

Vacuum Insulation Panels for Building Applications: A Review and Beyond

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Abstract

Vacuum insulation panels (VIPs) are regarded as one of the most promising high performance thermal insulation solutions on the market today. Thermal performances 3 to 6 times better than still-air are achieved by applying a vacuum to an encapsulated microporous material, resulting in a great potential combining the reduction of energy consumption in buildings with slim constructions. However, thermal bridging due to the panel envelope and a degradation of thermal performance through time occurs with the current technology. Furthermore, VIPs can not be cut for adaption at the building site and the panels are very fragile towards nail perforation and similar. These effects have to be taken into account in building applications as they may diminish the overall thermal performance.

This paper is as far as we know the first comprehensive review on VIPs. The properties, requirements and possibilities of foil encapsulated VIPs for building applications are studied based on available literature, with emphasis on the thermal bridging and the degradation through time. An extension is made towards gas-filled panels and aerogels, showing that VIPs may only be one way to achieve high performance thermal insulation solutions. Combining the technology of these solutions and others could lead to a new leap forward in high performance thermal insulation solutions. Feasible paths beyond VIPs are investigated and possibilities such as e.g. vacuum insulation materials (VIMs) and nano insulation materials (NIMs) are proposed.

Keywords: Vacuum insulation panel (VIP); Building insulation; Thermal bridge; Service life; Gas-filled panel (GFP); Aerogel; Vacuum insulation material (VIM); Nano insulation material (NIM).

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1. Introduction to vacuum insulation panels

Current vacuum-based insulating solutions can be subdivided into three categories: Vacuum insulation panels (VIPs), vacuum insulating sandwiches (VISs) or sheet-encapsulated vacuum insulation panels and vacuum insulating glazing (VIG) (see Fig.1). This review deals about VIPs as a high performance thermal insulating solution for building envelopes (Wang et al. 2007). Vacuum insulation panels can be defined as “an evacuated foil-encapsulated open porous material as a high performance thermal insulating material”.



Fig.1. [left] Vacuum technology as building insulation: VIPs, VIG and VISs (Cremers 2005) and [right] a comparison between a vacuum insulation panels and conventional insulation with the same overall thermal performance (Zwerger & Klein 2005).

The physics of the total heat transfer through an insulation material are well known. The total density of heat flow rate in such porous materials can be divided in four different heat transfer processes: Heat transfer q_r [W/m²] via radiation, heat transfer q_{cd} via conduction of the solid skeleton of the core and heat transfer via the gas inside the material. This last mentioned transfer via the internal gasses can be divided in heat transfer q_g due to gas conduction and heat transfer q_{cv} due to gas convection. The total density of heat flow rate q_{tot} can then be approximated by the sum of the densities of these different heat transfer mechanisms (Schwab 2004):

$$q_{tot} = q_r + q_{cd} + q_g + q_{cv} (+q_{coupling}) \quad (1)$$

The term $q_{coupling}$ in Eq.1 has to be added for powder and fibre materials, for which the total heat transfer will be larger than the sum of the separated heat transfer mechanisms due to interaction between them. The term $q_{coupling}$ can only be correctly omitted for materials with a coherent intern structure. Even though models on this coupling term are known (Rath 1989), the term is neglected in most literature and research due to its complexity.

The thermal transport through a material according to the thermal gradient can then be quantified by the materials thermal conductivity λ_{tot} [W/(mK)]. A standard simplified approach for this λ_{tot} is again to assume that the value represents a sum of single values which describe on their own one of the previous mentioned ways of thermal transfer, however they have to be considered simultaneously to be correct. This can be derived by rewriting Eq.1, dividing both sides of the equation with dT/dx (Brodt 1995):

$$\lambda_{tot} = \lambda_r + \lambda_{cd} + \lambda_g + \lambda_{cv} \left(+ \frac{dx}{dT} q_{coupling} \right) \quad (2)$$

where λ_r describes the radiation transfer between internal pore surfaces, λ_{cd} the solid conduction within the material skeleton, λ_g the gas conduction within the material pores and where λ_{cv} describes the air and moisture convection within the pores. For building insulation materials, all these parameters should be minimized to result in a low overall thermal conductivity λ_{tot} of the material in general.

1.1. The vacuum

The most effective reduction of the gas thermal conduction λ_g appears in a theoretical perfect vacuum, as proposed by Sir James Dewar (1892) (Fricke 2005). Here, the λ_g achieves its limit value of ‘zero’. Although such a perfect vacuum is pure theoretically, a low pressure has a positive influence on the gas conductivity.

A vacuum can be used to reduce the thermal conductivity of most traditional insulation materials, while the gaseous thermal conductivity λ_g of an evacuated material will not only be a function of the applied pressure but also from the core materials characteristics. The gaseous thermal conductivity of a porous medium at lower pressure is determined by the number of gas molecules (determined by the particle frequency of the vacuum or the internal pressure) as well as by the number of obstructions for the gas on the way from the hot to the cold side. While reducing the gas pressure in a material, the gas conductivity of the non convective gas remains almost unaffected until the mean free path of the gas molecules reaches values in the same order of size as the largest pores in the medium. When the pore diameter of the material becomes less than the average free length of path of gas molecules, the air molecules will only collide with the pore surfaces without transferring energy by this elastic impact (see Fig. 2). Equation 2 can then be reduced to the first two terms:

$$\lambda_{vac} = \lambda_r + \lambda_{cd} \quad (3)$$

However, to reduce the gas conductivity in conventional insulation materials as mineral wool, the pressure has to be reduced drastically to the range of 0.1 mbar or below and the thermal conductivity will rapidly increase with increasing pressure. Therefore, a nano-structured core material in combination with the pressure reduction is more favourable to be used in VIPs. In such material, a fine vacuum (Wutz et al. 2000) is already adequate to reduce the gas thermal conductivity in a such a medium to a calculation value $\lambda_g = 0$ W/(mK). Such a vacuum has a pressure around 10^{-3} bar, a particle frequency of 10^{10} m⁻³ and a free length of path of 10^{-4} m and the thermal conductivity of the material will stay affected by the reduced gas pressure up to one tenth of an atmosphere.

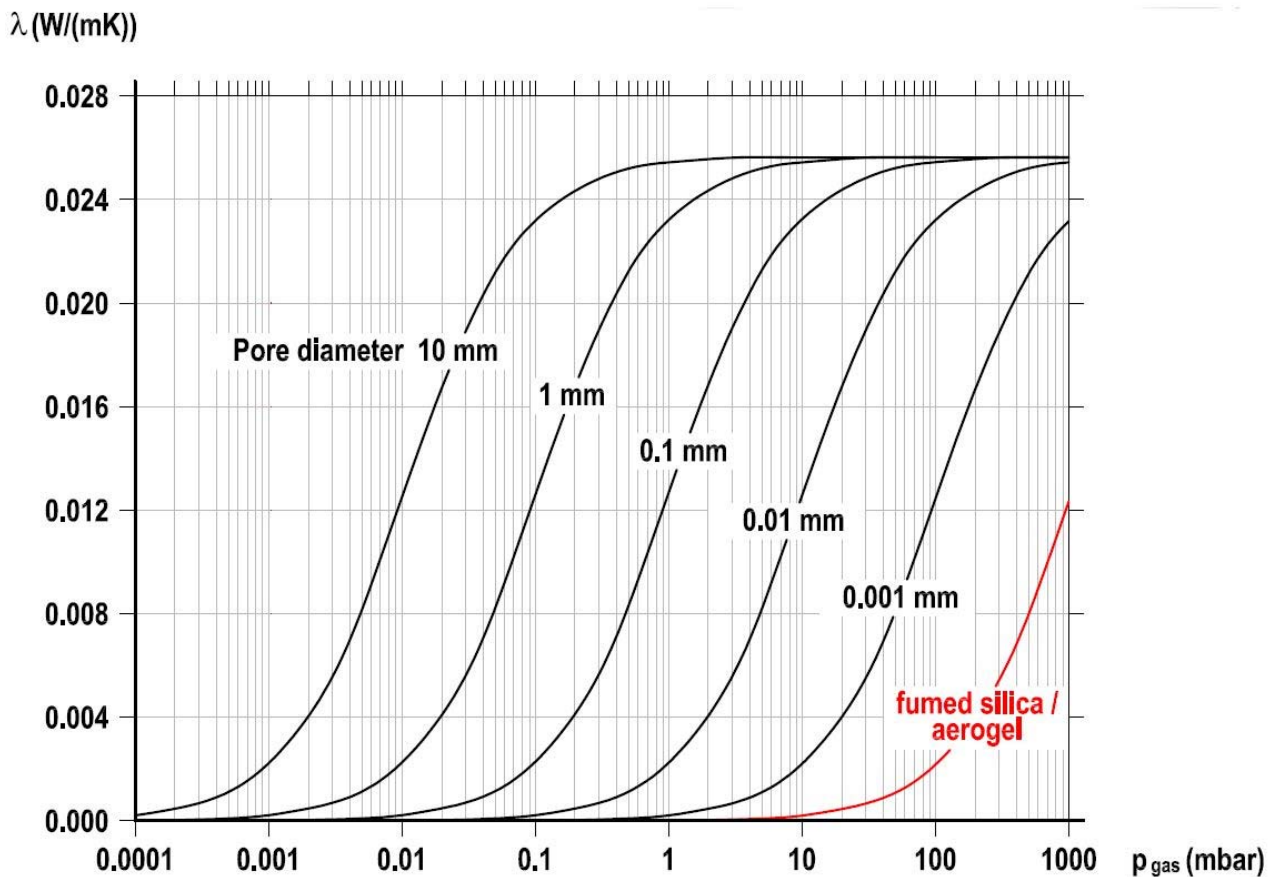


Fig. 2. The thermal conductivity of air as a function of the air pressure and the average pore diameter of the medium. Notice that the small pore size of aerogel and fumed silica reduce the gaseous conductivity even at the atmospheric pressure of 1 000 mbar (redrawn from IEA/ECBCS 2005a).

The influence of the air pressure on nano-porous materials can be expressed analytical. The gas conduction in a porous media can be written as follows (Kennard 1938):

$$\lambda_g = \frac{\lambda_{g,0}}{1 + 2\beta K_n} \quad (4)$$

where

$$K_n = \frac{l_{mean}}{\delta} \quad \text{and} \quad l_{mean} = \frac{k_B T}{\sqrt{2\pi} d_g^2 P_g} \quad (5)$$

where K_n the Knudsen number is, the ratio between the mean free path l_{mean} of air molecules and the characteristic size of pores δ , where d_g is the diameter of the gas molecules and β a constant between 1.5 and 2.0 characterising the efficiency of energy transfer when gas molecules hit the solid structure of the material. The constant β depends on the gas type, the solid material and the temperature. Because of the high porosity of insulation materials, the contribution of the gas conductivity λ_g will play an important role in the effective thermal conductivity at atmospheric pressure. However, the free air conduction $\lambda_{g,0}$ in Eq.4 will be strongly reduced due to the Knudsen effect if we consider the narrow pore size in nano-porous materials.

If we rewrite the previous Eq.4, a formula which accentuates the three main parameters for gaseous heat conduction in porous media appears (Caps et al. 2001): The gas pressure P_g , the characteristic pore size δ and the temperature T (see also Fig. 3).

$$\lambda_c = \lambda_{vac} + \frac{\lambda_{g,0}(T)}{1 + C \frac{T}{\delta P_g}} = \lambda_{vac} + \frac{\lambda_{g,0}(T)}{1 + \frac{P_{1/2,g}}{P_g}} \quad (6)$$

where $\lambda_{g,0}$ is the thermal conductivity of free gas, $p_{1/2,gas}$ the pressure at which the thermal conductivity of the gas reaches the value of one half of $\lambda_{free\ gas}$ and C a factor defined as $2\beta k_B / (\sqrt{2} \pi d_g^2)$. Equations for $\lambda_{g,0}$ and $P_{1/2,g}$ are given by Schwab (2004). The product $P_g \delta$ in Eq.6 strongly defines the gas conduction: If micro or nano-structured materials with small pore size are used as VIP cores, only a weak vacuum is required to reach a low thermal conductivity. The value $P_{1/2,gas}$ in Eq.6 is again strongly depending on δ and is influenced by the gas type.

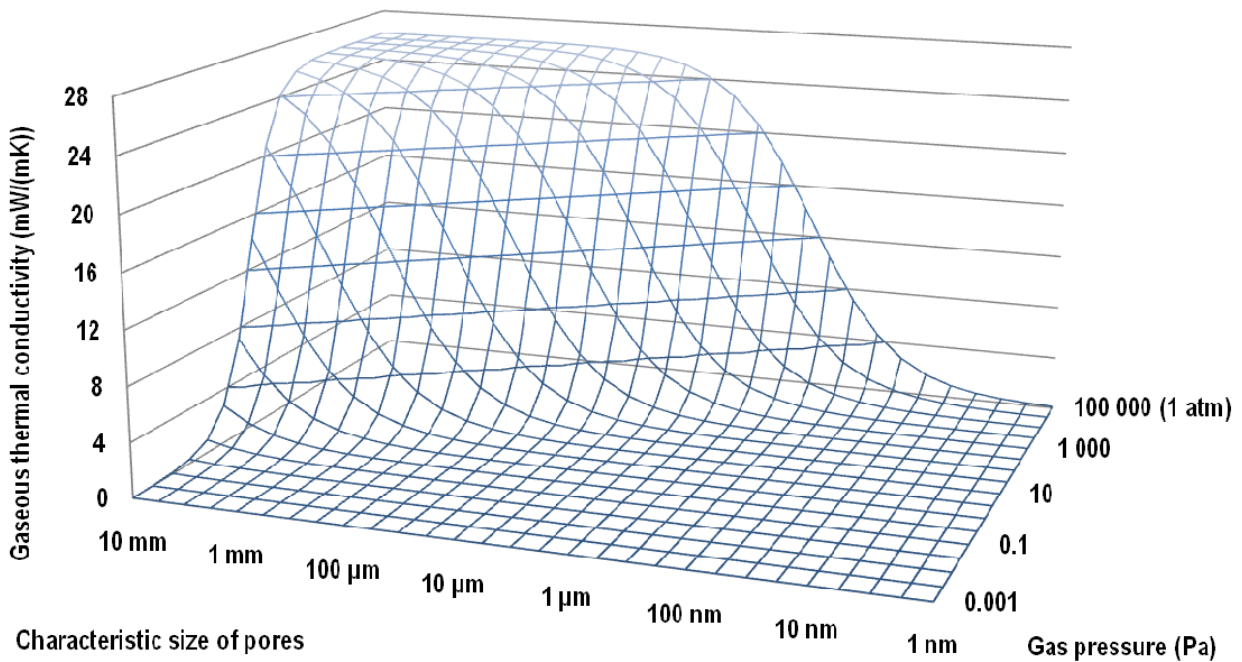


Fig. 3. Gaseous thermal conductivity of air (mW/(mK)) as function of the materials characteristic pore size and the gaseous pressure at a temperature of 300 K. The values have been retrieved from Eq.4-5 representing the Knudsen effect. Compare with Fig. 26 for krypton.

1.2. The core

Because of the relationship between the gas thermal conductivity of air and the pore diameter, the core material has to fulfil different requirements to be suitable for vacuum insulation:

1. The materials pore diameter has to be very small. To reduce the gas conductivity in insulation materials with large pore sizes, the pressure has to be very low which is difficult to maintain by envelopes primarily made of organic materials. Therefore, a nano-structured core material in combination with a fine vacuum is preferred in VIPs. Ideal would be a pore size of 10 nm or less, which would reduce the gaseous conductivity to zero even at atmospheric conditions.
2. The material has to have an 100 % open cell structure to be able to evacuate any gas in the material.

