity of the glass fiber board (λ_{EGF}) as the sum of λ_{SGF}, λ_{GGF} and λ_{RGF} (Eq. 3.6) [45]. For this purpose, the solid skeleton of the glass fiber board is assumed to be divided into two parts (Fig. 3.4)[45]. Where, α denotes the part of core's solid skeleton which is in parallel with the heat flow direction (and the air molecules inside pores), while, (1-α) denotes the part of core's solid skeleton which is in series with the heat flow direction (and the air molecules inside pores). ε_{pr} and ε_{se} are porosities of the part of core' solid skeleton, in parallel and in series with the heat flow direction (and the air molecules inside pores), respectively. The porosity is estimated using Eq. (3.7). α is in range of around (0.95-0.99[45]) for glass fiber boards. Whereas, ε_{pr} is in range of (0.99-1) and ε_{se} is in range of around (0.11-0.38).

$$\lambda_{EGFB} = \alpha.\left(1 - \varepsilon_{pr}\right).\lambda_{sf} + \alpha.\varepsilon_{pr}.\lambda_{ge} + (1-\alpha).\frac{\lambda_{sf}\lambda_{ge}}{\varepsilon_{se}\lambda_{sf}+(1-\varepsilon_{se}).\lambda_{ge}} \qquad \text{Eq. (3.6)}$$

$$\varepsilon = (1-\alpha).\ \varepsilon_{se} + \alpha\ .\ \varepsilon_{pr} \qquad \text{Eq.(3.7)}$$

Where, λ_{sf} is the thermal conductivity of each individual fiber. λ_{ge} is the effective thermal conductivity of the air molecules inside the internal pore structure of the core. λ_{SGFB} is estimated by the first term of Eq. (6), ($\alpha.\left(1 - \varepsilon_{pr}\right).\lambda_{sf}$). λ_{GGF} is estimated by the sum of second and third term of Eq.(6), ($\alpha.\varepsilon_{pr}.\lambda_{ge} + (1-\alpha).\frac{\lambda_{sf}\lambda_{ge}}{\varepsilon_{se}\lambda_{sf}+(1-\varepsilon_{se}).\lambda_{ge}}$), and λ_{RGF} is estimated by the fourth term of Eq. (3.6), ($\frac{16}{3}\frac{\sigma_s n^2 T_a^3}{E(T)}$). Fig 3.4 shows the unit volume of a glass fiber board as an open porous material.

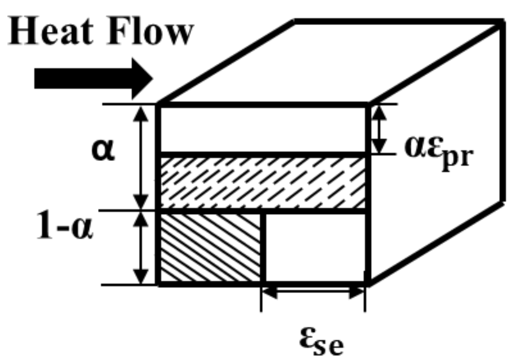

Fig 3.4: Unit volume a the glass fiber board

Smaller ε_{pr} indicates that more solid skeleton is in parallel with the air molecules and the heat flow. The air advection (convection) is thus more restricted due to smaller pores in the direction parallel to the flow of air molecules. Bigger ε_{se} indicates that less mass of solid skeleton is in series with the air molecules. Whereby, the air diffusion (convection) is more restricted due to less interaction between solid skeleton molecules and air molecules. As $\varepsilon_{pr} \rightarrow 1$ and $\varepsilon_{se} \rightarrow 0$, the thermal conductivity of air (λ_{GGF}) is maximized (Eq. (3.8)[45]) and contrastingly as ε_{pr} ⟶ 0 and ε_{se} ⟶ 1, the thermal conductivity of air (λ_{GGF}) is minimized, as expressed in Eq. (3.9)[45],

$$\lambda_{GGFmax} = \alpha . \lambda_{ge} + (1 - \alpha)\, \lambda_{sf} \qquad \text{Eq. (3.8)}$$

$$\lambda_{GGFmin} = (1-\alpha)\lambda_{ge} \qquad \text{Eq. (3.9)}$$

The effect of air inside the glass fiber board-which is quantified through the thermal conductivity of air (λ_{GGFB})- is reduced due to the smaller the porosity ratio $\left(\frac{\varepsilon_{pr}}{\varepsilon_{se}}\right)$. Bankvall [45]developed his model for estimating the effective thermal conductivity of the glass fiber board (λ_{EGF}) by using the effective porosity (ε) and the mean distance between fibers (D_M) , as expressed in Eq. (3.10)[45]. d_M is the mean fiber diameter. The mean distance between fibers (D_M) is estimated by using Eq. (3.11)[45]. λ_{SGFB} is estimated by the first term of Eq. (10 (by using the effective porosity (ε) and the thermal conductivity of each individual fiber (λ_{sf})). λ_{GGFB} is estimated by the second term of Eq.(3.10) [45] (by using thermal conductivity of free air ($\lambda_{g,o}$), the core vacuum level (P) and the mean distance between fibers (D_M)). G is a constant, depending on the gas type (for air, G=2.332 × 10^5 [45]) and T is the temperature of environment. λ_{RGFB} is estimated by the third term of Eq. (10) and by using D_M and the average temperature within the core (T_a)(for a thickness sufficiently large compared to D_M and sufficiently black boundary surfaces). σ_s= 5.7. 10^{-8} W/m^{2}K^4 is the Stefan-Boltzmann constant. T_a (K) is estimated by Eq. (3.13)[45]. T_h and T_c are the temperatures of hot side and cold side of the glass fiber board, respectively. The radiational properties of fibers and fiber layers are described by the factor B. As expressed in Eq. (3.12)[45], B depends on the temperature (T), the mean fiber diameter (d_M) and the porosity (ε)[45].

$$\lambda_{EGFB} = \frac{32(1-\varepsilon)^2 . \lambda_{sf}}{\Pi\,(3+\frac{\Pi}{4(1-\varepsilon)})} + \lambda_{g,o} . \frac{PD_m}{PD_m + G.T} + 4\sigma_s . D_M . B\, . T_a^3 \qquad \text{Eq.(3.10)}$$

$$D_M = \frac{\Pi . d_M}{4(1-\varepsilon)} \qquad \text{Eq.(3.11)}$$

$$B = \frac{\varepsilon_f}{2-\varepsilon_f} = f\,(T, d_M, \varepsilon) \qquad \text{Eq.(3.12)}$$

$$T_a = \sqrt[3]{(T_h^2 + T_c^2)(T_h + T_c)/4} \qquad \text{Eq.(3.13)}$$

Here, the mean distance between fibers (D_M) is considered as the mean effective pore size ($\delta_{MGFBs} = D_{MGFBs} =$ 100 to 300 μm) for glass fiber boards. Smaller D_M indicates that smaller part of the glass fiber board is in parallel with the heat flow and the air molecules (smaller (α)). Whereby, thermal conductivity of air (λ_{GGF}) is reduced for the same level of core vacuum level between (P =1 to 10^5Pa) , as expressed in Eq. (5) and Eq. (3.10) [45]). According to Banksvall's model, the mean distance between fibers (D_M) and the porosity ratio ($\frac{\varepsilon_{pr}}{\varepsilon_{se}}$) are identified as two controllable parameters for making high efficiency glass fiber board or glass fiber-silica powder composite VIP-Core.

2.2 Introduction to the glass fiber-silica powder composite

A glass fiber- silica powder composite (core B) is made by using a glass fiber board (core A) and silica powder (e.g. zeolite (ZE) or diatomaceous earth (DE)). For this purpose, Core A is cut into the layers of thickness in mm range and the silica powder particles are distributed uniformly on each layer of core A. The glass fiber-silica powder composite (Core B) is made by sandwiching layers of glass fiber and silica powder [1]. During the evacuation, silica powder particles place themselves between the fibers from different layers or between the fibers of the same layer. The porosity of the core's solid skeleton in parallel with the heat flow is reduced by the powder particles between different layers ($\varepsilon_{pr-B} < \varepsilon_{pr-A}$).While, the porosity of the core's solid skeleton in series with the heat flow ($\varepsilon_{se-B} > \varepsilon_{se-A}$) is increased by powder particles between fibers of the same layer [45]. By adding powder particles to the microstructure of the glass fiber board (core A), ε_{pr} of the core is decreased more considerably than the increase in ε_{se}, so that the effective porosity of the glass fiber board (ε = (1- α). ε_{se}+ α . ε_{pr})) is decreased ($\varepsilon_B < \varepsilon_A$). The glass fiber-silica powder composite has smaller mean effective pore size and smaller porosity ratio ($\frac{\varepsilon_{pr-B}}{\varepsilon_{se-B}} < \frac{\varepsilon_{pr-A}}{\varepsilon_{se-A}}$), compared to the glass fiber board used for making the composite. Consequently and following Eq. (3.5), the glass fiber-silica powder composite has smaller λ_G at various core vacuum levels between (P = 1 to 10^5Pa)[1], [45].This study is aimed at estimating the change in the mean effective pore size of a VIP-Core, by making glass fiber-zeolite powder composite and glass fiber-diatomaceous earth powder composite.