Two other requirements can be found due to the specific character of vacuum insulation panels:

3. The material has to be resistant to compression: Currently produced VIPs have an internal pressure in the range of 0.2 to 3 mbar. Hereby, the pressure load on the panel is approximately 1 bar or 100 kN/m². The core material has to be stable enough so the pores do not collapse when the panels are evacuated.
4. The material has to be as impermeable as possible to infrared radiation. This is necessary to reduce the radiation transfer in the material to reach a very low conductivity value of the panel.

Many organic and inorganic insulation materials with an open cell structure are available to use as a core for VIPs. For each of them, a specific heat conductivity can be defined (IEA/ECBCS 2005a, Kwon et al. 2009) as a function of the gas pressure, as shown in Fig.4.

λ (W/(mK))

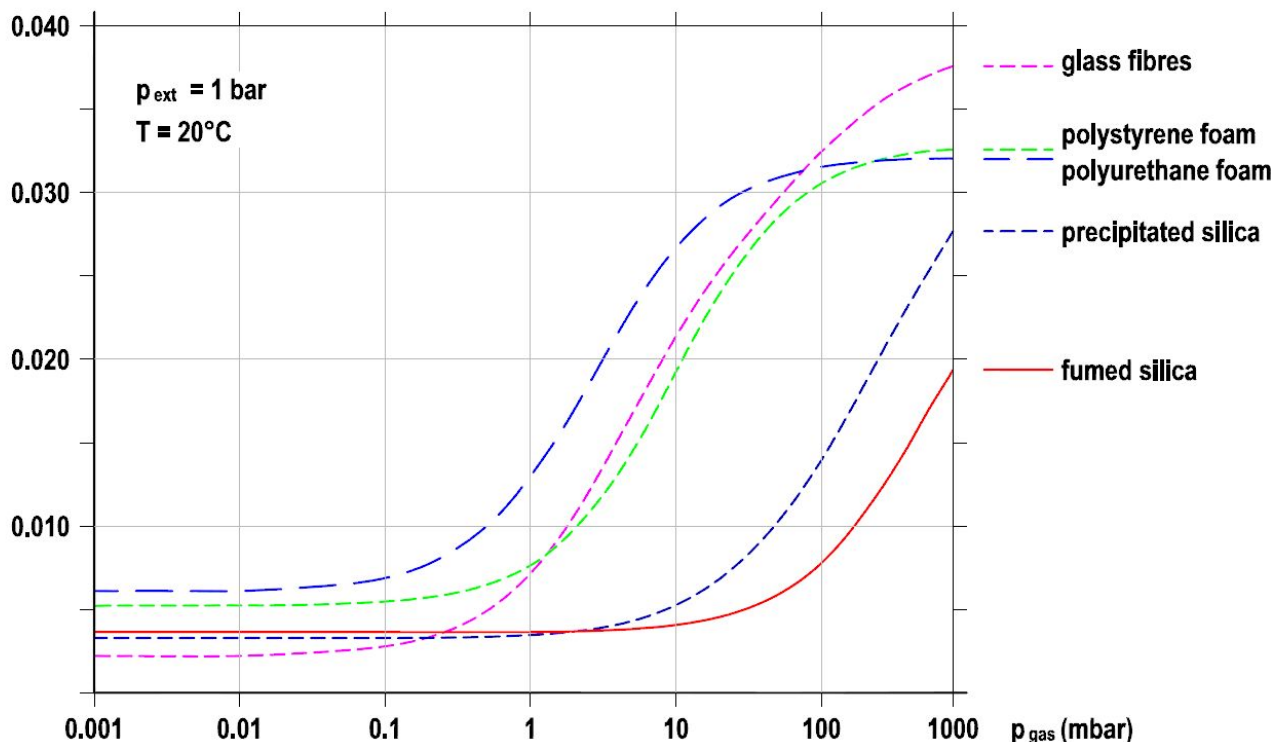


Fig.4. Thermal conductivity of different insulation materials as function of the atmospheric pressure (redrawn from IEA/ECBCS 2005a). Notice that the heat conductivity of fumed silica only rises above 50 mbar and that aerogel has a low thermal conductivity at the atmospheric pressure of 1 000 mbar.

Figure 4 illustrates clearly that the use of conventional insulation as a core material for VIPs results in the necessity of a very high quality of vacuum (~0.1 mbar). Common organic envelope materials can not maintain this inner pressure for a long period: A rapid intake of air through the envelope will occur, resulting in a fast

increase of the thermal conductivity. Solutions to maintain this high quality of pressure almost always go together with an envelope material with a higher thermal conductivity.

A material with very good achievement quality is pressed powder boards made of fumed silica (as shown in Fig.4), a fumed silicon dioxide SiO_x that is generally regarded for its unusual properties. It has a low conductivity close to 0.003 W/(mK) up to 50 mbar and has a conductivity of 0.020 W/(mK) at ambient pressure in dry conditions, half the thermal conductivity of traditional insulation materials. The physical, hygric and thermal properties of this material will be discussed.

1.2.1. Physical properties of fumed silica

The bulk density of a fumed silica material is in the range of 160 to 220 kg/m³ which is nearly one order of magnitude higher than the density of a traditional insulating material, but similar in weight as conventional insulation if the same total thermal resistance of a layer is assumed. Despite this, their porosity is higher than 90 % what means that the specific surface area is very high: Commercial products have a specific surface area of 100 to 400 m²/g. However, measurements done by Morel et al. (2007) have shown that this specific surface area can decrease with values up to 20 % by ageing due to high relative humidity or high temperatures

Important for VIP core materials are the pore size distribution PSD and the largest pore size diameter: These define the range of vacuum necessary for the low thermal conductivity. Fumed silica materials have their largest pore size (300 nm) in the same order of magnitude as the mean free path of air molecules at standard temperature and pressure (70 nm). Hereby, the material gas conductivity is even at atmospheric pressure affected by his fine structure.

The mean value of the specific heat of dry fumed silica is 850 J/(kgK), which is approximately the same value as a traditional insulation material like glass wool.

Powder boards of fumed silica have also a very low intrinsic permeability κ in the range of $2.6 \cdot 10^{-5}$ to $3.0 \cdot 10^{-5}$ m²/s at a pressure gradient of 1 bar (Schwab 2004).

1.2.2. Water vapour adsorption of fumed silica

The adsorption-isotherm of fumed silica is derived (IEA-ECBCS 2005a) by fitting experimental results with an analytical model:

$$u = \frac{0.01721\varphi}{0.08356 + \varphi} e^{2.82429\varphi^{2.26663}} \quad (7)$$

However, the sorption-isotherm of fumed silica is approximately linear with the relative humidity for a relative humidity RH up to 50 % (see Fig.5). The slope of the sorption-isotherm can be approximated as defined in Eq.8 within this range, as determined by Schwab (2004) :

$$u(\varphi) = \alpha\varphi \quad \text{where} \quad \alpha = \frac{du}{d\varphi} = 0.08 \quad (8)$$

By considering the inverse function $\varphi(u)$ of the sorption isotherm $u(\varphi)$ in Eq.8, the internal water vapour pressure in the material can be defined in function of the water content as $p_{wv} = \varphi(u)p_{wv,sat}(T)$ with $p_{wv,sat}$ the saturation pressure of water vapour at temperature T. The amount of absorbed water in fumed silica powder boards will stay low ($u < 0.05$ kg/kg) for a relative humidity lower than 60 %. In this range, the water molecules will only cover the surface of the silica grains by adsorption. However, for a higher humidity up to 95 % will an exponential increase due to the capillary condensation in the small pores be noticed. An important condition for building insulation is the moisture equilibrium at a relative humidity of 45 %, the average relative humidity of an indoor climate: A value u of approximately 0.04 kg/kg is found for fumed silica (see Fig.5) which means that the gravimetric water content of the VIP core would never exceed this value. This value matches approximately the saturation levels between 0.03 and 0.07 kg/kg that are found by Schwab et al. (2005e) in applied VIPs in typical German constructions (different values were found, depending on the structure and orientation).

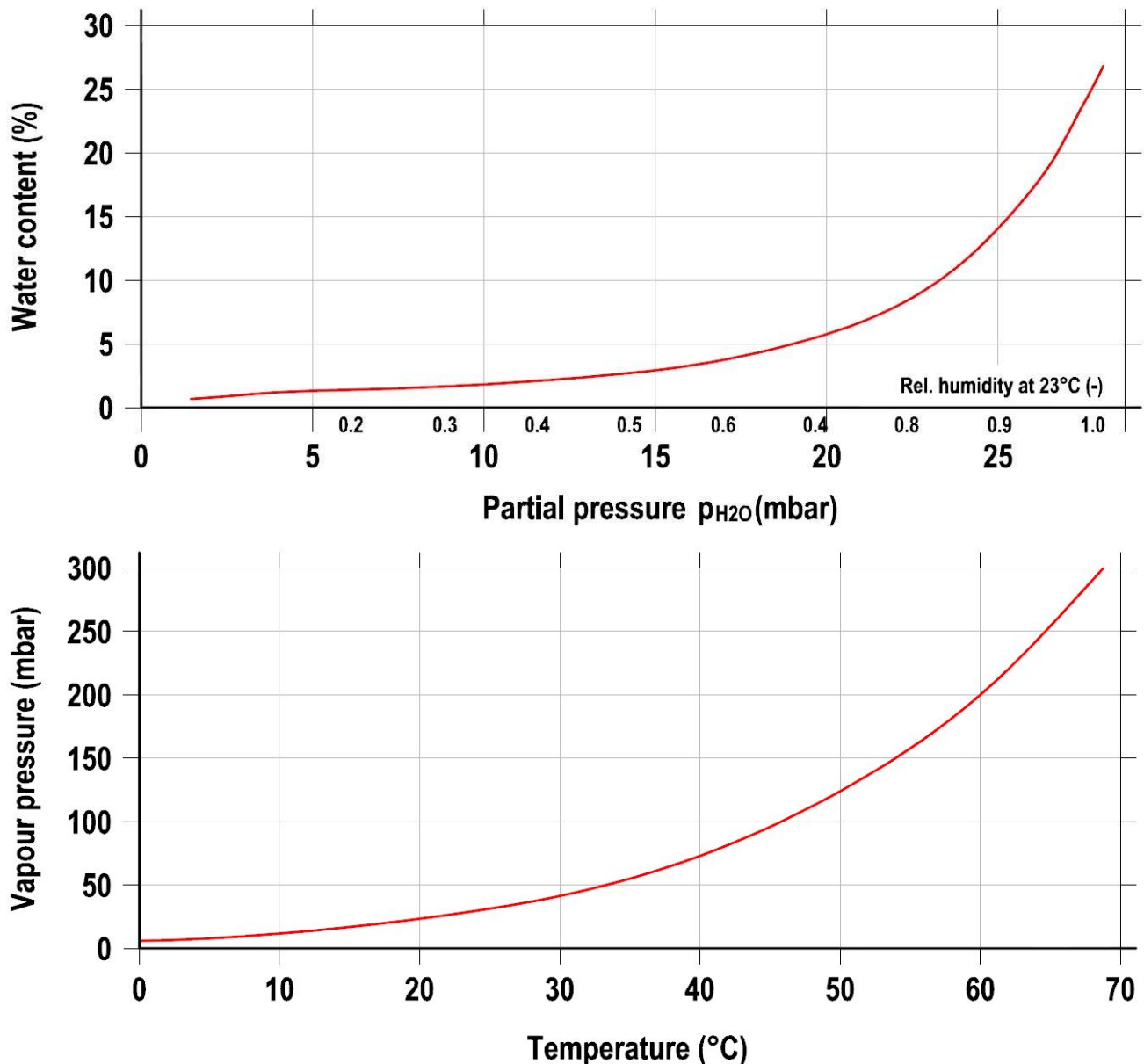


Fig.5. The adsorption isotherm $\chi(p_{H_2O})$ of fumed silica [upper] and the partial water vapour pressure $p_{H_2O}(T)$ of saturated air [bottom] if water vapour is allowed to enter the core material (redrawn IEA/ECBCS 2005).

This water content equilibrium, reacting on the changing outdoor and indoor conditions, will affect the thermal conductivity of the core material: An increasing water content of the core material will result in an increase of the thermal conductivity of the VIP. The influence will be discussed in the next subchapter, because it is important for estimating the service life of the VIPs.

1.2.3. Thermal Conductivity of fumed silica

It has been said that the good thermal achievements of fumed silica are caused to the structure of the material. The free air conduction $\lambda_{g,0}$ in Eq.4 will be reduced due to the Knudsen effect if we consider the narrow maximum pore size in porous silica of 300 nm: The mean free path of air l_{mean} in normal conditions (23°C and 1 atm) is 70 nm which means that the Knudsen effect will strongly reduce the gas conductivity in fumed silica with approximately 40 % at ambient pressure. Fumed silica has a typical value $P_{1/2}$ of ~630 mbar while a conventional PUR foam has a $P_{1/2}$ of 2.6 mbar, which proves again that fumed silica is very suitable as a core material in VIPs.

THE DEPENDENCY ON TEMPERATURE of the thermal conductivity is commonly described as (Caps 2000, Hostler et al. 2008, Reim et al. 2005):

$$\lambda_{vac}(T) = \lambda_{cd}(T) + \frac{16}{3} \frac{n^2 \sigma T_r^3}{E(T_r)} = \lambda_{cd}(T) + \lambda_r(T_r) \quad (9)$$

where n is the index of refraction (≈ 1 for low density fumed silica), σ the Stefan-Boltzmann constant, λ_{cd} the conductivity of the solid matrix, T_r the ‘‘Rosseland’’ average temperature within the insulation material and where E [m^{-1}] is the extinction coefficient. T_r (Caps 2000) and E [m^{-1}] (Hostler et al. 2008, Reim et al. 2005) are described as:

$$T_r^3 = (T_1 + T_2) \frac{T_1^2 + T_2^2}{4} \quad \text{and} \quad ET_r = e^*(T) \rho_{eff} = \frac{\rho_{eff} K}{\rho_c} \quad (10)$$

where T_1 and T_2 are the temperatures of the VIP surfaces and where ρ_{eff} the effective density of the porous material, $e^*(T)$ the specific extinction coefficient as a temperature-dependent material value characterizing the radiative attenuation. Furthermore, the extinction coefficient E in Eq.9 is the reciprocal of the mean free path of length l_{ph} of thermal photons and has to be estimated by fitting experimental data: For opacified silica cores, a value of $l_{ph} \approx 100 \mu m$ is given by Fricke et al. (2006) which means that VIPs of 2 cm block off infrared radiation. More attention to the function of opacifiers in fumed silica cores will be paid in Ch.1.4.

Equation 9 is introduced by Hottel (1967) and is applied to VIPs by Brodt (1995), where the second term of the equation was defined as the radiative heat conductivity λ_r . The equation is valid for all grey media, materials for which the mean free path for photons is independent of their wavelength. It must be noticed that also the thermal conductivity λ_{cd} of the core skeleton in Eq.9 depends on the temperature. This dependency can be approximated by $\lambda_{cd} \sim T^a$ with a between 0.5 and 1.0 depending on the material. However, the influence of temperature on λ_{cd} will be much smaller than the effect on λ_r and will be mostly neglected. An equation for this dependency is given (Caps et al. 2001), assuming that the dependency for fumed silica is similar as for silica glass:

$$\lambda_{cd}(T) = 0.0021 \left[(-8.5 \cdot 10^{-12}) T^4 + (2.1 \cdot 10^{-8}) T^3 - (1.95 \cdot 10^{-5}) T^2 + (0.00883) T \right] \quad (11)$$

Measurements (Schwab 2004, IEA/ECBCS 2005a) showed us that the thermal conductivity λ_{cd} of the solid matrix of commercial fumed silica products in Eq.9 comes out in the range of 0.0021 to 0.0034 W/(mK) and that the radiative heat conductivity can be found between 0.001 and 0.004 W/(mK) at a low gas pressure of 1 mbar, depending on the temperature.

Considering the application temperatures for building insulation, a linear approach can be made for the temperature dependency of the thermal conductivity (Heinemann 2005) taking into account the effect on the solid conduction and the effect on radiation:

$$\lambda_{vac,dry} = (0.0124T + 0.0808) \cdot 10^{-3} W / (mK) \quad (12)$$

THE DEPENDENCY ON WATER CONTENT of the thermal conductivity of fumed silica is measured once (IEA/ECBCS 2005a, Schwab 2004, Beck et al. 2007) and shows a significant increase of heat transfer through powder boards of fumed silica with an increasing water content. For the specific static circumstances and panel sizes of the tests, an increase of approximately 0.5 mW/(mK) per mass percent of content is observed in both papers. However, the value is corrected by Schwab (2004) by deducting the increase of the gas conductivity due to the water vapour pressure from the total thermal conductivity increase to come to a lower limit of 0.29 mW/(mK) per mass percent water content. For the moisture equilibrium u of 0.04 kg/kg at ambient conditions of 50 % relative humidity, a final thermal conductivity of 6 mW/(mK) can be found, starting with an initial thermal conductivity of 4 mW/(mK) for the dry core.

Because of the moisture increase in a VIP, three more types of heat transport are possible: Heat conduction via water vapour with a partial pressure p_{wv} , heat conduction by adsorbed water at the inner surface of the core and heat transfer via evaporation of adsorbed water, diffusion and condensation of water vapour. Measurements (Schwab et al. 2005d, Beck et al. 2007) show us the results of the increase of thermal conductivity per mass percent water content for a panel size of 30 cm x 30 cm x 1 cm at a mean temperature of 10°C, what makes it possible to define the thermal conductivity as function of the water content as in Eq.13. However, the total effect of moisture on the thermal conductivity of a vacuum insulation panel is much more complex than the mentioned linear relationship. Complex non-linear relations between thermal

conductivity, relative humidity, water vapour pressure and temperature determine the effect of the moisture content on the overall thermal conductivity of VIPs (Beck et al. 2007, Heinemann 2008, Morel et al. 2007, Coquard & Quenard 2007).

$$\frac{\partial \lambda_c}{\partial u} \approx 0.05 \text{ W / (mK)} \quad (13)$$

The total water content in a VIP will not be distributed uniformly in the VIP (Beck et al. 2007, Heinemann 2008, Platzer 2007): The partial water vapour pressure p_{wv} will vary with the temperature gradient, conform the different $p_{wv,sat}$ for the corresponding temperatures. This distribution is non-linear but can be approximated as linear for VIPs within a low temperature spread $\Delta T < 20$ K. The spreading of the moisture is shown in Fig.6 and the upper limit of the p_{wv} (and as consequence of λ_{wv} in Eq.14) is given by the coldest point in the VIP.

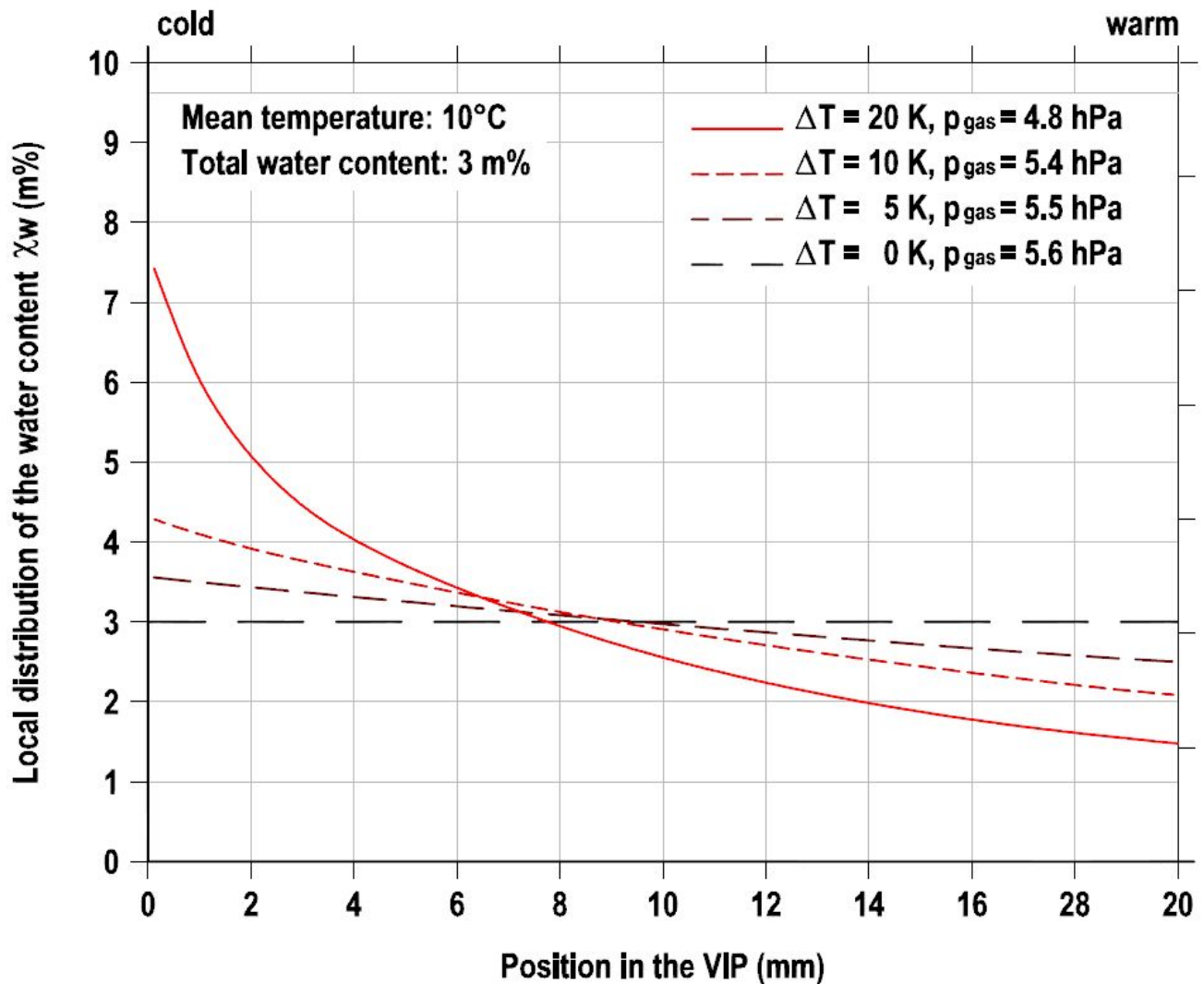


Fig.6. Moisture distribution based on numerical simulations in a VIP with a thickness of 20 mm and a total water content of 0.03 kg/kg (redrawn from Heinemann 2008). Note that the graph should be corrected including gravity.

The consequences of this distribution can be clarified by expanding Eq.2 for dry VIPs with two more terms to include the effect of moisture:

$$\lambda_{vip,moist} = \lambda_{cd,s} + \lambda_{rad} + \lambda_g + \lambda_{humid}(u_w(T(x))) + \lambda_{wv} \quad (14)$$

where λ_{humid} is the thermal conductivity by conduction of adsorbed water in the core and λ_{wv} the thermal conductivity by heat conduction in water vapour. As shown in Fig.6, λ_{humid} will depend on place due to the dependency of moisture content and the spreading of it. As a consequence, the total thermal conductivity of a

humid VIP should be written as different thermal conductivities in series or as a Riemann sum of $\lambda(x)$ divided by the panel thickness.

However, the water gradient due to the temperature spread in a VIP will lead to a liquid transport back to the warm side. As consequence, the pressure gradient in the VIP should be in equilibrium with a vapour transport equalling the liquid transport under stationary conditions. This rearrangement of moisture is a latent heat transport from the warm side of the VIP to the cold side and introduces another type of heat transport in the VIP, called the 'heat pipe effect'.

The effect on the thermal conductivity can be expressed using Fourier's second law expressed in Eq.15 (Beck et al. 2007) describing the heat flow due to the temperature gradient and the enthalpy transport due to the water vapour flow and using Eq.16 describing the time and position dependency of the moisture content due to an effusion process driven by the potential ρ/\sqrt{T} and a liquid transport due to a water gradient:

$$\rho c_c \frac{\partial T}{\partial t} = \frac{\partial \lambda(u(x))}{\partial x} \frac{\partial T}{\partial t} + h_D \frac{\partial}{\partial x} D_E \frac{1}{\sqrt{T}} \frac{\partial p}{\partial x} \quad (15)$$

$$\rho \frac{\partial u}{\partial t} = \frac{\partial}{\partial x} D_E \frac{1}{\sqrt{T}} \frac{\partial p}{\partial t} + \frac{\partial}{\partial x} D_K \frac{\partial u}{\partial x} \quad (16)$$

where h_D is the enthalpy, D_E the effusion transport coefficient and where D_K is the liquid transport coefficient. The result of the equations can be seen in the corrected graph in Fig.6 where the assumed water content distribution is corrected by the liquid transport. Fitting both models of Eq.15 and Eq.16 with experimental data from Beck et al. (2007) resulted in

$$D_E = 1.05 \cdot 10^{-11} \text{ kg} \sqrt{\text{K}} / (\text{msPa}) \quad \text{and} \quad D_K = 4.03 \cdot 10^{-7} \text{ kg} / (\text{msPa}) \quad (17)$$

and a linear model for the dependency on the moisture content described as

$$\lambda_{vip,moist}(u) = \lambda_{vip,dry} + u \left[\frac{\text{kg}}{\text{kg}} \right] \cdot 0.0024 \left[\frac{\text{W}}{\text{mK}} \right] \quad (18)$$

It must be noticed that this thermal conductivity increment of $0.24 \cdot 10^{-3} \text{ W}/(\text{m}^2\text{K})$ per mass percent water content in the VIP retrieved in (Beck 2007) approximates closely the corrected thermal conductivity increment of $0.29 \cdot 10^{-3} \text{ W}/\text{m}^2\text{K}$ per mass percent water of (Schwab 2004). In addition, the heat pipe effect will increase the heat transport, described by a pseudo thermal conductivity λ_{HP} . The same measurements (Beck et al. 2007) resulted in a λ_{HP} from 0.0005 up to 0.0017 $\text{W}/(\text{mK})$ for increasing moisture contents and increasing mean temperatures.

However, it is hard to predict the rate of increase of the total water content u : The increase depends on the water vapour permeance of the foil, the climatic conditions and on the sorption isotherm of the core material (defined in Eq.8 and Fig.7). So are by example different saturation levels of the core material between 0.03 and 0.07 kg/kg found in typical German conditions (Schwab et al. 2005e), depending on the considered construction and orientation. This means an increase of thermal conductivity between 0.0015 of 0.0035 $\text{W}/(\text{mK})$ with Eq.18 due to the intake of water vapour and also means that the service life of a VIP can not be defined unambiguous, but has to be expressed in function of the application conditions.

The same measurements (IEA/ECBCS 2005a) show a linear relation as in Eq.19 between the increase of the internal total gas pressure (see Fig.4) and thermal conductivity in the range up to 100 mbar. The prediction of the increase of internal air pressure and water content in building constructions (Schwab et al. 2005e) is based on the knowledge of the OTR and WVTR of the complete VIP envelope and on the atmospheric conditions as driving force. These envelope properties have been subject of research in (Schwab et al. 2005c) to come to a model of service life prediction and will discussed in Ch.3.2.

THE DEPENDENCY ON GAS PRESSURE of the thermal conductivity of fumed silica is shown in Eq.4 and the same measurements (IEA/ECBCS 2005a) show a linear relation between the increase of the internal gas pressure and thermal conductivity in the range up to 100 mbar:

$$\frac{\partial \lambda}{\partial p_g} \approx 3.5 \cdot 10^{-7} \frac{W}{mKPa} \quad (19)$$

This means a thermal conductivity increase of 0.001 W/(mK) for a dry gas pressure increment of 30 mbar. Analytical models on both effects (an increasing moisture content and an increasing inner gas pressure) and the influence of the effects on each other are discussed in detail in Ch.3 about the prediction of the VIP service life.

1.2.4. Fire Behaviour

Powder boards of fumed silica are not flammable M1 according to the French Standard NF P 92-510, which can be compared to the 'non flammable' label A1 conform with the new European classification norms EN 13501-1 and the EN ISO 1182. Commercial available VIPs have a flammability label B2 according to DIN 4102, which is the lowest label of non flammability that is accepted within building applications.

1.3. The envelope

The outer envelope is one of the critical components of a VIP and is responsible to maintain the vacuum in the panel.

The envelope of VIPs is composed off multi layer films covering the whole element, including the edges. The use of an aluminium layer in these multi layer films is common because of the very low gas and water vapour permeation. Due to the relatively high thermal conductivity of such an envelope, the heat flux increases at the edges and corners. Because of this, the design of a VIP envelope will not only be done from the point of view of gas and water vapour tightness, but also from the point of view to minimize these thermal edge losses.

The multilayer films usable for VIP envelopes consist of different layers with an overall thickness of 100 to 200 μm . Currently, three different film types are being used for VIP envelopes:

- Metal foils consisting of a central aluminium barrier layer, laminated between an outer PET layer for scratch resistance and an inner PE sealing layer. (see foil type 'a' in Fig.7)
- Metallized films made from up to three layers of aluminium coated PET films and an inner PE sealing layer. (see foil types 'b,c,d' in Fig.7)
- Polymer films with different plastic layers laminated to each other. The gas and vapour permeation rate through these materials is higher than with metal or metallized films. These films are only useful if the required lifetime is not too extensive or if special getters are integrated in the VIPs (see also Ch.1.4).