3. Experiments

3.1 Preparation of specimens

The VIP-Cores involved in this experiment are the glass fiber board (GFB), the glass fiber- zeolite composite (GFB-ZE), and the glass fiber-diatomaceous earth composite (GFB-DE). The glass fiber board (GFB) under consideration has a density of 201 kg/m^3 (a mass of 650 g (m_{GFB}= 650 g) and the dimensions of (30cm×30cm× 3.6cm) at atmospheric pressure). The GFB has a density of 285 kg/m^3 and a thickness of 2.54 cm , at high vacuum. The GFB is consisted of compacted fiber layers. The pore and fiber structure of GFB is shown in scanning electron microscopic (HITACHI S4800) pictures (Figs. 3.5 to 3.6). The pictures (Figs. 3.5 and 3.6)), having different magnification factor (× 450 and × 800), clearly demonstrate the difference in the diameters of fibers and the pore spaces between the fibers with sizes up to around 300μm. As shown in pictures (Figs. 3.5 and 3.6), the distribution of the core's solid skeleton (fibers) is random and the diameters of the fibers vary between 1 and 10 μm while most of the fibers have diameters in the range of 4 to 7 μm.

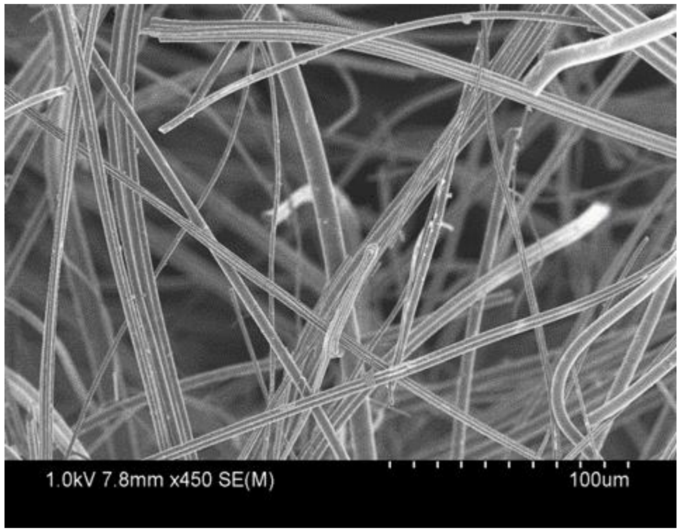

Fig 3.5: The pore and fiber structure of the GFB (× 450 magnification)

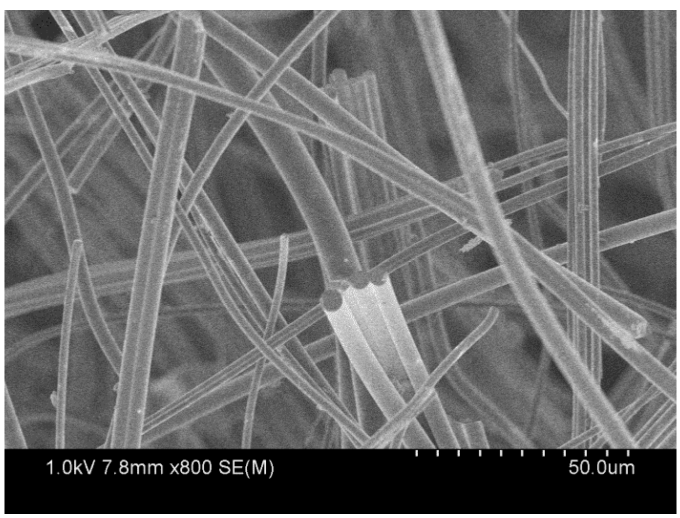

Fig 3.6: The pore and fiber structure of the GFB (× 800 magnification)

The powders under consideration are diatomaceous earth (DE) and Zeolite (ZE). The silica powders are provided by ZMM® Canada Minerals Corp, BC, Canada. Diatomaceous earth (DE) consists of amorphous silicon dioxide. Zeolite (ZE) consists of aluminum minerals formed by reacting volcanic rock and ash layers with alkaline groundwater. The micro structure of diatomaceous earth is shown in scanning electron microscopic (HITACHI S4800) picture (Fig. 3.7). There are a number of holes on each DE particle which have sizes around 5nm. These holes are additional channels for the air molecules in the pore structure of DE powder. The microstructure of zeolite is shown in scanning electron microscopic (HITACHI S4800) picture (Fig. 3.8).

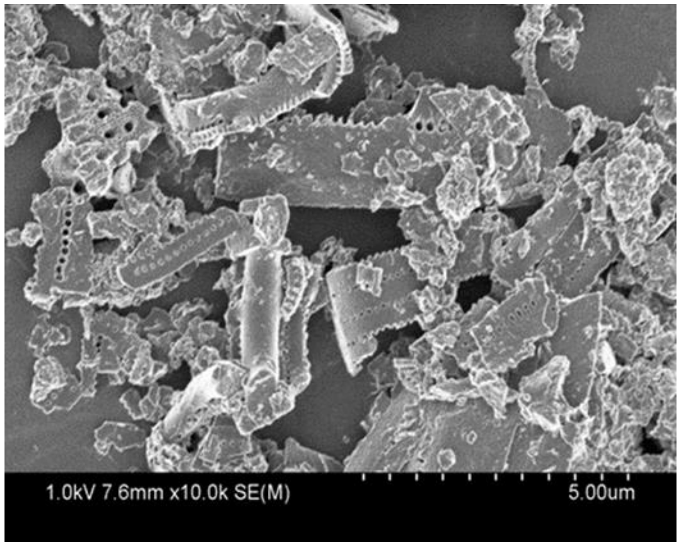

Fig 3.7: The microstructure of diatomaceous earth particles (× (10^3) magnification)

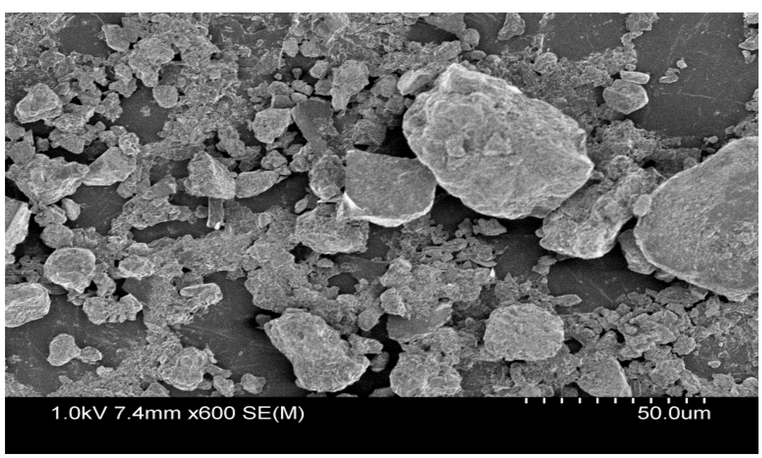

Fig 3.8: The microstructure of zeolite particles (× 600 magnification)

The particle size distribution curve of diatomaceous earth (DE) and zeolite (ZE) powders are generated by using scanning electron microscopic (HITACHI S4800) pictures and ImageJ software. As shown in Fig. 3.9, 91% of ZE particles have diameters (d_P) of around 1μm, 10% of ZE particles have d_P of 0.1 μm, and 9% of ZE particles have d_P of 10 μm. The mean particle size is d_{MPZE} = 2 μm for zeolite powder. As shown in Fig. 10, around 68% of DE particles have d_P of 1μm, 32% of DE particles have d_P of 10 μm, around 2% of DE particles have d_P= 0.1 μm, and 0.5 % of DE particles have d_P of 100 μm. The mean particle size is d_{MPDE} = 4 μm for diatomaceous earth powder.