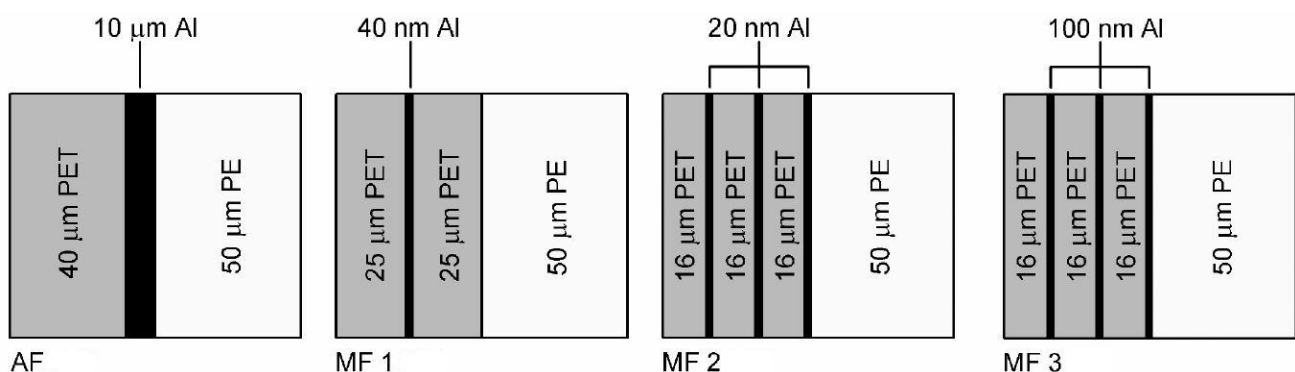


Fig.7. Cross sections of some typical envelope materials for VIPs, commonly named AF (a metal film), MF1 (a single layer metallized film), MF2 and MF3 (both three-layer metallized films) in scientific literature (Willems & Schild 2006). However, one must note that different types of foil with the same name are used in literature (IEA/ECBCS 2005; Brunner et al. 2006).

The permeability κ [$\text{m}^2/(\text{sPa})$] for air and moisture of the envelope material is one of the determining criteria for the service life of the VIP: The pressure in the VIP should not rise above 100 mbar after 30 to 50 years as a first rule. The permeation mechanisms of gases and water vapour through a pure polymer film depend on the gas solubility coefficient S [$\text{m}^3(\text{STP})/(\text{m}^3\text{Pa}^{-1})$] and the gas diffusion coefficient D [m^2/s] of the foil material.

The permeability is then given by their product $\kappa = DS$ (IEA-ECBCS 2005a). The total permeability of a laminated foil can be calculated with the permeability's κ_i of the single layers of which the laminate consists (analogue to Kirchhoffs Law for electrical conductivities in series):

$$\frac{1}{\kappa_{tot}} = \sum \frac{1}{\kappa_i} = \sum \frac{1}{D_i S_i} \quad (20)$$

The permeability of air and the permeability of water vapour through a barrier layer depends on two different mechanisms: The gas permeation predominantly occurs at macroscopic defects in the range of $0.1 \mu\text{m}^2$ to $1 \mu\text{m}^2$, while the gas permeation through the bulk material is practically not existing. In contrast to the dominating factor of macroscopic defects for gas permeation, the permeation of water vapour depends also on the microstructure of the layer: Capillaries can be formed at microscopic defects and grain boundaries.

To obtain a low permeable laminate by using the synergy effect, the two main technical requirements are

- a low density of (microscopic) defects in the barrier layer and
- a polymer possessing a low permeability next to the vacuum coated layer.

The barrier properties of a layer material are expressed in terms of the water vapour transmission rate WVTR and the gas transmission rate GTR. Edge and corner effects have been examined on the WVTR and the GTR in VIPs (IEA/ECBCS 2005a, Schwab et al. 2005c), while also deterioration by heat and moisture loads at defects has been subject of research (Brunner et al. 2006, 2008). The characteristics of these WVTR and GTR will be further discussed in Ch.3.2 about gas pressure and moisture content increment in VIPs.

A typical VIP envelope foil with three metallized layers has a air transmission rate ATR of 2 to $5 \cdot 10^{-10}$ $\text{m}^3(\text{STP})/(\text{m}^2\text{day})$ at 23°C and a 50 % relative humidity and a water vapour transmission rate WVTR of 1 to $5 \cdot 10^{-6}$ $\text{kg}/(\text{m}^2\text{day})$ at 23°C and 85 % relative humidity (Brunner et al. 2008). However, measurement standards do not yet exist for the GTR and WVTR of vacuum insulation foils because it was impossible to measure these extremely low ranges of transmission until in IAE/ECBCS (2005a). Moreover, fast measurement methods for very low gas transmissions are proposed in (Caps et al. 2008) based on the Helium transmission of the foils.

The influence of the choice of envelope material on the service life and on the thermal bridge effects will be discussed in Ch.2 and Ch.3.

1.4. Getters, desiccants and opacifiers

Important for the service life of the VIPs is maintaining the inner vacuum. To increase their service life, getters and desiccants are often added in the VIPs: Continuously adsorbing the gasses (getters) and the water vapour (desiccants) in the VIP core material, they prevent the increase of the internal gas and vapour pressure. The inner water vapour pressure and gas pressure will stay equal to the manufacturing conditions until the capacity of the getters and desiccants is reached. As a consequence, they prevent the increase of the thermal conductivity due to the higher pressure and they increase the lifetime of the VIP. Some core materials of VIPs have the possibility to fulfil the function of getters and desiccants themselves, but not all of them. This makes it important to add these chemicals to the core although they decrease the thermal resistance of the VIP and increase the manufacturing costs.

Opacifiers are added to the fumed silica in order to make it opaque to infrared and hereby to reduce the radiative conductivity to a low level. A common opacifier for fumed silica cores is silicon carbide powder.

2. Thermal bridges

It is clear that VIPs cannot be seen as a material but that they have to be seen as a system of materials and properties. These have all their influence on the total thermal performance and the possible applications of vacuum insulation panels. A lot of research has been done on reducing and estimating the thermal bridging and on increasing and estimating the service life time.

The better the insulation material the higher the importance of the heat flux due to thermal bridges. In a assembly insulated with vacuum insulation panels, we can notice three levels of thermal bridges: The level of the VIP due to the barrier envelope, the level of the building component (in VISs) and structural thermal

bridges. The thermal bridge due to the envelope has been yet subject of many researches, while the structural thermal bridges with VIP insulated details has not yet been subject of large scale studies. The first two types of thermal bridges will be discussed in detail in the next two chapters.

2.1. Thermal bridge effect on the scale of VIPs

Thermal bridges on the VIP level are due to the continuing of the thin high barrier envelope from the cold to the warm side of the VIP and due to small air gaps between two adjacent panels. Both have a not unimportant influence on the overall thermal performance of a VIP insulation layer: Due to this thermal bridge, the effective conductance Λ_{eff} of the vacuum insulation panel is higher than the centre-of-panel thermal conductance that is determined in Ch.1.2.1:

$$\Lambda_{\text{eff}} = \Lambda_{\text{cop}} + \psi_{\text{edge}} \frac{P}{A} \quad (21)$$

The linear transmittance ψ_{edge} in this equation depends on the panel thickness d , the centre-of-panel thermal conductivity λ_{cop} , the barrier film thickness t_f and the equivalent foil thermal conductivity λ_f . This will result in different values for ψ_{VIP} depending on the laminate layers and their thermal properties.

An analogue expression can be written with the direct heat transmission coefficient H_{direct} of an assembly (Schwab et al. 2005a, Ghazi et al. 2004) or insulation layer according ISO 14683:2007(E):

$$H_D = \sum_i U_i A + \left(\sum_k \psi_{k,\text{line}} l_i + \sum_j \chi_{j,\text{point}} n_j \right) \quad (22)$$

The value U_i of a wall without the thermal bridges, can be written as:

$$U_i = \left\{ \frac{1}{\alpha_{\text{in}}} + \sum_l \frac{d_l}{\lambda_l} + \frac{1}{\alpha_{\text{out}}} \right\}^{-1} = \left\{ \frac{1}{\alpha_{\text{in}}} + \sum_l \frac{1}{\Lambda_l} + \frac{1}{\alpha_{\text{out}}} \right\}^{-1} \quad (23)$$

where α_i is the heat transmission coefficient at boundary surface i . This show us that the influence of the thermal bridge depends on the composition of the other layers of the wall and on the heat transition coefficients at the surface. Notice that ψ_{line} in Eq.22 will be zero for the VIP edge if U_i is calculated with the Λ_{eff} from Eq.21.

2.1.1. Thermal bridging due to VIP envelope

Measurements (IEA/ECBCS 2005b, Schwab et al.2005a) show values of the linear transmittance ψ_{edge} from 0.001 to 0.400 W/(mK) and an effective conductivity λ_{eff} in the range of 0.0051 to 0.0086 W/(mK) for VIPs with a panel size of 1.00 m by 0.50 m by 0.02 m and with a centre-of-panel conductivity λ_{cop} of 0.004 W/(mK), depending on the properties of the envelope material. This wide range of the data show us the importance of the prediction of the influence of the panel edges to come to a calculation value of the overall thermal conductivity of an insulation layer or assembly. Analytical models (Tenpierik & Cauberg 2007a, Tenpierik et al. 2008, Ghazi et al. 2004) and numerical investigations (Willems et al. 2005, Quenard & Sallée 2005, Bundi et al. 2003, Ghazi et al. 2004, 2005) have been proposed on the calculation and prediction of this thermal bridge effect. Numerical investigations or parts catalogues are more likely to be used to be used to estimate thermal bridge effects in the common application of VIPs (Fine 1989, Glicksman 1991, Glicksman et al. 1991, Kollie et al. 1991, Degen et al. 1992, Griffith & Arasteh 1995, Mukhopadhyaya et al. 2008), while analytical models are of more interest to be programmed in an ordinary spreadsheets.

2.1.1.a. Analytical Models

Originally, the high barrier laminate consisted of stainless steel or glass (Glicksman & Burke 1991) envelopes, aluminium foils or laminated polymer films but gradually developed into laminated metallized polymer films with a low GTR and WVTR to decrease the thermal conductivity of the foil. The analytical models (Tenpierik & Cauberg 2007a, Tenpierik et al. 2008) consider the thermal bridges due to the VIP envelope and they are

developed to understand the systems of heat transfer at the panel edges, which is impossible if only numerical simulations are used.

The models of [Tenpierik and Cauberg \(2007\)](#) start with the same formulae of the direct heat transmission coefficient as in Eq.22 as [Schwab \(2005a\)](#) and ISO 14683:2007(E). The third term of the equation with the point thermal transmittance is neglected in the model, assuming that the corner thermal bridge effect is much smaller than the effect of the panel edge. The equation clearly shows us the importance of the size and shape of the VIP panels: The larger the panels and the smaller the perimeter length, the smaller is the influence of the linear thermal conductivity of the barrier envelope on the overall U-value of the insulation layer. In many older texts, a minimum size of 0.50 m by 0.50 m for VIPs is proposed. Two single step analytical models for estimating the $\psi_{vip,edge}$ are found ([Tenpierik & Cauberg 2007a](#)).

- THE SIMPLIFIED MODEL of [Tenpierik & Cauberg \(2007\)](#) starts from the assumption that the thermal conductivity of the core material λ_c equals 0.0 W/(mK), which is valid as long as λ_c or the ratio λ_c/λ_f is sufficiently small. This equals the assumption that the energy flux through the bulk material is zero and hereby that every energy flux at the edge is caused by the thermal bridge of the barrier envelope. The equation for the linear transmittance is then given by

$$\psi_{vip,edge,0} = \left\{ \frac{1}{\sqrt{\alpha_1 d_f \lambda_f}} + \frac{\varphi d_p}{d_f \lambda_f} + \frac{1}{\sqrt{\alpha_2 d_f \lambda_f}} \right\}^{-1} \quad (24)$$

where α_n is the heat transmission coefficient at boundary surface n, d_p the thickness of the VIP, d_f the thickness of the laminate, d'_f the thickness of the laminate at the panel edge, φ the ratio of d_f/d'_f , and λ_f the equivalent laminate thermal conductivity of the VIP laminate.

- THE ADVANCED MODEL of [Tenpierik & Cauberg \(2007\)](#) is given to make a general equation for $\psi_{vip,edge}$ for models for which the previous assumption in the simplified model can not be made. The equation for the linear thermal transmittance of the VIP envelope is here formulated as:

$$\psi_{vip,edge,0} = \left\{ \frac{\lambda_c}{\sqrt{\alpha_1 d_p}} + 1 + \frac{\lambda_c}{\sqrt{\alpha_2 d_p}} \right\}^{-1} \cdot \left[\frac{\alpha_1 (N_2^2 - B)}{\frac{\varphi d_p \lambda_f}{\lambda_f'} (N_1^2 N_2^2 - B^2) - \lambda_1 \sqrt{N_1^2 N_2^2 - B^2} \left(\frac{2B}{\sqrt{D}} - 1 \right) - \lambda_2 \sqrt{N_1^2 N_2^2 - B^2} \left(1 - \frac{2B}{\sqrt{D}} \right)} \right] \quad (25)$$

where λ'_f is the thermal conductivity of the laminate at the panel edge. The result of this equation is graphically shown in Fig.8. A distinction is made between the thermal conductivity of the envelope foil and the VIP edge to include the possibility that the edges are reinforced, e.g. with a tape. In Eq.25 are N_i and B parameters which are defined as:

$$N_i = \sqrt{\frac{\alpha_i}{d_f \lambda_f} + \frac{\lambda_c}{d_f \lambda_f d_p}} \quad \text{and} \quad B = \frac{\lambda_c}{d_f \lambda_f d_p} \quad (26)$$

and where λ_1 and λ_2 are eigenvalues of the linear system of differential equations derived ([Tenpierik & Cauberg 2007a](#)) to represent the thermal phenomenon. Two remarks can be given on these Eqs.24 and 25: If the limit for Eq.25 is taken for $\lambda_c \rightarrow 0$, the Eq.24 for zero thermal conductivity of the core material appears, and both Eqs.24 and 25 derive the model of the linear thermal transmittance of the edge of one single panel. If two panels are adjoined, the sum of the linear thermal transmittances of both panels have to be taken, to come to the total linear thermal transmittance of the joint.

- THE PARAMETERS which can influence $\psi_{vip,edge}$ can now be discussed. The linear thermal transmittance of the VIP envelope depends on four parameters: The laminate thicknesses d_f and d'_f , the laminate thermal conductivity λ_f , the core material thermal conductivity λ_c and the panel thickness d_p .

The influence of the laminate material on the $\psi_{vip,edge}$ is dual: The laminate thickness d_f has an influence and the laminate thermal conductivity λ_f has his influence (see Fig.8). First, the linear thermal transmittance $\psi_{vip,edge}$ increases for an increasing laminate thickness d_f : An increase in laminate thickness from 6 to 20 μm can increase the $\psi_{vip,edge}$ with 130 % (Tenpierik & Cauberg 2007a). Secondly, the linear thermal transmittance $\psi_{vip,edge}$ increases for an increasing laminate thermal conductivity λ_f .

The influence of the core material is unambiguous in Eq.25: An increasing thermal conductivity of the core material λ_c makes the linear thermal transmittance decrease (see Fig.9). The effect of this is stronger as the panel thickness is smaller. The heat flux through the bulk material of the VIP will become larger, which makes the relative importance of the heat flux through the panel edge decrease.

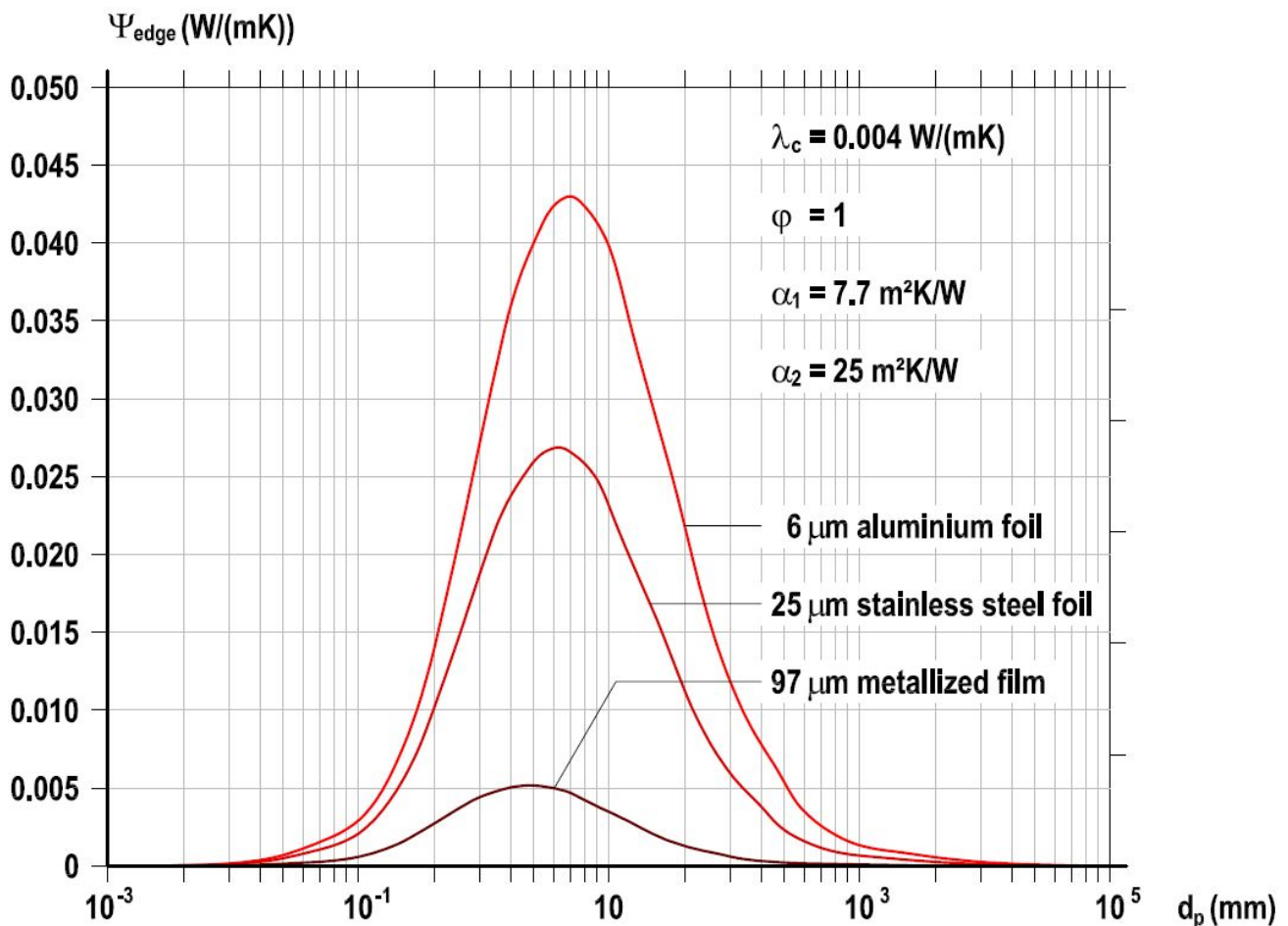


Fig.8. Behaviour of the linear thermal transmittance as function of the panel thickness d_f for different VIP envelopes and for a centre-of-panel thermal conductivity of 0.004 W/(mK) (redrawn from Cauberg & Tenpierik 2007).

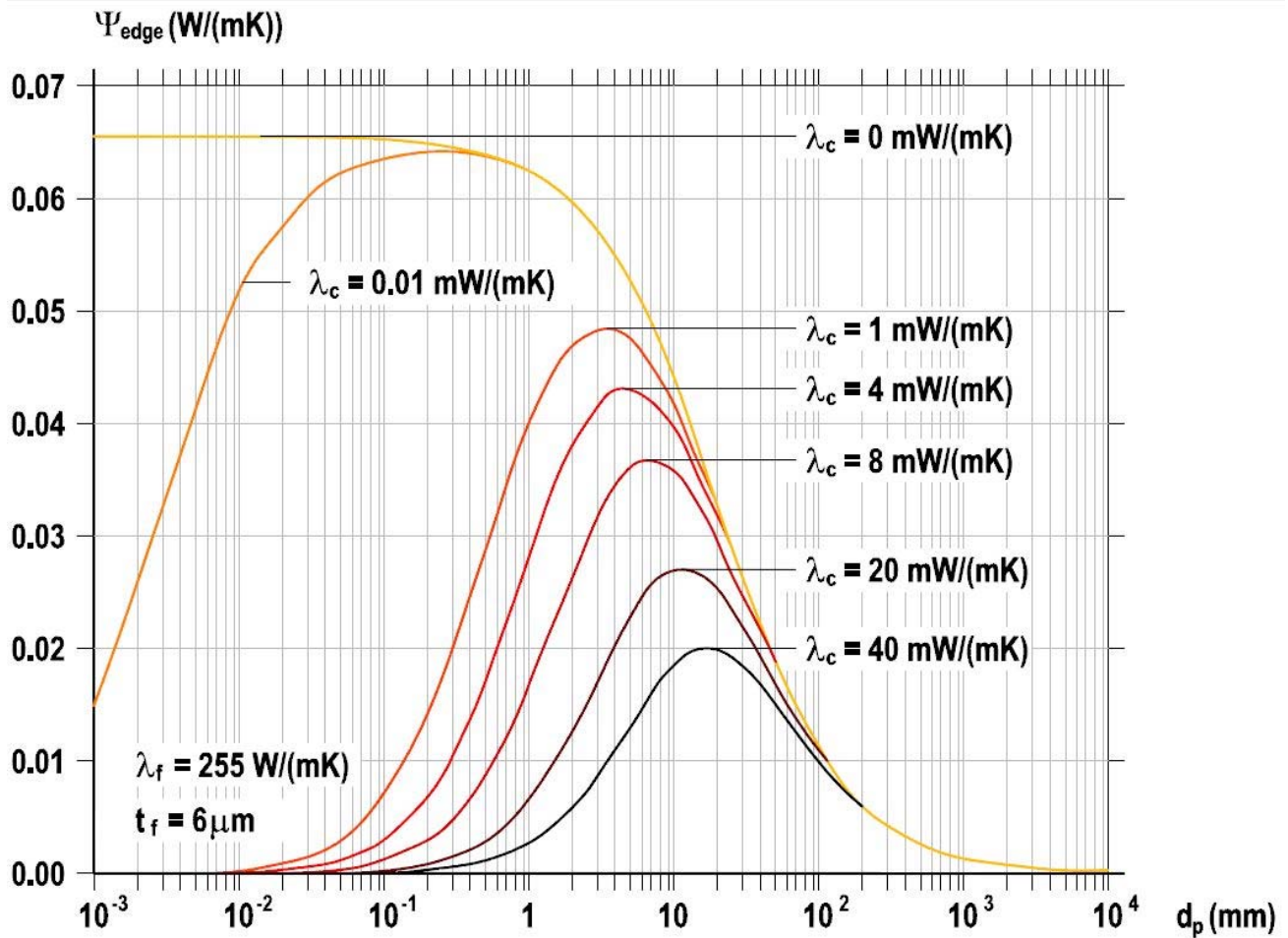


Fig.9. Behaviour of the linear transmittance as function of the panel thickness for different centre-of-panel thermal conductivities and a 6 μm thick aluminium barrier (redrawn from Cauberg & Tenpierik 2007).

The influence of the seam modelling can be calculated with the analytical model of Tenpierik & Cauberg (2007) with the right choice for the ratio ϕ . The ratio $\phi = d_p/d'_f$ can be used to integrate the thickness difference in the laminate at the seam, but a limitation to this thickness d'_f of the panel edge has to be introduced: If this thickness increases, an additional heat flow over the width of the foil has to be considered. However, this limitation will disappear when using the analytical model for building components (see also Ch.2.2).

- THE LIMITS OF THE ANALYTICAL MODELS are checked by comparing model predictions with numerical data: A deviation $< 5\%$ for idealized envelopes and $< 7\%$ for realistic seams has been found. This proves that the model is a good alternative for complex numerical models to predict the linear thermal conductivity of the barrier envelope in film based VIPs with an envelope and edge thickness of 10 to 300 μm . However, significantly larger deviations were noticed for VIPs with a barrier envelope of two- or three-layer metallized films (i.e. whereas three-layer metallized films are recommended in IEA/ECBCS 2005a), a centre-of-panel thermal conductivity of 0.020 W/(mK) and a panel thickness less than 20 mm.

2.1.1.b. Numerical Simulations

Numerical simulations have been made to predict the linear thermal conductivity of the VIP envelope (van Went 2002, Bundi et al. 2003, Ghazi et al. 2005, Schild & Willems 2005a, Quenard & Sallée 2005, Schwab et al. 2005a, Tenpierik & Cauberg 2007a). Here, the overall heat flow $\phi_{q,\text{total}}$ [W] is calculated using thermal analysis software and the corresponding linear thermal transmittance is obtained from

$$\psi_{vip,edge} = \frac{\phi_{q,tot} - \phi_{q,cop}}{l^{2D} \Delta T} = \frac{\phi_{q,tot}}{l^{2D} \Delta T} - U_{cop} b_p \quad (27)$$

where $\phi_{q,cop}$ [W] is the centre-of-panel heat flow, ΔT the temperature difference, b_p the simulated panel width and where l^{2D} is the simulated length. The simulated panel width is 200 mm in older articles, but has been shown (van Went 2002) that this was not adequate to obtain adiabatic boundary conditions for AF-laminates whereas a simulated panel width of 500 mm is (Tenpierik & Cauberg 2007a, Ghazi et al. 2005).

The similarity between the results of the analytical models and the results retrieved from numerical simulations with widespread computer programs was used to prove the accuracy of the analytical model, whereas the numerical simulations have been validated previously (Nussbaumer et al. 2006).

2.1.1.c. Discussion

The result of both numerical and analytical models show us that laminated aluminium foils (foil type AF in Fig.7) have a big influence on the total overall conductance of the VIP (see Table 1): values up to 50 times higher are found for ψ_{edge} for AF-VIPs compared to aluminium coated multilayer foils if no air gaps between the panels are assumed (see Ch.2.1.2). The increase of the overall thermal conductance will range values of 360 % for this foil, while values between 2 and 44 % are found for the Al coated multilayer foils (foils MF1, MF2 & MF3 in Fig.7).

Table 1. Thermal and linear thermal conductivities [W/(mK)] of the four main foil types for vacuum insulation panels in function of the panel thickness [mm]. The values are retrieved from equation Eq.24. and slightly higher compared to the values retrieved from IEA/ECBCS 2005b due to the neglect of heat transfer through the core.

	λ_r	5 mm	10 mm	15 mm	20 mm	25 mm	30 mm	35 mm	40 mm	45 mm
AF-VIP	25	0.0760	0.0660	0.0583	0.0522	0.0473	0.0432	0.0397	0.0368	0.0343
MF1-VIP	0.38	0.0045	0.0028	0.0021	0.0016	0.0013	0.0011	0.0010	0.0009	0.0008
MF2-VIP	0.42	0.0049	0.0031	0.0023	0.0018	0.0015	0.0012	0.0011	0.0010	0.0009
MF3-VIP	0.90	0.0087	0.0059	0.0044	0.0036	0.0030	0.0025	0.0022	0.0020	0.0018

Improvements on this seam edge have been proposed in several papers: Numerical models show us (Schwab et al. 2005a, Willems et al. 2005) that the high linear thermal conductivity of the edge of these AF-VIPs can be reduced drastically by encapsulating the VIP with an other insulation material such as expanded polystyrene (EPS) or extruded polystyrene (XPS). However, the obtained values will still exceed the linear thermal conductivities of VIPs with aluminium coated multilayer foils. For these laminates, another - so far theoretical - improvement is the serpentine edge (Thorsell & Källebrink 2005, Willems et al. 2005) where the path for the heat flux is prolonged with a reduced heat flow through the edge as a result. It was proven that by optimizing the depth and increasing the amount of slots, the linear thermal conductivity of the edge can be decreased drastically. However, the practical consequences such as feasibility and thermo-hygric behaviour of this edge model are very complex and have not been studied yet.

2.1.2. Thermal bridging due to air gaps between two adjacent envelopes

Because of the irregular shapes of the VIP edge, it is possible that an air gap occurs between two adjacent VIPs. The influence of this gap was investigated (Ghazi et al. 2004, Schwab et al. 2005a) and no air leakage from one side of the panel to the other side through the gaps was assumed. It became clear that the influence of the air gap with laminated aluminium foils has a minor influence on the linear thermal transmittance for laminated aluminium foils: An increase in the range of 7 to 15 % of $\psi_{vip,edge}$ is noticed for air gaps up to 5 mm. However, an average value of $\psi_{vip,edge} = 0.320$ and 0.170 W/(mK) is noticed for panel-thicknesses of respectively 10 and 20 mm. Therefore, VIPs with laminated aluminium foils should not be used in buildings if the panel size is smaller than 1 m² due to the high relative importance of the linear transmittance of the edges.

Compared to the aluminium foil laminates, the $\psi_{vip,edge}$ changes more with the variation of the air gap when aluminium-coated multilayer foils are used: An increase in the range of 600 to 900 % of $\psi_{vip,edge}$ is noticed for air gaps of 5 mm compared to 0 mm air gaps. However, the value of the $\psi_{vip,edge}$ stays in the range of 0.012 to 0.022 W/(mK) which is a factor 10 smaller compared to laminated aluminium foils. Hereby, the gap for

aluminium coated multilayer high barrier foils should be as small as possible to make proper use of the high thermal resistance of VIPs.

2.2. Thermal bridge effect on the scale of a building component

A building component is defined as a VIP fixed in two protection skins linked with a spacer. This spacer is a link between the inner protection skin and the outer skin, which is a clear example of a thermal bridge. Numerical simulations have been done (van Went 2002, Willems et al. 2005, Quenard & Sallée 2005, Nussbaumer et al. 2005) and show us what one could expect: The lowest linear thermal conductivity ψ_{spacer} can be found with facings and spacers which have the lowest thermal conductivity and the ψ_{spacer} is in all cases higher than the calculated ψ_{edge} at the VIP level.

The best results are found for a plastic tape as a spacer (see Fig.10). However, this tape is no structural link between the two facings: Loads are transferred by gluing the facings and the VIP together and the tape will only have a safety function in case the glue fails due to ageing or in case of mechanical damage. Depending on the size of the panels and the face materials, values for ψ_{spacer} in the range of 0.001 to 0.005 W/(mK) can be found (van Went 2002, Cauberg & Tenpierik 2005a) for VIP panels with a thickness of 20 mm due to the plastic tape as a spacer.

If the protection skins on one or both sides of the VIP have a high thermal conductivity a “heat drainage effect” will occur along the surface towards the spacers. Result of this are the very high values of ψ_{spacer} for components with facings in glass or steel: Values in the range of 0.010 up to 0.020 W/(mK) (Quenard & Sallée 2005) occur for metal facings.

An extension of the model of Tenpierik & Cauberg (2007) about thermal bridges due to the high barrier envelope has been proposed to include the effect of the facing materials and the edge spacer: A heat flow over the surface of the panel edge is considered. This model is discussed in the next subchapter.