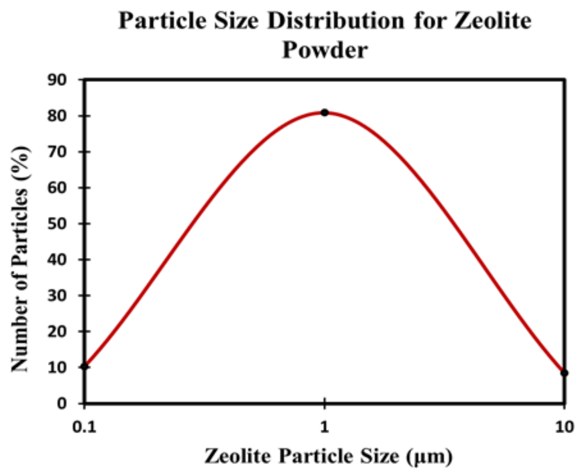

Fig 3.9: The particle size distribution for Zeolite powder

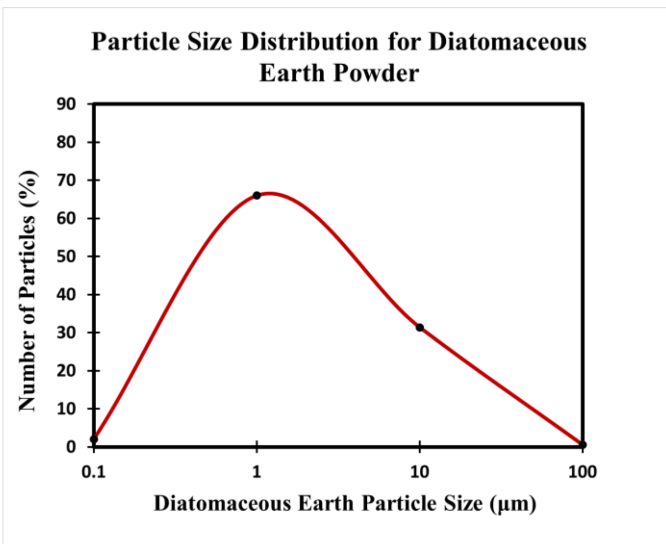

Fig 3.10: The particle size distribution of diatomaceous earth (DE) powder

In this study, two glass fiber-silica powder composites are considered as VIP-Cores. As shown in Fig. 3. 11, the first composite has thin layers (around 3.6 mm) of glass fiber and zeolite powder (which are sandwiched together). In the second composite, the zeolite powder is replaced by diatomaceous earth. The same procedure is followed for making glass fiber-zeolite composite (GFB-ZE) and glass fiber-diatomaceous earth composite (GFB-DE). First, the GFB is cut into 10 layers each with a thickness of 3.6 mm (t_l= 3.6 mm). Thereafter, 6.25 g of powder is uniformly spread by hand on each of 8 layers of GFB.

The rest two layers are the lowest and highest layers, as all 10 layers are sandwiched together for making a glass fiber-silica powder composite (GFB-DE or GFB-ZE).

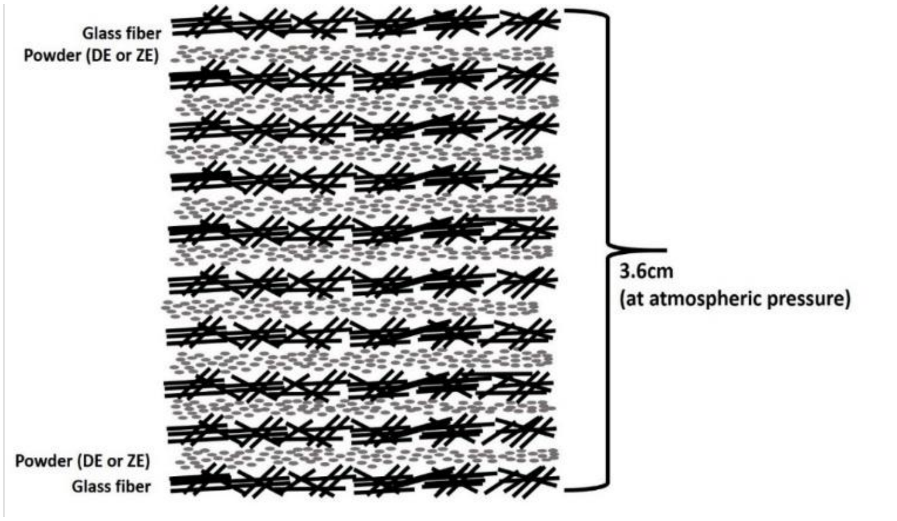

Fig 3.11: Glass fiber-Powder composite

A total mass of 50 g of powder is used for each composite (m_p= 50 g). GFB-ZE and GFB-DE composites have both a density of about 216 kg/$m^3$and the thickness of 3.6 cm at P=1 atm. They have a density of about 306 kg/m^3 and the thickness of 2.54 cm, at high vacuum..Table 3.1 shows the densities of GFB, GFB-ZE and GFB-DE.As seen in this table the percentage (by weight) of powder is $\frac{m_{ZE}}{M_{GFB-ZE}} = \frac{m_{DE}}{M_{GFB-DE}}$ = 7.1 % for both composites..

Table 3-1: Density, powder and fiber weight (%) for VIP-Cores

VIP-Core	Density at P=1atm (kg/m^3)	Density at high vacuum (kg/m^3)	Powder weight percent (%)	Fiber weight percent (%)
Glass fiber board (GFB)	201	285	0	100
Glass fiber – Zeolite composite (GFB-ZE)	216	306	7.1	92.9
Glass fiber-Diatomaceous Earth composite (GFB-DE)	216	306	7.1	92.9

Figs. 3.12 and 3.13 show the facility for characterizing thermal transmission properties of VIP. The facility consists mainly of a multi-laminated barrier envelope, turbo molecular vacuum pump, air flow manual control valves, digital air pressure gauges and aluminum pipe assembly. For each experiment, the core material (GFB, GFB-ZE or GFB-DE) is dried in an electric oven at a temperature of 125 ^{0}C for 24 hours.

Then, the core material (GFB, GFB-ZE or GFB-DE) is put into a multilayer laminated envelope. Heat sealing is used for joining the edges of the envelope. Three sides of the envelope are sealed on the edges. The core material (GFB, GFB-ZE or GFB-DE) is inserted into the envelope through the fourth (open) side. Then, the fourth side is also heat sealed and the envelope is linked to the turbo molecular vacuum pump by using aluminum pipe assembly. As shown in Fig. 3.14, the envelope is divided into two rectangular shape parts: (1) The Supporting-Part, (2) The VIP- Part, containing the core material (GFB, GFB-ZE, GFB-DE).

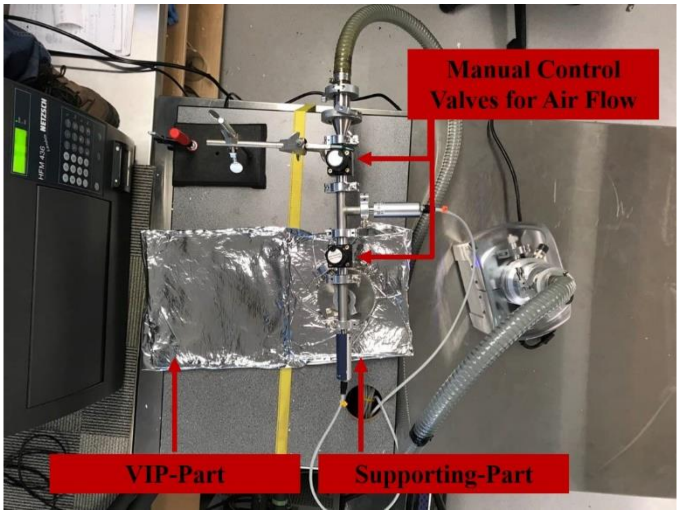

Fig. 3.12: Facility for characterizing thermal transmission properties of VIP (VIP-Part, Supporting-Part and Manual Control Valves)

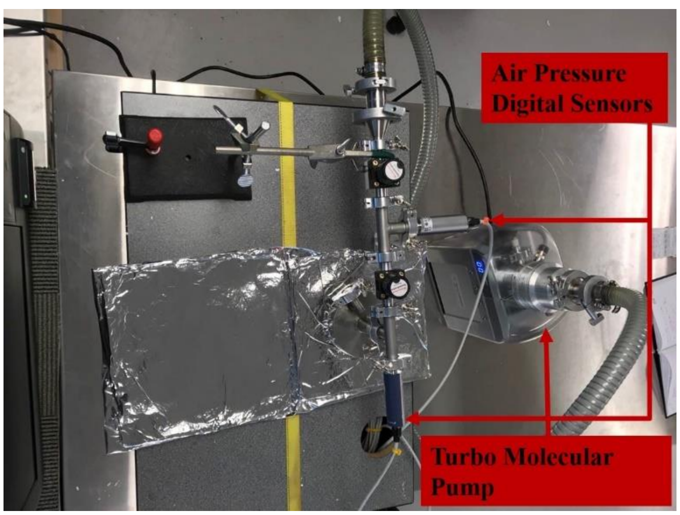

Fig 3.13: Facility for characterizing thermal transmission properties of VIP (Air Pressure Digital Sensors and Turbo Molecular Pump)

A support structure made from glass wool is inserted inside the Supporting-Part of envelope beforehand. The support structure is coupled with the pipe assembly through a hole on the envelope surface. As seen in

Fig. 14, the VIP- part is the other rectangular part of envelope (30 cm × 30cm), containing the core material (GFB, GFB-ZE or GFB-DE). Two manual control-valves and two air pressure gauges are connected to aluminum pipe assembly. After around 24 hours of vacuuming, the core vacuum level (the core internal air pressure) is drastically decreased to around P= 1Pa. The core vacuum level is controlled using the turbo molecular pump, two manual control valves for air flow and two air pressure gauges (Fig. 3.14). The core vacuum level is continuously measured by two digital pressure sensor (INFICON VGC503) and stabilized at relevant values of 1, 10, 10^2, 10^3, 10^4, 10^5 Pa. As shown in Fig. 14, for hydraulic pressing, the VIP-part is put under the hydraulic press machine (HPM) during the evacuation. At this point, the HPM is transported close to the heat flow meter (HFM 436/3). As seen in Figs. 3.15 and 3.16, the VIP-Part is inserted into the heat flow meter (HFM 436/3) for measuring the effective thermal conductivity of the VIP at the specific core vacuum level between (P= 1-10^5Pa).

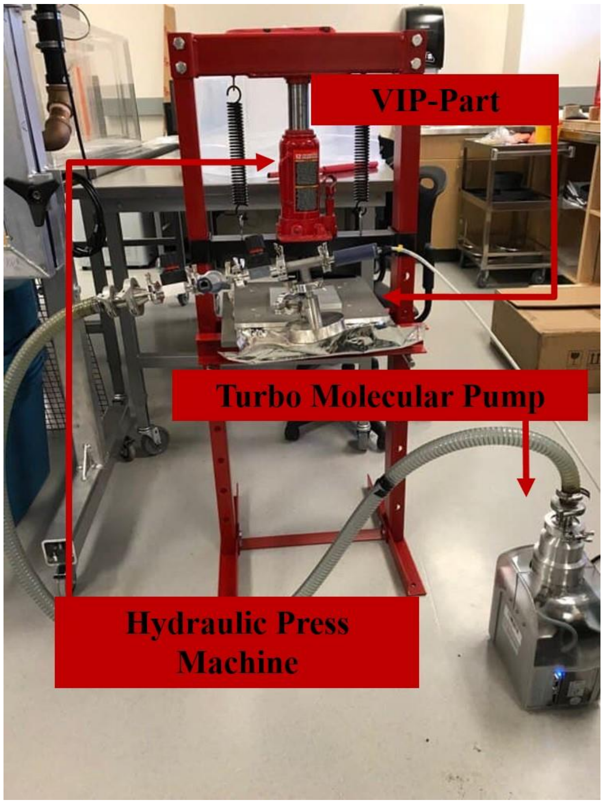

Figure 3.14: Pressing of VIP during evacuation

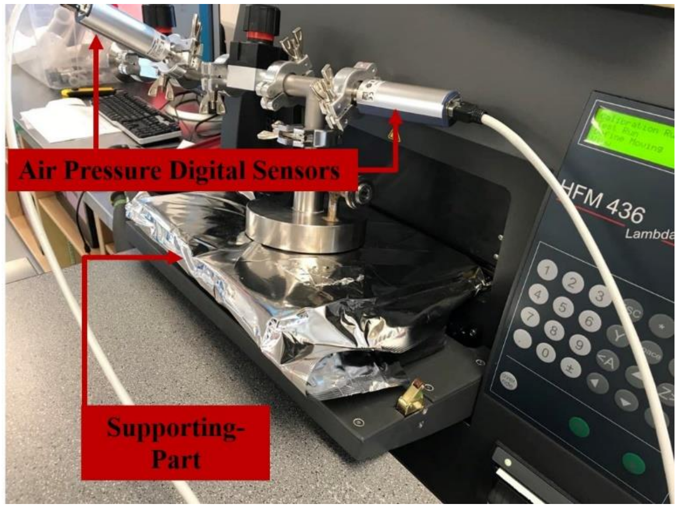

Figure 3.15: The measurement of effective thermal conductivity of VIPs by the heat flow meter

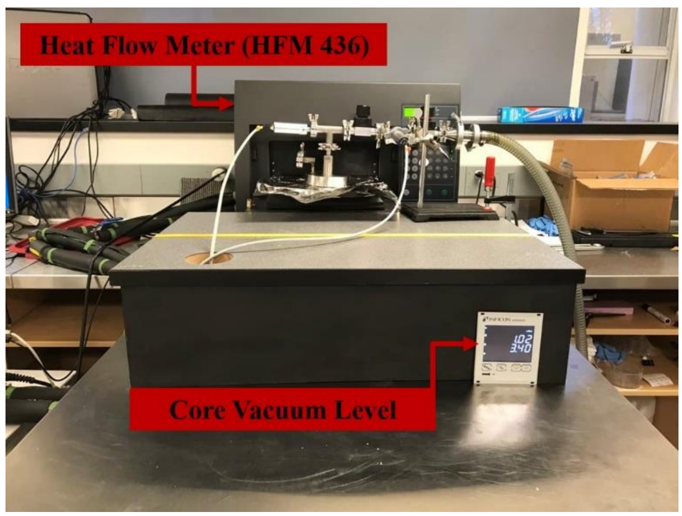

Fig 3.16: The heat flow meter

3.2 Measurement of the effective thermal conductivity by heat flow meter

The heat flow meter (HFM 436/3) is used for investigating the thermal performances of the VIP-Cores, Whereby, the effective thermal conductivities of VIPs are measured by means of one-dimensional integral form of Fourier's law during steady state condition at the core vacuum levels (core internal air pressures) between 1 and 10^5 Pa, as expressed in Eq. (2). The VIP (300 cm × 300 cm × 2.54 cm) is placed between hot plate and cold plate of HFM. Due to the temperature gradient between these two plates, heat flows vertically through the VIP from hot plate to cold plate. The heat flux (W) is measured by heat flux transducers over the metering area of (A=10 cm × 10 cm). As the measurement process progresses toward equilibrium, temperature and heat flux are detected once each minute by temperature and heat flux transducer sensors, respectively. Firstly, the measurement progresses until the rough error criteria of 3% is satisfied. At this point a rough equilibrium is achieved, whereby, each measurement is deviated by less than

3% from the average value for the last 15 measurements. Then, the measurement continues toward fine equilibrium (steady state condition), whereby each measurement is less than 0.2% deviated from the average value for last 10 measurements. Fig. 3.18 illustrates schematically the construction of HFM 436/3 used in this study. As seen in Fig. 17, the VIP is heated from above by the hot plate. The hot surface assembly consists of the hot plate and the upper heat sink (hot fluid circulation). The cold surface assembly is placed below the VIP, consisting of the cold plate and lower heat sink (cold fluid circulation). The thermal interaction between the HFM 436/3 apparatus and the environment is restricted using edge insulations. The heating loss in HFM mainly comprises of the heat loss from the hot plate to upper heat sink and the heat loss from the cold plate to lower heat sink. Peltier modules are used to detect the temperature difference between the hot plate and upper heat sink and the cold plate and lower heat sink.