2.2.1. Analytical model of Tenpierik & Cauberg, 2008

Two modifications are made (Tenpierik et al. 2008) on the previous model to meet to the scale of a building component: First, the heat balance at the corners of the component are modified. Second, the equation for the linear transmittance is extended to include the additional heat flow through the edges. The linear thermal transmittance of the thermal bridge is now calculated as:

$$\psi_{\text{edge}}^{(c)} = \frac{\alpha_1}{(T_1 - T_2)} \cdot \left[w(T_1 - T_{\text{sx}}) - \frac{B_1(T_{\text{sy}} - c_{0y})(\lambda_1 - \lambda_2) + B_1B_2(T_{\text{sx}} - c_{\text{ox}}) \left(\frac{\lambda_2}{N_2^2 - \lambda_2^2} - \frac{\lambda_1}{N_2^2 - \lambda_1^2} \right)}{\sqrt{CD}} \right] \quad (28)$$

where w is the width of the panel edge and where N_i and B_i are parameters defined as

$$N_i = \sqrt{\frac{\alpha_i}{d_{f,i}\lambda_{f,i}} + \frac{\lambda_c}{d_{f,i}\lambda_{f,i}d_{p,i}}} \quad \text{and} \quad B_i = \frac{\lambda_c}{d_{f,i}\lambda_{f,i}d_{p,i}} \quad (29)$$

and where λ_1 and λ_2 are the eigenvalues of the linear system of the differential equation derived to represent the thermal phenomenon (Tenpierik & Cauberg 2007a)

$$\lambda_1 = -\sqrt{\frac{(N_1^2 + N_2^2) - \sqrt{(N_1^2 - N_2^2) + 4B_1B_2}}{2}}; \lambda_2 = -\sqrt{\frac{(N_1^2 + N_2^2) + \sqrt{(N_1^2 - N_2^2) + 4B_1B_2}}{2}} \quad (30)$$

and with D the discriminator of the second square root of the eigenvalues and C a parameter:

$$D = (N_1^2 - N_2^2) + 4B_1B_2 \quad \text{and} \quad C = N_1^2N_2^2 - B_1B_2 \quad (31)$$

The terms c_{0x} and c_{0y} are temperatures of the face sheets at a place where only the one-dimensional effect of the VIP occurs and T_{sx} and T_{sy} are fictive temperatures of the face sheets in front of the thermal bridge. The

resistance of the edge spacer is included in the equation to determine the fictive temperatures of the face sheets in front of the thermal bridge and the analytical formulae for those values are given by [Tenpierik et al. \(2008\)](#). It seems that the linear thermal transmittance depends on the environmental temperatures, but it can be proven that, after some rewriting, that these are eliminated from the equation.

Example studies on thermal bridges in high performance building components have been investigated for four different edge spacers ([van Went 2002](#), [Bundi et al. 2003](#), [Cauberg & Tenpierik 2005a](#), [Quenard & Sallée 2005](#), [Tenpierik et al. 2008](#)) in function of facing materials and barrier envelopes as shown in Fig.10. Remarkable in the analysis of these four examples is the increasing thermal conductivity of the aluminium spacer for an increasing panel thickness from 3.75 W/(mK) for a 10 mm VIP to 9.61 W/(mK) for a 40 mm VIP, while this value for the three other edge types stays constant within in the same range of panel thickness. This means that the maximum value for the linear transmittance according Fig.8 can be found at thicker panels for an aluminium spacer. However, for the three other edge spacers are the calculated ψ_{spacer} a factor 10 smaller and as result more interesting for applications from which can be concluded that aluminium spacers are less suitable for with VIP insulated façade panels. The best results are found for a reinforced non-metallic tape with a $\lambda_{\text{tape}} = 0.33 \text{ W/(m}^2\text{K)}$ and $d_{\text{tape}} = 0.15 \text{ mm}$ as an edge spacer (edge spacer ‘c’ in Fig.10).

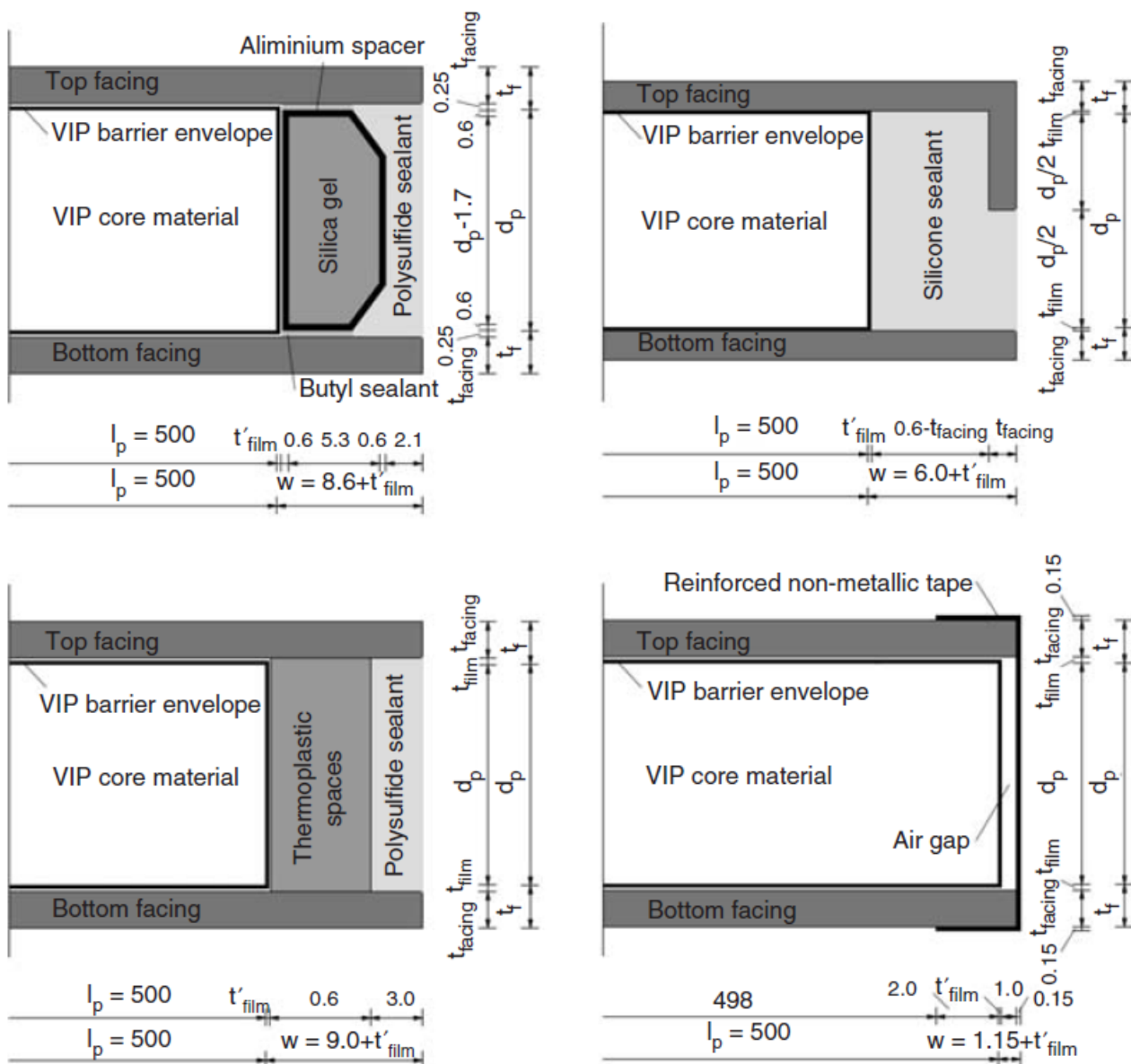


Fig.10. Four edge spacer construction types: (a) Aluminium spacer of double glazing, (b) folded edge construction, (c) thermoplastic spacer and (d) reinforced non-metallic tape ([Tenpierik et al. 2008](#)). A similar division is made in [IEA/ECBCS \(2005\)](#) and [Bundi \(2003\)](#).

- THE LIMITS OF THE ANALYTICAL MODELS are checked by comparing model predictions with numerical data. The deviations between both data were smaller than 5 % for building components with a facing with high thermal conductivity. However, the deviations increase for low conductivity facings but remain below 10 %, caused by errors in the approximation of the edge construction and simplifications in the equation: The edge construction has to be characterized by two parameters (the equivalent edge thermal conductance K and the edge width) to use the equation. It is in the calculation of this equivalent thermal conductance K that a schematization error occurs. Hereby is the analytical model error significantly smaller than the total noticed deviation. Besides this, the deviations on the linear thermal transmittance will stay lower than 5 %, except if the linear thermal transmittance is lower than 0.1 W/(mK).

The error analysis (Tenpierik et al. 2008) indicates that the possibility to use the equation strongly depends on the ratio ξ , the product of foil thermal conductivity and thickness to the product of facing thermal conductivity and thickness and on the equivalent edge thermal conductance K .

2.2.2. Numerical models

Analogue as for the VIP edge is the similarity between the results of the analytical models and the results retrieved from numerical simulations used to prove the accuracy of the analytical model.

2.3. Thermal bridge effect on the scale of the building

The relative importance of structural thermal bridges on the overall thermal performance of assemblies increases strongly with the quality of the insulation material. Compared to the thermal bridges of the other levels, the structural thermal bridge has the largest influence on the overall thermal properties of an assembly. Building details have been sporadically studied based on numerical simulations (Bundi et al. 2003, Ghazi et al. 2005, Quenard 2005, Schwab 2005a) or in a large-scale study (Nussbaumer et al. 2005, 2006).

The small studies on the building details show the high potential of vacuum insulation panels but show also that joints and connections with other components have to be solved carefully: The risk on condensation damage is higher due to possible low surface temperatures and air leakage. The thermal bridges will also depend on the edge effect on the vacuum insulation panels, which means that the edge effect of the VIP should have to be considered in combination with (every possible) other material(s) that make contact with the edge. However the thermal behaviour of structural thermal bridges is already complicated, also the combined thermo-hygric behaviour should be studied for this details. Due to the complication of this models, the best thermal solutions should be looked for first and to continue afterwards with the combined thermo-hygric behaviour of the details.

3. Service life prediction for VIPs

The service life of vacuum insulation panels depends on several factors. A first important factor is the assumed definition of the service life and the assumed requirements according to this definition. Secondly, the core material will have a great influence on the service life, determining the increase of the thermal conductivity of the VIP according to inner gas pressure and water content. A last important factor is the type and the quality of the VIP envelope around the core and the atmospheric conditions in which the VIP is applied, which will determine the increase of the inner gas pressure and water content.

3.1. Service life definition

Two different definitions for the service life t_{SL} can be found in literature (see also Fig.11). The first and most commonly used definition - e.g. by manufacturers - for the VIP service life can be described as ‘the time elapsed from the moment of manufacturing t_0 until the moment the effective thermal conductivity λ_{eff} of the vacuum insulation panel has exceeded a certain limiting value $\lambda_{lim}(t=t_{SL})$ ’ (ISO 15686-2, ASTM C1484-01, Lacasse & Sjoström 2004) or

$$\lambda_{eff} \Big|_{t=t_{SL}} = \lambda_{lim} \quad (32)$$

The second - less used - definition can be described as ‘the time elapsed from the moment of manufacturing t_0 until the moment the time-averaged effective thermal conductivity of the vacuum insulation panel equals a critical value $\lambda_{critical}(t=t_{SL})$ ’ or

$$\bar{\lambda}_{eff} \Big|_{t=t_{SL}} = \lambda_{critical} : \bar{\lambda}_{eff} = \frac{1}{t} \int_0^t \lambda_{eff}(t) dt \quad (33)$$

The thermal conductivity limit is in general defined for the core material λ_c , to exclude the effect of the thermal bridge. This limit thermal conductivity is generally defined as 0.008 W/(mK) (Simmler & Brunner 2005b) or as 0.011 W/(mK) in the American standard ASTM C1484-01, starting from an in general accepted centre-of-panel thermal conductivity of 0.004 W/(mK) for a dry VIP. A reference temperature T_0 of 296 K should be used for the service life because the regression properties of the core material are defined at this temperature.

λ (W/(mK))

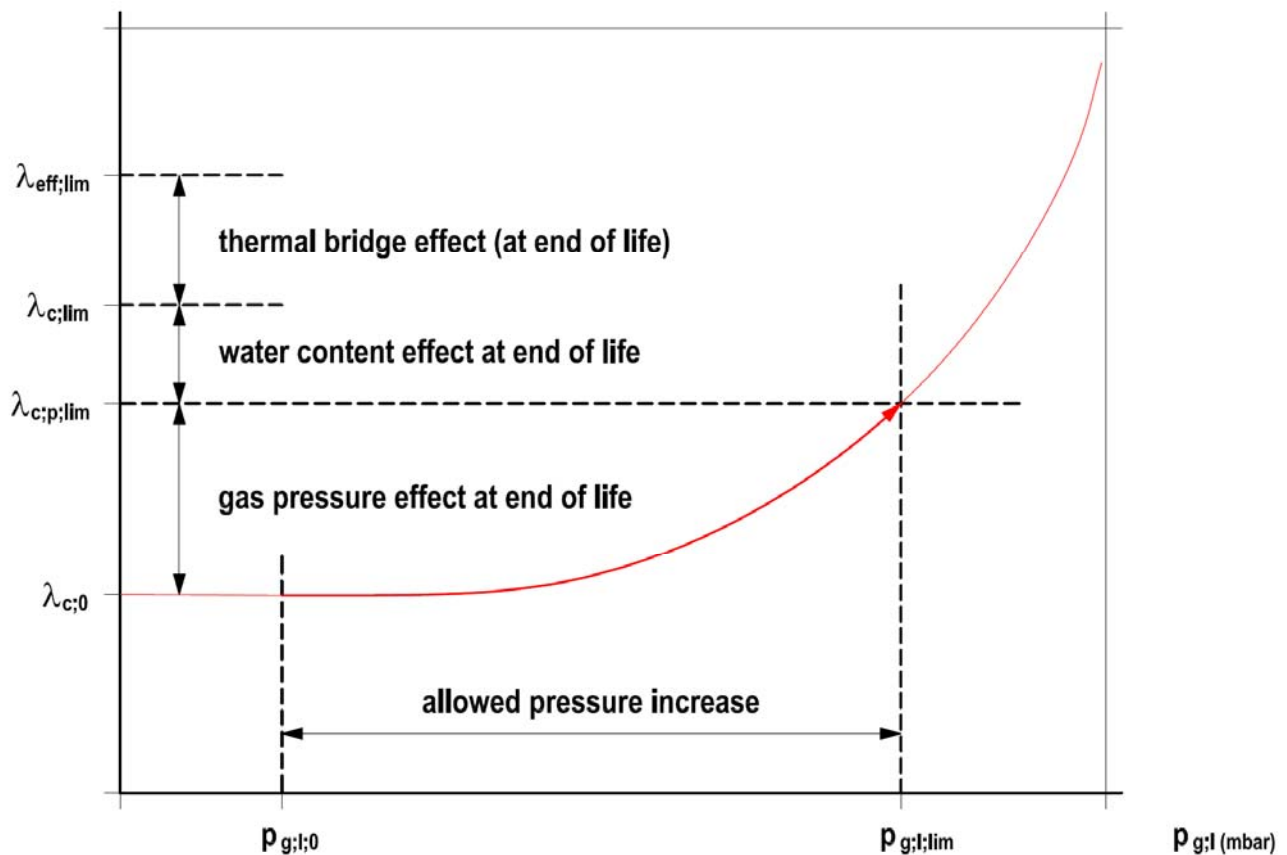


Fig.11. Service life definition of a vacuum insulation panel (redrawn from Tenpierik et al. 2007). Note that the slope of the increasing thermal conductivity is not realistic compared to the real slope.