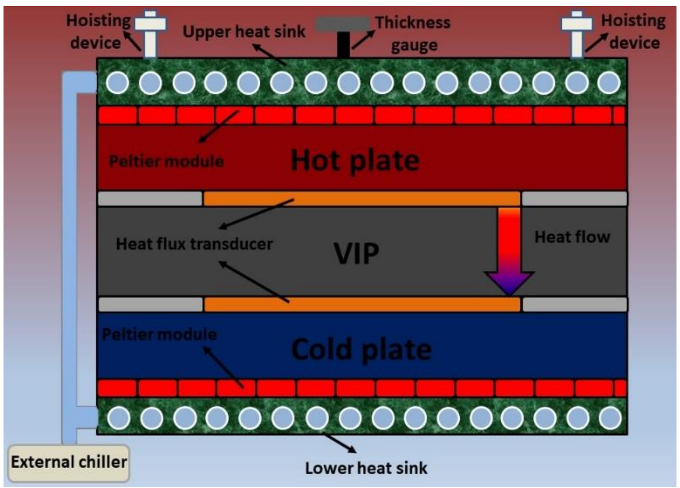

Fig 3.17: Schematic of the Heat flow meter used in the experimental set-up

3.3 Benchmarking of the experimental setup

For the purpose of benchmarking the experimental setup, this study investigates the thermal performances of a Glass fiber-VIP and a Fumed silica-VIP. The results of which are compared with the measurements done by ZAE Bayern [1]. The experimental setup is benchmarked by measuring the effective thermal conductivity of VIPs, at the core vacuum levels (core internal air pressures) between 1 and 10^5Pa. As seen in Fig. 3.18, for fumed silica, the results matches with the values reported by ZAE Bayern [1] at all core vacuum levels. For the glass fiber boards, although the trend is the same for both measurements, lower values are reported by ZAE Bayern for the effective thermal conductivities up to the core vacuum level (core internal air pressure) of 10^4 Pa. This is possibly due to difference between the mean fiber diameter and the mean distance between fibers for glass fiber boards used for each measurement.

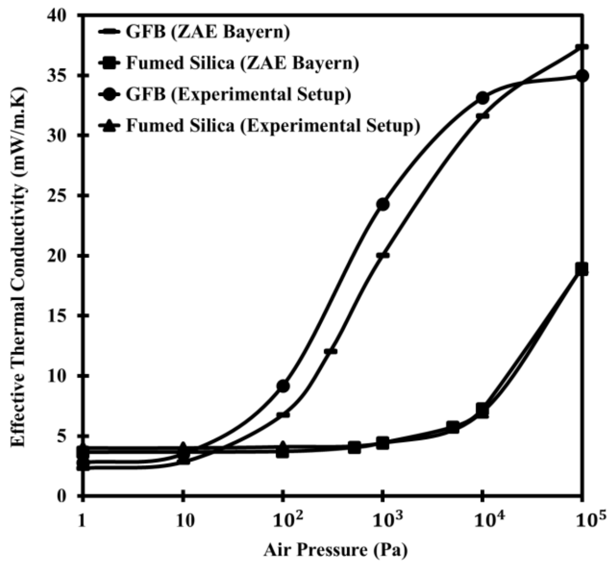

Figure 3.18: Comparison of effective thermal conductivity measurement for Glass fiber-VIP and Fumed silica-VIP with the measurement done by ZAE Bayern (not the same specimen and results are not expected to be same but similar)

4. Results and discussion

Fig. 3.19 presents the thermal performances for the VIP-Cores which are not pressed during evacuation. These VIP-Cores are the glass fiber board (GFB (not pressed)), the glass fiber-zeolite composite (GFB-ZE (not pressed)) and the glass fiber-diatomaceous earth composite (GFB-DE (not pressed)). At the core vacuum level of 1 Pa, the GFB (not pressed) has the effective thermal conductivity of 2.8 mW/m.K ($\lambda_{\mathrm{EGFB}} = 2.8\,\mathrm{mW/m.K}$) which is the same as the value reported by Kwon et al. [10] for a glass fiber board. It indicates that at P = 1Pa, λ_{GGFB} is at the negligible level (< 0.3 mW/m.K). λ_{EGFB} is increased by 0.7 mW/m.K to 3.5 mW/m.K at P = 10 Pa, indicating that λ_{GGFB} is increased by 0.7 mW/m.K, compared to P = 1 Pa. Consequently, at P = 10 Pa, λ_{GGFB} is estimated as 1mW/mK (0.3 + 0.7 mW/m.K). Following Eq. (5), the mean effective pore size is estimated to be around 130μm ($\delta_{\mathrm{MGFB}} = D_{MGFB} = 130\ \mu\mathrm{m}$) for the GFB (not pressed). DE powder has the mean particle size of 4μm ($d_{MPDE} = 4\ \mu\mathrm{m}$) while ZE powder has the mean particle size of 2 μm (d_{MPZE} =2 μm). The mean distance between fibers is extremely large compared to the mean particle sizes of DE and ZE particles ($D_{MGFB} = 70\ d_{MPZE}$, $D_{MGFB} = 32.5\ d_{MPDE}$). In other words, DE and ZE particle are too small to fill up the pores of the GFB (not pressed) with the mean size of 130 μm ($\delta_{\mathrm{MGFB}} = D_{MGFB} = 130\ \mu\mathrm{m}$). As a consequence, the microstructure of GFB (not pressed) is only slightly affected due to the addition of both powder particles. As seen in Fig. 21, three VIP-cores (not pressed) have similar thermal performances especially at high core vacuum levels between (i.e. P=1 to10 Pa). Compared to the GFB (not pressed), GFB-DE (not pressed) and GFB-ZE (not pressed) have slightly lower effective thermal conductivities at low vacuum levels (P>10^2 Pa). GFB-DE (not pressed) and

GFB-ZE (not pressed) have lower porosity ratios ($\frac{\varepsilon_{pr}}{\varepsilon_{se}}$) due to the addition of powder particles to the microstructure of the GFB. The fiber diameters vary between 1 and 10 µm, most of which are in the range of 4 and 7 µm. Around 81% of ZE particles have diameters d_P of around 1µm and around 10% of ZE particles have d_P of 0.1 µm, while around 70% of DE particles have d_P of around 1µm or less (around 2% have d_P= 0.1 µm). The most of both powder particles are smaller than fiber diameters and when they are placed between the fibers of the same layer, ε_{se} of the GFB is increased. On the other hand, around 32% of DE particles have diameters d_P of around 10 µm, while only around 9% of ZE particles have d_P of around 10 µm. Whereby, ε_{pr} of the GFB (not pressed) is slightly more reduced due to the addition of DE particles, compared to ZE particles. Consequently, the GFB-DE (not pressed) has slightly lower porosity ratio ($\frac{\varepsilon_{pr}}{\varepsilon_{se}}$) , and therefore lower effective thermal conductivities, at low core vacuum levels (P>10^2 Pa), compared to the GFB-ZE (not pressed).

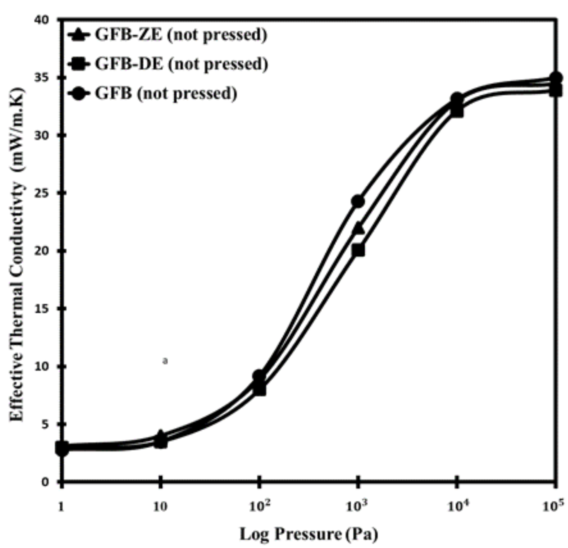

Fig 3.19: The comparison of the effective thermal conductivity measurements for VIP-Cores which are not pressed during evacuation (glass fiber board (GFB), glass fiber-zeolite composite (GFB-ZE) and glass fiber-diatomaceous earth composite (GFB-DE)

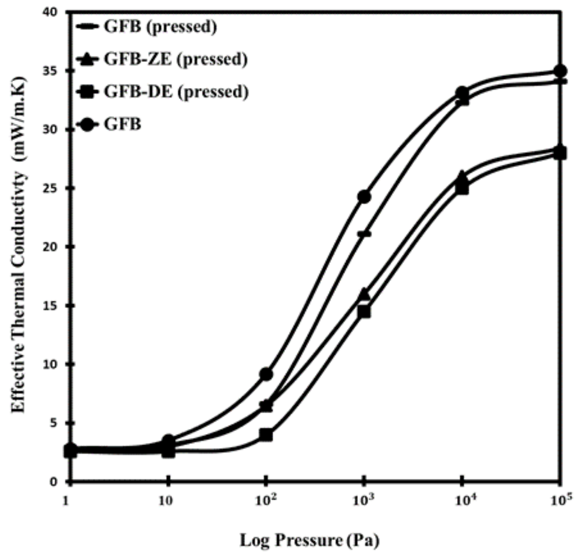

Fig 3.20: The comparison of the effective thermal conductivity measurements for VIP-Cores which are pressed during evacuation (glass fiber board (GFB), glass fiber-zeolite composite (GFB-ZE) and glass fiber-diatomaceous earth composite (GFB-DE)

Fig. 3.20 illustrates the comparison of the thermal performances for the VIP-Cores which are pressed during evacuation. These VIP-Cores are the glass fiber board (GFB (pressed)), the glass fiber-zeolite composite (GFB-ZE (pressed)) and the glass fiber-diatomaceous earth composite (GFB-DE (pressed)). At the core vacuum level of P = 1Pa, the GFB (pressed) has the effective thermal conductivity of ($\lambda_{EGFBP} = 2.8$ mW/m.K) the same as the GFB (not pressed) ($\lambda_{EGFBP} = \lambda_{EGFB} = \lambda_{SGFB} + \lambda_{RGFB}$ = 2.8 mW/m.K). It indicates that, at P = 1Pa, λ_{GGFBP} is at the negligible level (< 0.3 mW/m.K). λ_{EGFBP} is increased by 0.3 mW/m.K to 3.1mW/m.K by decreasing the core vacuum level to P= 10Pa, indicating that λ_{GGFBP} is increased by 0.3 mW/m.K , compared to P = 1Pa . Consequently, at P= 10Pa, λ_{GGFBP} is estimated to be around 0.6 mW/mK (0.3 + 0.3 mW/mK). Following Eq. (5), the GFB (pressed) has the mean effective pore size of ($\delta_{MGFBP} = D_{MGFBP} = 75\ \mu m$). The mean distance between fibers is reduced from (D_{MGFB}=130 µm) to (D_{MGFBP} =75 µm) by pressing the VIP-Core during the evacuation. By means of which, the ratio of $\frac{D_{MGFB}}{d_{MP}}$ is reduced for both composites ($D_{MGFBP} = 37.5\ d_{MPZE}, D_{MGFBP} = 18.7\ d_{MPDE}$). At the core vacuum level of (P = 1Pa), the GFB-ZE (pressed) has the effective thermal conductivity of 2.8 mW/m.K, the same as the GFB (not pressed) and the GFB (pressed) ($\lambda_{E(GFB-ZE)P}$ =2.8 mW/m.K). It indicates that, at P = 1Pa, $\lambda_{G(GFB-ZE)P}$ is at the negligible level (< 0.3 mW/m.K). $\lambda_{E(GFB-ZE)P}$ is increased by 0.2 mW/m.K to 3 mW/m.K at P = 10Pa, indicating that $\lambda_{G(GFB-ZE)P}$ is increased by 0.2 mW/m.K to around 0.5 mW/mK , compared to 1Pa . Consequently and following Eq. (5), the mean effective pore size of the GFB- ZE (pressed) is estimated to be around 61μm ($\delta_{(GFB-ZE)p} = 61\ \mu m$) . This indicates, the effective pore size of the VIP-Core (GFB) is reduced from around 130 μm to around 61 μm due to the pressing during evacuation and the addition of ZE particles to the microstructure of the GFB.

At the core vacuum level of 1 to 10 Pa, the GFB- DE (pressed) has the effective thermal conductivity of 2.6 mW/m.K ($\lambda_{E(GFB-DE)p} = 2.6\ mW/m.K$) and $\lambda_{G(GFB-ZE)p}$ is at the negligible level (< 0.3 mW/m.K). $\lambda_{E(GFB-DE)p}$ is increased by 1.4 mW/m.K to 4 mW/m.K by decreasing the core vacuum level to 10^2 Pa, indicating that $\lambda_{G(GFB-DE)p}$ is increased by 1.4 mW/m.K at P= 10^2 Pa, compared to P = 1 Pa, and P = 10Pa. Consequently, at p =10^2 Pa, $\lambda_{G(GFB-DE)p}$ is estimated to be around 1.7 mW/mK (0.3 + 1.4 mW/m.K). Following Eq. (5), the mean effective pore size of the GFB-DE (pressed) is estimated to be around 21μm ($\delta_{(GFB-DE)p} = 21\ \mu m$). This is mainly contributed to the DE particles with d_P=10 μm which place themselves between the fibers (with the mean distance of D_{MGFBP} =75 μm for the GFB (pressed)). This indicates, the effective pore size of the VIP-Core (GFB) is reduced from around 130 μm to around 21 μm due to the pressing during evacuation, and the addition of DE particles to the microstructure of the GFB. The GFB-DE (pressed) has the least mean effective pore size and the least porosity ratio ($\frac{\varepsilon_{pr}}{\varepsilon_{se}}$) among three VIP-Cores under consideration.

Fig 3.21 illustrates the comparison for the enhancing effects of three alterations on the thermal performance of the glass fiber board (GFB) as the VIP-Core: (1) Pressing during evacuation, (2) The combination of pressing during evacuation and the addition of ZE particles, (3) The combination of pressing during evacuation and the addition of DE particles. Due to the pressing during evacuation, the effective thermal conductivities of the GFB (as the VIP-Core) is reduced by between 0 and 28.3 % at the core vacuum levels between 1 and 10^5 Pa. Where, the enhancing effect is highest (28.3 %) at the core vacuum level of10^2 Pa, and the average of enhancing effects is around 10%. It indicates, that the thermal performance of the VIP-Core (the GFB) is on average enhanced by 10 % due to the pressing during evacuation (at the core vacuum levels between 1 and 10^5 Pa.

Due to the combined effects of the pressing during evacuation and the addition of ZE particles, the effective thermal conductivities of the VIP-Core is reduced by between 0 and 34.1 % at the core vacuum levels between 1 and 10^5 Pa. Where, the increase in the thermal performance is highest (34.1 %) at the core vacuum level of 10^3 Pa and the average of the increase in the thermal performance is around 20%. It indicates, that the thermal performance of the VIP-Core is on average enhanced by 20 % due to the combined effects of the pressing during evacuation and the addition of ZE particles (at the core vacuum levels between 1 and 10^5 Pa). Where, the ratio between the mean distance between fibers and the mean particle size of ZE Powder is 37.5 ($i.e. \frac{D_{MGFBP}}{d_{MPZE}}$ is 37.5). In other words, when $\frac{D_{MGFB}}{d_{MP}} = 37.5$, the glass fiber – silica powder composite has on average 20 % higher thermal performance (at the core vacuum levels between 1 and 10^5 Pa), compared to the glass fiber board used for making the composite.

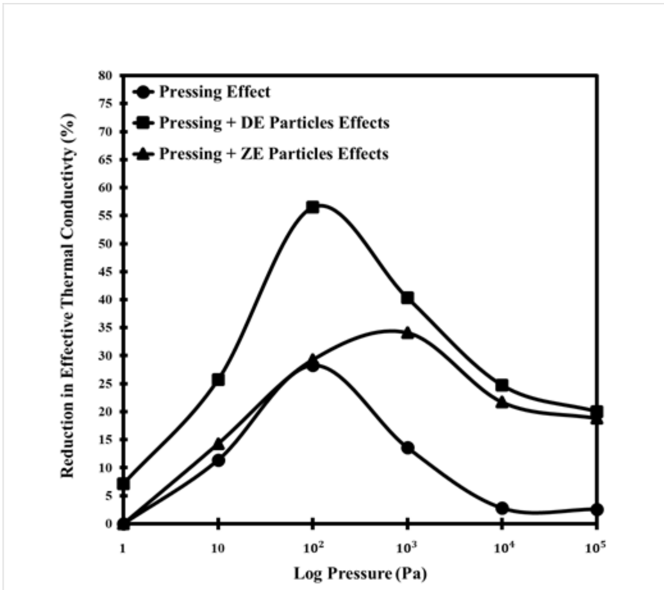

Fig 3.21: The comparison of the different effects on the reduction of effective thermal conductivity of the glass fiber board (Pressing effect, Pressing + ZE Particles Effects, and Pressing +DE Particles Effects)