Different ageing mechanisms can be assumed to predict this service life of vacuum insulation panels. A first failure of the VIP can occur in the first days after manufacturing: The seams of the VIP can be established to be of low quality with a rapid increase of the internal gas pressure as consequence or the envelope can become damaged during the installation in the assembly or on site. The chances on the first type of failure will be reduced by preserving the VIPs the first 10 days in the factory, the second possibility of failure can be expelled by pre-fabricate the assemblies in a factory. However, both failures are neglected in the prediction of service life, assuming that the damaged VIPs will be excluded before application.

During service, pressure increase will occur due to slow permeation of gas molecules through the envelope. Also will the water content of the VIP core increase due to intake of moisture through the barrier. Both effects will be postponed or slowed down by the added getters and desiccants in the core, but still they will result in an increase of the thermal conductivity of the VIP core. These three factors (the pressure increase, the increase

of water content and the influence of getters and desiccants) are the common factors used to define the service life of a VIP for a specific lambda-criterion. The change in thermal conductivity can then be written for constant environmental conditions as Eq.34 (Tenpierik et al. 2007a) which is an extension of the equation of Brunner & Simmler (2005a, 2008).

$$\frac{d\lambda_c}{dt} = \frac{\partial\lambda_c}{\partial p_g} \frac{dp_g(T, \varphi)}{dt} + \frac{\partial\lambda_c}{\partial p_{wv}} \frac{dp_{wv}(T, \varphi)}{dt} + \frac{\partial\lambda_c}{\partial u} \frac{du(T, \varphi)}{dt} \quad (34)$$

Every term of these equation can be studied in detail to come to a final equation for the service life of a vacuum insulation panel.

3.2. Thermal conductivity of the core as function of moisture content and air pressure

In Ch.1.2.1, we've seen that the thermal conductivity of the core material depends on the air and moisture pressure in the material. A first approximation of the dependency was expressed in Eq.13 and Eq.19. Later on, the dependency has been investigated in detail (Tenpierik & Cauberg 2005, Heinemann 2005, Schwab et al. 2005d). The conclusions on the pressure and moisture dependency of the thermal conductivity can be summarized by Fig.12.

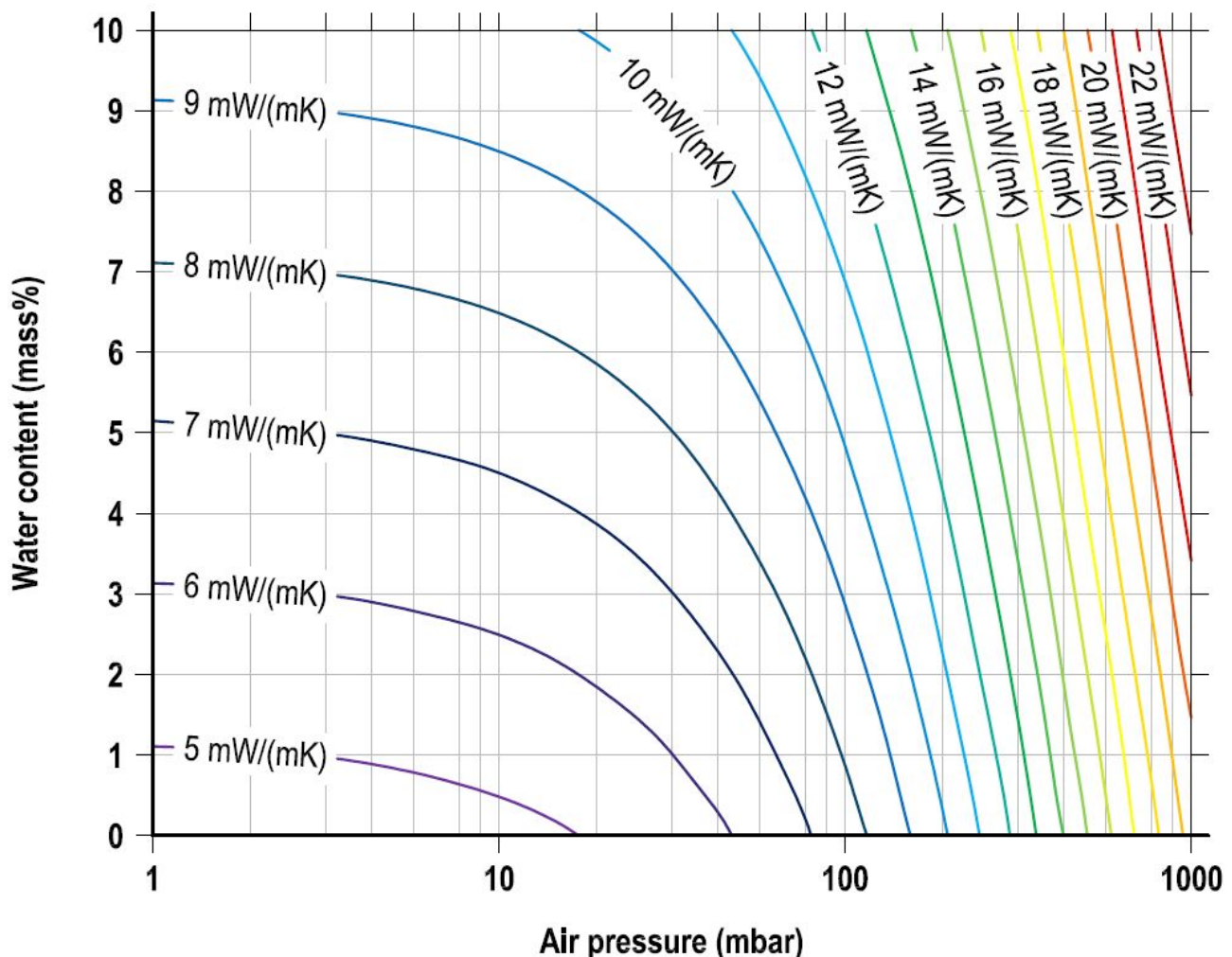


Fig.12. Thermal conductivity (mW/(mK)) of the common core material fumed silica as function of both the air pressure (mbar) with an external load of 1 bar on the sample and the water content (mass%), at a mean temperature of 20°C.

3.3. Pressure and moisture content increase as function of envelope material properties

The total gas transmission rate GTR_{tot} [$m^3(STP)/day$] determining the amount of gas that permeates into the VIP per given time is defined from the measured total permeance Q_{gas} [$m^3(STP)/(m^2dayPa)$] of the envelope foil (Schwab et al. 2005c):

$$GTR_{tot} = (AQ_{g,A} + LQ_{g,L} + Q_{g,P})\Delta p_{g,e} = GTR_A A + GTR_L L + GTR_P \quad (35)$$

where subscript P denotes point defects. A relation between the pressure increase dp_g/dt and the total permeance $Q_{g,tot}$ or the GTR_{tot} can be written from the law of mass conservation and with the ideal gas equation:

$$\frac{dp_g}{dt} = \frac{Q_{g,tot}\Delta p_{g,e}}{V_{eff}} \left(\frac{T_m p_0}{T_0} \right) = \frac{GTR_{tot}}{V_{eff}} \left(\frac{T_m p_0}{T_0} \right) \quad (36)$$

Solving the differential equation in Eq.36 for p_g yields:

$$p_g = p_{g,e} - (p_{g,e} - p_{g,t=0}) e^{-\frac{Q_{g,tot}}{V_{eff}} \left(\frac{T_m p_0}{T_0} \right) t} \quad (37)$$

where $\Delta p_{g,e} = p_{g,e} - p_g$ is the difference between the atmospheric pressure and the inner VIP gas pressure, and V_{eff} the total pore volume, which can be obtained by multiplying the core volume with its porosity and where $(T_m p_0)/T_0$ is a conversion factor from standard conditions to measurements conditions. The result of this equation is graphically shown in Fig.14.

An analogue relation can be written for the water vapour transmission rate WVTR [g/day] as:

$$WVTR_{tot} = Q_{wv,tot}\Delta p_{wv} = \frac{dX_w}{dt} \quad (38)$$

where Δp_{wv} is the difference between the inner VIP water vapour pressure. The penetrated water vapour will be partially absorbed by the fumed silica. The dX_w/dt will depend on the adsorption of water or water vapour of the core material. This adsorption is expressed in Eq.8 and expresses as a consequence also the relation between $Q_{wv,tot}$ and Δp_{wv} of Eq.38. The term dX_w/dt can then be written as:

$$\frac{dX_w}{dt} = \frac{Q_{wv,tot}}{m_{vip,dry}} p_{wv,sat}(T) [\varphi_{wv,out} - \varphi_{wv,in}(X)] \quad (39)$$

where $m_{vip,dry}$ is the dry mass of the VIP core and $\varphi_{wv,out}$ and $\varphi_{wv,in}$ are the relative humidity inside and outside the VIP. This equation has an analytical solution $X_w(t)$ (Schwab et al. 2005b) assuming the linear relation $X_w = k\varphi$ of Eq.8:

$$X_w(t) = k\varphi_{wv,out} \left(1 - e^{-\frac{Q_{wv,tot} p_{wv,sat}(T)}{m_{vip,dry} k} t} \right) \quad (40)$$

The result of this equation is graphically shown in Fig.13 for a core material with a saturated water content of 6 %. It becomes clear that water content will not infinitely increase but will evolve to the saturated water content, while the inner air pressure will increase approximately linearly with the time in the first decades.

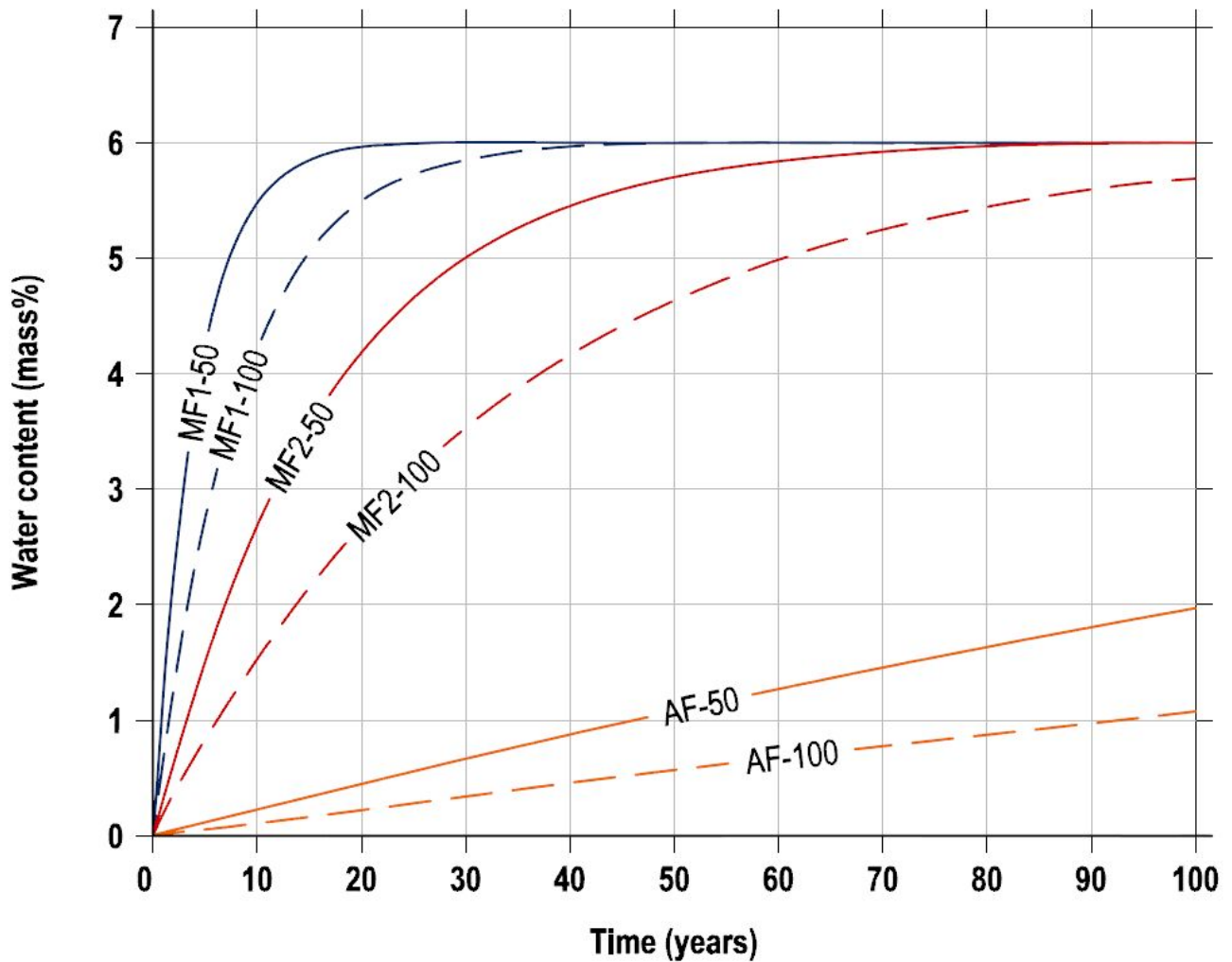


Fig.13. Calculated increase of the total water content in VIPs defined using Eqs.40,46-47, for panel sizes of 50 by 50 by 1 cm³ and 100 by 100 by 2 cm³ and for three different foil types AF, MF1 and MF2 (see Fig.7). The graph is calculated with values for the envelope WVTR envelope determined at 23°C and 75 % relative humidity, as mentioned in Table 4 (Schwab *et al.* 2005b), a dry core density of 200 kg/m³, $u(\varphi)$ as defined in Eq.8 and p_{sat} as defined in Fig.5, and matches the short-term increase of water content as defined by Schwab *et al.* (2005b). No getters and desiccants have been taken into account and one assumes that the VIP envelope properties remain the same, i.e. that no degradation will occur through time, which is unlikely (see Ch.3.5).