Due to the combined effects of the pressing during evacuation and the addition of DE particles, the effective thermal conductivities of the VIP-Core is reduced by between 7.1 and 56.5 % at the core vacuum levels between 1 and 10^5 Pa. Where, the increase in the thermal performance is highest (56.5 %) at the core vacuum level of 10^2 Pa, and the average of the increase in the thermal performance is around 30%. It indicates, that the thermal performance of the VIP-Core is on average enhanced by 30 % due to the combined effects of the pressing during evacuation and the addition of DE particles (at the core vacuum levels between 1 and 10^5 Pa. Where, the ratio between the mean distance between fibers and the mean particle size of the powder particle is ($i.e. \frac{D_{MGFBP}}{d_{MPDE}} = 18.7$). Fig 3.22 shows the comparison of thermal performances for the GFB-DE (pressed), the glass fiber board used for making the composite (GFB), and precipitated silica. The GFB- DE composite has a comparable thermal performance with precipitated silica, up to the vacuum level of 10^2 Pa. In other words, by halving the ratio of $\frac{D_{MGFB}}{d_{MP}}$ from 37.5 (or around 38) to 18.5 (around 19), the powder effect is further increased by 10 % to 30 %. Whereby, the glass fiber- silica powder composite has a comparable thermal performance with precipitated silica, up to the core vacuum level of 10^2 Pa, and has on average 30% higher thermal performance at the core vacuum levels between 1 and 10^5 Pa, compared to the glass fiber board used for making the composite. Hereby, it can be estimated that by further halving of $\frac{D_{MGFB}}{d_{MP}}$ from 18.5 to around 9 or10, the thermal performance is further increased by on average 10 % at the core vacuum levels between 1 and 10^5 Pa. Consequently, by using a silica powder with the mean particle size of around $d_{MP} = 8$ μm, the glass fiber-silica powder composite is estimated to have on average 40 % higher thermal performance at the core vacuum levels between 1 and 10^5 Pa, compared to the glass fiber board used for making the composite.

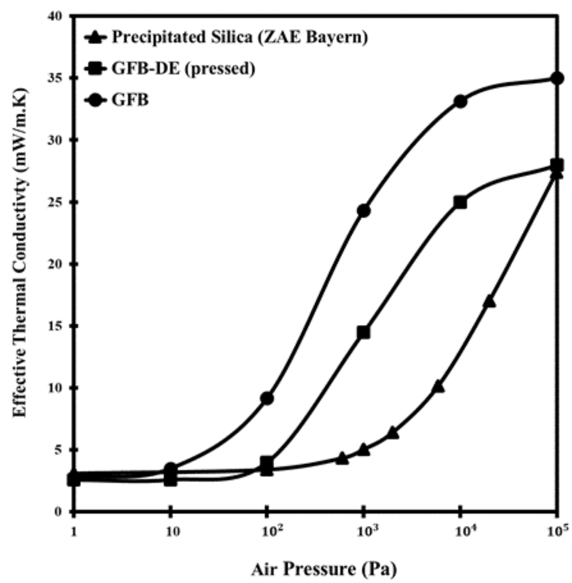

Fig 3.24: The comparison of the effective thermal conductivity measurements for the glass fiber board (GFB) and glass fiber- diatomaceous earth composite (GFB-DE) and precipitated silica (ZAE Bayern)

Finally, this study recommends the making of glass fiber–silica powder composite VIP-Core, with the ratio of the mean distance between fibers to the mean particle of the silica powder equals to 10 ($i.e. \frac{D_{MGFB}}{d_{MP}} = 10$). The glass fiber- silica powder composite is estimated to have the mean effective pore size of around or less than 10μm ($\text{i.e.}\ \delta_{GFB-Silica}$ <10μm) and $\lambda_{G(GFB-Powder)}$ is maintained at the negligible level (< 0.3 mW/m.K) up to the core vacuum level of 10^2 Pa, and at the low level (1 mW/m.K) up to the core vacuum level of 10^3 Pa. Therefore, the glass fiber–silica powder composite has a comparable thermal performance with precipitated silica, up to the core vacuum level of 10^4 Pa.

5. Conclusions

Glass fiber-VIPs offer super insulating capacity in pristine condition (i.e. at high vacuum, P =1 Pa). However, they are sensitive to decrease in the core vacuum level due to the air and water vapor penetration through the envelope into the pores of the glass fiber board. This contributes to their larger mean effective pore sizes (δ_{GFB} =100-300 μm), compared to precipitated silica- VIPs (δ_{PS} =1-3 μm), and fumed silica-

VIPs (δ_{FS} = 40-70 nm). The glass fiber-silica powder composites can be used for making VIP-Cores, which are less sensitive to decrease in the core vacuum level, compared to glass fiber core VIPs. For this purpose, two glass fiber-silica powder composites are made by using a glass fiber board (with the mean effective pore size of 130 µm (i.e. $\delta_{MGFB} = D_{MGFB} = 130$ µm) and two silica powders, the zeolite powder (ZE) with the mean particle size of 2 µm (*i.e.* $d_{MPZE} = 2$ µm) and the diatomaceous earth powder (DE) with the mean particle size of 4 µm (*i.e.* $d_{MPDE} = 4$ µm). The mean distance between the fibers` is large compared to the mean particle sizes of DE and ZE particles ($\frac{D_{MGFB}}{d_{MPZE}} = 70$ and $\frac{D_{MGFB}}{d_{MPDE}} = 32.5$). Both powder particles are too small to fill up the pores of the GFB. Consequently, by $\frac{D_{MGFB}}{d_{MPZE}} = 70$ and $\frac{D_{MGFB}}{d_{MPDE}} = 32.5$, the mean effective size of the VIP-Core ($\delta_{(GFB)} = 130$ µm) is slightly reduced due to the exclusive effect of the addition of both powder particles to the pore structure of the glass fiber board. As a result, the glass fiber–zeolite composite (GFB-ZE (not pressed) and glass fiber-diatomaceous earth composite (GBB-DE (not pressed) have similar thermal performances with the glass fiber board, especially at high core vacuum levels. Therefore, hydraulic pressing is employed during the evacuation to investigate the effects of three alterations on the thermal performance of the glass fiber board (GFB) as the VIP-Core: (1) Pressing during evacuation, (2) The combination of pressing during evacuation and the addition of ZE particles, and (3) The combination of pressing during evacuation and the addition of DE particles. The effective pore size of the VIP-Core is reduced from $\delta_{(GFB)} = 130$ µm to $\delta_{(GFB)p} = 75$ µm due to the pressing during evacuation. The effective pore size of the VIP-Core is reduced to $\delta_{(GFB-ZE)p} = 61$ µm due to combined effects of the pressing during evacuation and the addition of ZE particles. The GFB-ZE (pressed) has $\frac{D_{MGFB}}{d_{MPZE}} = 37.5$, the mean effective pore size of $\delta_{(GFB-ZE)p} = 61$ µm , and on average 20 % higher thermal performance (at the core vacuum levels between 1 and 10^5 Pa), compared to the glass fiber board (with the mean effective pore size of 130 µm (*i.e.* $\delta_{MGFB} = D_{MGFB} = 130$ µm) used for making the composite. Meanwhile, the effective pore size of the VIP-Core is reduced to $\delta_{(GFB-DE)p} = 21$ µm, due to combined effects of the pressing during evacuation and the addition of DE particles. The GFB-DE (pressed) has $\frac{D_{MGFB}}{d_{MPDE}} = 18.5$, the mean effective pore size of $\delta_{(GFB-DE)p} = 21$ µm and on average 30 % higher thermal performance (at the core vacuum levels between 1 and 10^5 Pa), compared to the glass fiber board (with the mean effective pore size of 130 µm ($\delta_{MGFB} = D_{MGFB} = 130$ µm) used for making the composite.

This study concludes that the glass fiber- silica powder composite is a viable method for making high efficiency VIP-Cores which have higher thermal performance, compared to glass fiber-VIPs. Whereby, the effective pore size of the VIP-Core is reduced and the effectiveness of the method depends mainly on the relation between the mean distance between the fibers and the mean particle size of the silica powder. By

$\frac{D_{MGFB}}{d_{MP}} = 37.5$, the glass fiber – silica powder composite has on average 20 % higher thermal performance (at the core vacuum levels between 1 and 10^5 Pa, compared to the glass fiber board used for making the composite. By halving of $\frac{D_{MGFB}}{d_{MP}}$ from 37.5 (or around 38) to 18.5 (around 19), the glass fiber- silica powder composite has a comparable thermal performance with precipitated silica, up to the core vacuum level of 10^2 Pa, and has on average 30% higher thermal performance (at the core vacuum levels between 1and 10^5 Pa, compared to the glass fiber board used for making the composite. By another halving of $(\frac{D_{MGFB}}{d_{MP}})$ from 18.5 to around 9-10, the glass fiber-silica powder is estimated to have on average 40 % higher thermal performance (at the core vacuum levels between 1 and 10^5 Pa), compared to glass fiber used for making the composite. Consequently, this study suggests the $\frac{D_{MGFB}}{d_{MP}} = 10$ for making high efficiency glass fiber-silica powder composites as VIP-Core. By means of which, the mean effective pore size of the VIP-Core is estimated to be up to 10 µm ($i.e.\ \delta_{GFB-Silica}$ <10µm) and therefore the thermal performance of the VIP-Core is estimated to be comparable with precipitated silica, up to the core vacuum level of 10^4 Pa.

Chapter 4: Conclusion, and future work

1. Conclusions

VIPs, in pristine condition (at high core vacuum level, P =1Pa), offer the highest thermal performance and the least effective thickness among all insulation materials for building applications. The supremacy of VIPs roots in the employment of air and vapor evacuation to the pore structure of the VIP-Core. By means of which, a large portion of the effective thermal conductivity is eliminated for the open porous VIP-Core and the slim construction is combined with the high insulating capacity for building envelopes. However, the core vacuum level decreases gradually over the service life of VIPs (30-50 years for buildings) due to the air and water vapor penetration through the envelope into the pores of the VIP-Cores. Glass fiber boards, precipitated silica and fumed silica are mostly used as VIP-Cores. Glass fiber-VIPs are sensitive to the air intake and the thermal performance of Glass fiber- VIPs deteriorate considerably more rapidly compared to Precipitated Silica-VIPs and Fumed Silica-VIPs, as the core internal air pressure exceeds the level of P = 10^2 Pa. This is contributed to the larger mean effective pore size of glass fiber boards (up to $D_M = \delta_{GFB} = 300$ μm), compared to precipitated silica- VIPs (δ_{PS} =1 to 3 μm), and fumed silica-VIPs (δ_{FS} = 40 to 70 nm). However, fumed silica and precipitated silica are expensive, challenging their large-scale application in buildings. Alternative to the production of glass fiber boards with small mean fiber diameters in the range of $d_M = 0.1$ to 1 μm, which is constrained to the high cost of production, this study shows that the glass fiber- silica powder composite is a viable cost effective method for making high efficiency VIP-Cores which are less sensitive to the air and vapor intake, compared to the glass fiber board used for making the composite. By means of which, the effective pore size and the porosity ratio of the VIP-Core are reduced. The porosity ratio ($\frac{\varepsilon_{pr}}{\varepsilon_{se}}$) , the mean fiber diameter (d_M), and the mean distance between fibers (D_M) are controllable parameters to make high efficiency glass fiber boards or hybrid core materials by using glass fiber boards. The thermal performance of glass fiber-silica powder composites depends mainly on the relation between the mean distance between fibers (D_M) and the mean particle size of the silica powder (d_{MP}). Hence, the mean fiber dimeter (d_M) and the mean particle size of silica powder (d_{MP}) are relatively flexible options considering the economy of production and various applications.

In this study, two glass fiber-silica powder are made by using a glass fiber board (with the mean effective pore size of ($\delta_{MGFB} = D_{MGFB} = 130$ μm) and two silica powders: the zeolite powder (ZE) with the mean particle size of ($d_{MPZE} = 2$ μm)and the diatomaceous earth powder (DE) with the mean particle size of ($d_{MPDE} = 4$ μm). The mean distance between fibers is large compared to the mean particle sizes of DE and ZE particles ($\frac{D_{MGFB}}{d_{MPZE}} = 70$ and $\frac{D_{MGFB}}{d_{MPDE}} = 32.5$) Both powder particles are too small to fill up the pores of the GFB. Consequently, by $\frac{D_{MGFB}}{d_{MPZE}} = 70$ and $\frac{D_{MGFB}}{d_{MPDE}} = 32.5$, the mean effective size of the VIP-Core

($\delta_{(GFB)} = 130$ μm) is slightly reduced due to the exclusive effect of the addition of both powder particles to the pore structure of the glass fiber board. As a consequence, the glass fiber – zeolite composite (GFB-ZE (not pressed) and the glass fiber -diatomaceous earth composite (GBB- DE (not pressed) have similar thermal performances with the glass fiber board, especially at high core vacuum levels. Therefore, hydraulic pressing is employed during the evacuation to investigate the effects of three alterations on the thermal performance of the glass fiber board (GFB) as the VIP-Core: 1) Pressing during evacuation 2) The combination of pressing during evacuation and the addition of ZE particles 3) The combination of pressing during evacuation and the addition of DE particles. The effective pore size of the VIP-Core is reduced from $\delta_{(GFB)} = 130$ μm to $\delta_{(GFB)p} = 75$ μm due to the pressing during evacuation. The effective pore size of the VIP-Core is reduced to $\delta_{(GFB-ZE)p} = 61$ μm due to combined effects of the pressing during evacuation and the addition of ZE particles. The GFB-ZE (pressed) has $\frac{D_{MGFB}}{d_{MPZE}} = 37.5$, the mean effective pore size of $\delta_{(GFB-ZE)p} = 61$ μm and on average 20 % higher thermal performance (at the core vacuum levels (1 – 10^5 Pa)), compared to the glass fiber board (with the mean effective pore size of ($\delta_{MGFB} = D_{MGFB} = 130$ μm) used for making the composite. Meanwhile, the effective pore size of the VIP-Core is reduced to $\delta_{(GFB-DE)p} = 21$ μm, due to combined effects of the pressing during evacuation and the addition of DE particles. The GFB-DE (pressed) has $\frac{D_{MGFB}}{d_{MPDE}} = 18.5$, the mean effective pore size of $\delta_{(GFB-DE)p} = 21$ μm and on average 30 % higher thermal performance (at the core vacuum levels (1 – 10^5 Pa)), compared to the glass fiber board (with the mean effective pore size of ($\delta_{MGFB} = D_{MGFB} = 130$ μm) used for making the composite. Consequently, by $\frac{D_{MGFB}}{d_{MP}} = 37.5$, the glass fiber – silica powder composite has on average 20 % higher thermal performance (at the core vacuum levels (P= 1 -10^5 Pa)), compared to the glass fiber board used for making the composite. By halving of $\frac{D_{MGFB}}{d_{MP}}$ from 37.5 (or around 38) to 18.5 (around 19), the glass fiber- silica powder composite has a comparable thermal performance with precipitated silica, up to the core vacuum level of (P = 10^2 Pa), and has on average 30% higher thermal performance (at the core vacuum levels (P=1-10^5 Pa)), compared to the glass fiber board used for making the composite. By another halving of ($\frac{D_{MGFB}}{d_{MP}}$) from 18.5 to around 9-10, the glass fiber-silica powder is estimated to have on average 40 % higher thermal performance (at the core vacuum levels (P= 1-10^5 Pa)), compared to glass fiber used for making the composite. Consequently, this study suggests the ($\frac{D_{MGFB}}{d_{MP}} = 10$) for making high efficiency glass fiber-silica powder composites. By means of which, the mean effective pore size of the VIP-Core is estimated to be up to ($\delta_{GFB-Silica}$ <10μm) and therefore the thermal performance of the VIP-Core is estimated to be comparable with precipitated silica, up to the core vacuum level of (P=10^4 Pa).

2. Future Work

Future research work that could complement and extend the results presented in this thesis may include the followings:

- Characterization of the proposed method to different mean fiber diameters between 0.1 to 10 μm and different mean powder particle sizes between 1 to 20 μm.
- Development of alternative glass fiber-silica powder composites of comparable thermal performances with precipitated silica (by using a silica powder with the mean particle size of $d_P = 10\ \mu m$, and/or glass fiber board with the mean fiber diameter $d_M = 1$ to $5\ \mu m$; and therefore the mean effective pore size (the mean distance between fibers) of up to $D_M = \delta_{GFB} = 130 \mu m$.
- Development of alternative glass fiber-silica powder composites with comparable thermal performances with fumed silica (by using a silica powder with the mean particle size of ($d_{MP} = 260$ nm), ad/or glass fiber boards with the mean fiber diameter $d_M = 0.1$ to1 μm; and therefore the mean distance between fibers of up to $D_M = \delta_{GFB} =< 26 \mu m$.

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