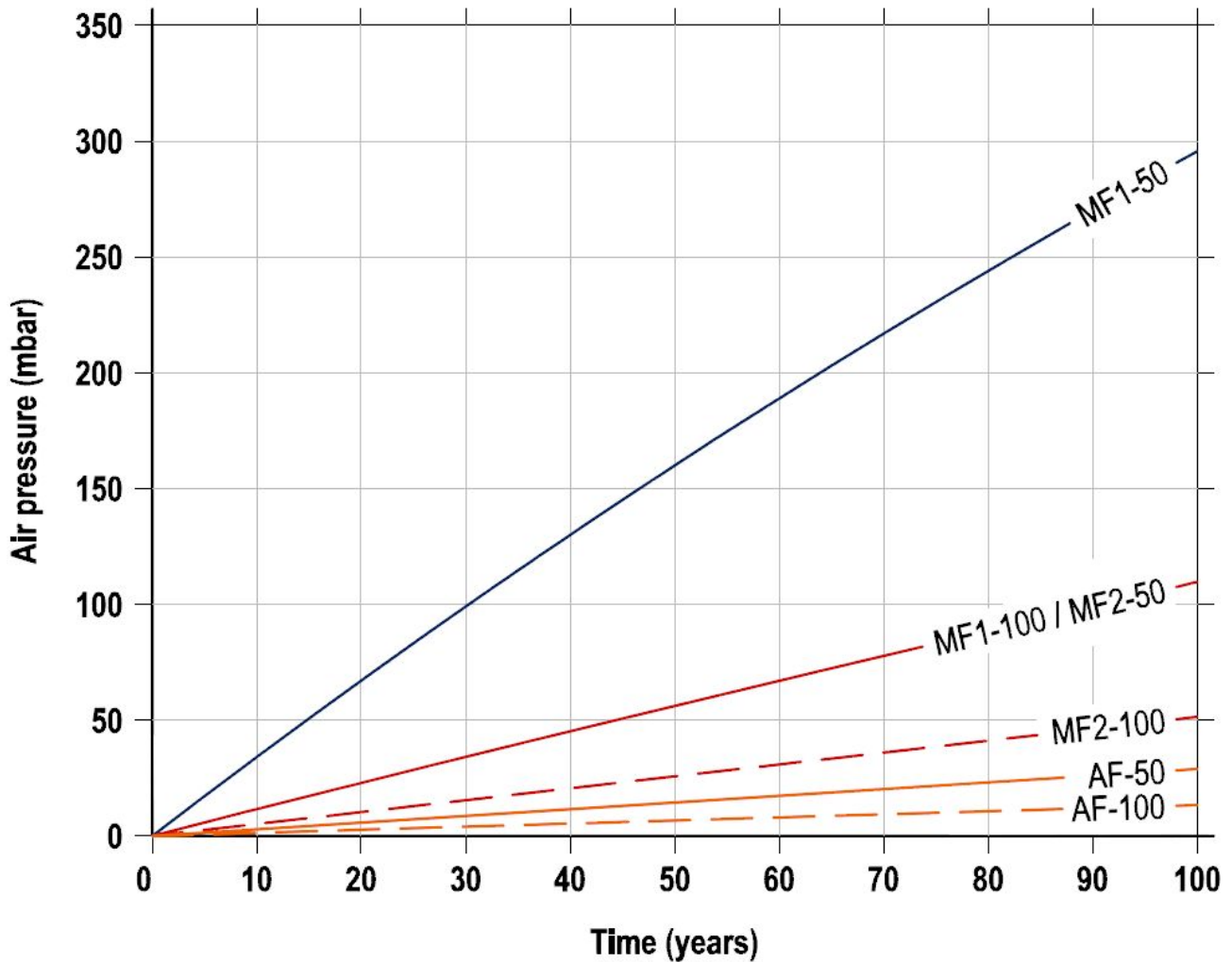


Fig.14. Calculated increase of the total air pressure in VIPs defined using Eqs.37,46-47, for panel sizes of 50 by 50 by 1 cm³ and 100 by 100 by 2 cm³ and for three different foil types AF, MF1 and MF2 (see Fig.7). The graph is calculated with values for the envelope GTR determined at 23°C and 75 % relative humidity, as mentioned in Table 4 (Schwab *et al.* 2005b) and with a porosity of 90 % for the fumed silica core. The inner air pressure is assumed to be zero at $t_0 = 0$ years whereas commercial products have an inner air pressure between 0.5 and 5 mbar and no getters and desiccants have been taken into account. One assumes that the VIP envelope properties remain the same, i.e. that no degradation will occur through time, which is unlikely (see Ch.3.5). Note also that the same results have been found for MF1-100 and MF2-50 as a consequence of the chosen panel sizes and the foil type.

The values GTR and WVTR are foil properties and can be obtained from measurements done (Schwab *et al.* 2005c) for the laminated aluminium foil AF and the aluminium coated multilayer foils MF1 and MF2 (see Fig.7). However, the results of these measurements depend significantly on temperature, relative humidity and panel size.

3.3.1. Dependency of WVTR and GTR on panel size

As seen before can we write the ATR_{total} as function of the size (area A and perimeter L) or the side K for a square panel as Eq.35 or as

$$\frac{ATR_{tot}}{L} = ATR_A \frac{K}{2} + ATR_L \quad (41)$$

No dependency of ATR_{tot}/L on the panel size is found in (Schwab *et al.* 2005c) for the AF and MF2 foil types (see Fig.7), from which can be concluded that infusion of gasses mainly occurs through the VIP edges. For MF1-covered VIPs, the ratio ATR_{total}/L increases with an increasing panel size, which means that surface permeation contributes to the total infusion. In general, it may be concluded that the gas permeation will

mainly occur through the seams of the VIP specified by ATR_L , due to the dependency of gas permeance on the macroscopic defects as mentioned previously in Ch.1.3, while area related defects will be of at least same order of importance for large panels, e.g. above 1 m^2 (IEA ECBCS 2005a).

This conclusion is not valid for the WVTR: Water vapour permeation will occur through the barrier layer as well as through the seams due to the dependency of microscopic defects. However, it is very difficult to separate the water vapour permeation across the surface and the edge of a vacuum insulation panel. Only an upper value of the $WVTR_A$ and the mass increase can be estimated if the length related permeation is neglected:

$$WVTR_A \approx \frac{WVTR_{tot}}{A} \quad (42)$$

An example of the influence of the panel size on the water vapour permeance can be noticed in Fig.14 where the increase of water content is expressed for 2 different panel sizes.

3.3.2. Dependency of WVTR on relative humidity

A MF1 foil has a typical $WVTR_A$ of $0.0096 \text{ g}/(\text{m}^2\text{day})$ (Schwab et al. 2005c) at 25°C and at the ambient water vapour pressure p_{wv} of 14 mbar, which equals approximately a relative humidity of 45%. However, the same MF1 foil has a $WVTR_A$ of $0.360 \text{ g}/(\text{m}^2\text{day})$ at 25°C and 75 % RH. The general influence of the relative humidity on the $WVTR_{tot}/A$ is expressed in Table 2.

Table 2. Influence of the relative humidity on the WVTR of a VIP envelope (Schwab 2005c).

	Panel size	conditions	Foil AF	Foil MF1	Foil MF2
$WVTR_A$ [g/(m ² day)]	10 x 10 x 1 cm ³	25°C, 45% RH	$1 \cdot 10^{-3}$	$9.6 \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$
		25°C, 75% RH	$2 \cdot 10^{-3}$	$36 \cdot 10^{-3}$	$18 \cdot 10^{-3}$

Compared to MF1, an AF foil (see Fig.7) has a typical water vapour transmission rate WVTR that is a factor 10 smaller: $0.001 \text{ g}/(\text{m}^2\text{day})$ at 25°C and ambient p_{wv} . The measured pressure will always consist of both $p_{dry \text{ air}}$ and p_{wv} , but only at high relative humidity will p_{wv} have a certain influence on the total pressure.

3.3.3. Dependency of WVTR and GTR on temperature

For both the WVTR and the GTR can the dependency on temperature be written as an Arrhenius type of equation (Schwab 2004, Simmler & Brunner 2005a, Brunner & Simmler 2008):

$$Q(T) = Q(T_0) e^{\left(\frac{E_a}{R} \left(\frac{1}{T_0} - \frac{1}{T} \right) \right)} \quad (43)$$

where R is the gas constant and E_a the activation energy. The values for this activation energy are given in Table 4 for every type of VIP foils. An analogue table as Table 2 can be written to show the influence of the temperature on the (WVTR and the) GTR (Schwab 2005c):

Table 3. Influence of the temperature on the GTR of a VIP envelope. (Schwab 2005c).

	Panel size	conditions	Foil AF	Foil MF1	Foil MF2
GTR_{tot}/L [m ³ /(m.day)]	20 x 20 x 1 cm ³	23°C, 14 mbar	$3 \cdot 10^{-9}$	$9 \cdot 10^{-9}$	$1.5 \cdot 10^{-9}$
		45°C, 14 mbar	$7 \cdot 10^{-9}$	$36 \cdot 10^{-9}$	$2 \cdot 10^{-9}$
		65°C, 14 mbar	$10 \cdot 10^{-9}$	$49 \cdot 10^{-9}$	$4 \cdot 10^{-9}$

Later will be shown that, as consequence, the service life of a vacuum insulation panel will depend on the same Arrhenius type of equation if the water vapour saturation pressure curve is assumed to be linear in a certain temperature interval.

The values of all these properties are put in Table 4 for the three layer materials AF, MF and MF2 (see Fig.7) for which measurements are done in (Schwab et al. 2005c) and (Brunner et al. 2008).

Table 4. Properties of high barrier foils AF, MF1, MF2 and MF3. (Schwab 2005c; Brunner et al. 2008). It must be noted that the values for the MF3-type of laminate have been retrieved at 23°C and a RH of 50 %.

	Measurement conditions			Barrier envelope materials			
	T	p _{H2O}	Size [cm ³]	Foil AF	Foil MF1	Foil MF2	Foil MF3
GTR _A [m ³ /(m ² day)]	25°C	14 mbar	20 x 20 x 1	(30 ± 2)·10 ⁻⁹	87·10 ⁻⁹	(14 ± 2)·10 ⁻⁹	(3 to 8)·10 ⁻⁹
GTR _L [m ³ /(m ² day)]	25°C	14 mbar	20 x 20 x 1	(3.2 ± 0.2)·10 ⁻⁹	8.1·10 ⁻⁹	(1.2 ± 0.3)·10 ⁻⁹	/
GTR _L [m ³ (STP)/(m ² day)]	25°C	14 mbar	20 x 20 x 1	(2.9 ± 0.2)·10 ⁻⁹	7.5·10 ⁻⁹	(1.1 ± 0.3)·10 ⁻⁹	/
Pressure increase [mbar/yr]	25°C	14 mbar	20 x 20 x 1	2.6 ± 0.2	7.2	1.0 ± 0.1	/
			100 x 100 x 2	0.23	0.59	0.09	/
E _a [kJ/mol]				26 ± 2	40 ± 7	28 ± 3	/
WVTR _A [g/(m ² day)]	25°C	14 mbar	20 x 20 x 1	0.0005 ± 0.0003	0.0067	0.0011 ± 0.0004	0.001 to 0.002

It becomes clear that MF1-covered VIPs have a high pressure and mass increase rate, which makes them unattractive for use as a high barrier envelope in vacuum insulation panels. The values of AF and MF2 foils are comparable and useful for VIPs. However, it must be said that AF foils have a much higher linear thermal conductivity as shown in Ch.2, which makes the AF-foil less attractive for vacuum insulation panel envelopes and the MF2-foil the most promising of them all.

3.3.4. Measuring the internal pressure

Furthermore, the method of measuring the increase of gas and water vapour pressure has been studied (Caps 2005, Caps 2008). A distinction is made between non-thermal methods and thermal methods.

A first technique was introduced based on the foil lift-off method: A vacuum insulation panel is completely or partially placed between two evacuable chambers (see Fig.15[Left]). The upper and lower spaces are simultaneously evacuated and as soon the pressure in the chamber drops below the internal pressure of the VIP, the envelope of the panel lifts off. However, this method is unpractical for pressures below 0.5 mbar (Caps 2005). A second non-thermal method is developed for non-thermal testing (Uzzo 1986, Wilson et al. 2001) of VIPs applied in a building construction (Caps et al. 2008). The method is based on RFID, the radio frequency identification technique that receives data remotely from so called RFID-tags incorporated in a product. Passive tags (tags which do not require an internal power source) and active tags transmit information from an additional sensor which measures the temperature or pressure. An analogue system is developed by 'va-Q-tec' to detect damaged VIPs: No signal of the tag will be received if the internal pressure has reached a certain value (e.g. 600 mbar). The tags can only be used for VIPs with thin metallized foils, because thick metal foils will completely shield the signal.

Furthermore, a thermal detector for gas pressure measurements in VIPs is developed by 'va-Q-tec' (Caps 2005). A thin fibre fleece is placed below the VIP envelope above a thin metal plate. The thermal conductivity of the fibre fleece is measured by placing a transmitter/detector on it from the outside, introducing a heat flow through the envelope and the fleece to the metal plate. A steady state heat flux is reached after a few seconds, measured by the detector (see Fig.15 [right]). From this result, a value for the thermal conductivity of the fleece can be calculated, which is function of the internal pressure. The thickness of the fleece will determine the measurable pressure range.

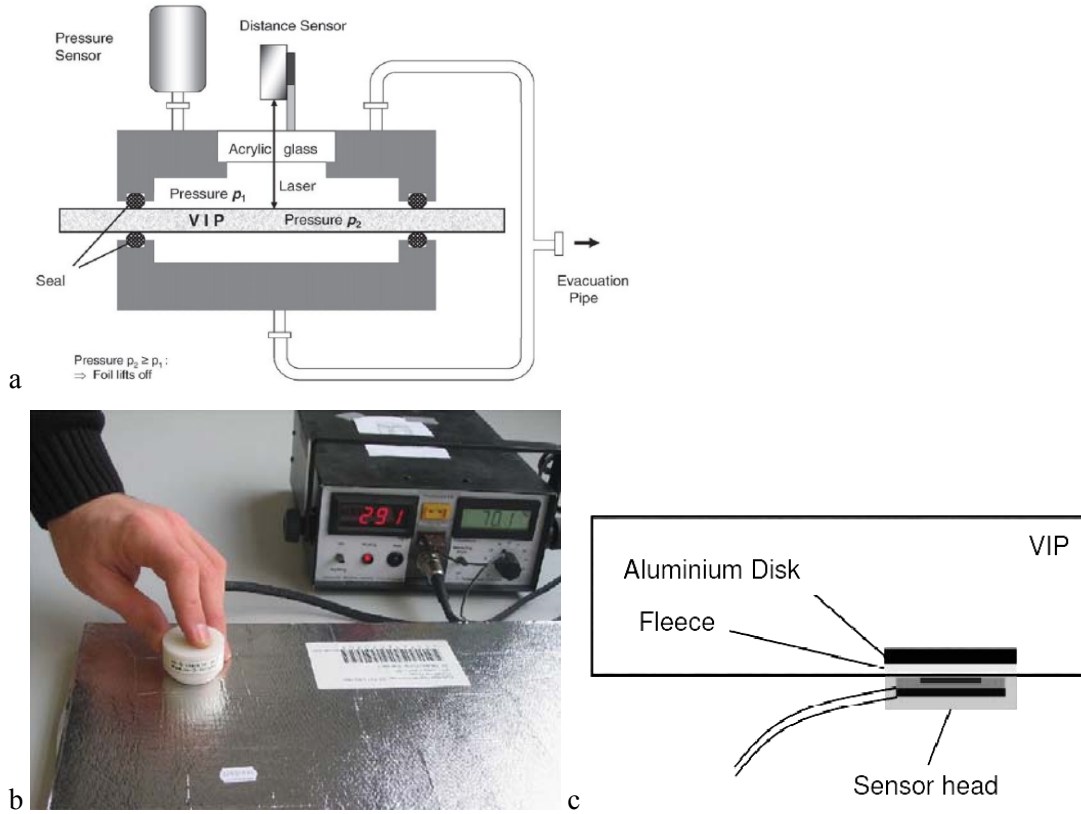


Fig.15. [a] Principle of the foil lift-off method with two evacuatable spacers (Caps 2008) and [b,c] measuring of the heat flux through an inner fleece with the thermal method *va-Q-check* developed by *va-Q-tec* (Brunner & Simmler 2007).

3.4. Service life prediction for VIPs with a fumed silica core and foil envelope

An analytical model for the service life can now be written with the information of Ch.3. Equation 34 can be rewritten with

$$\frac{dp_g}{dt} = \frac{p_0 Q_g(T, \varphi, l)}{V_i} \Delta p \quad (44)$$

$$\frac{du}{dt} = \frac{Q_{H_2O}(T, \varphi, A, L)}{m_{dry}} \Delta p_{H_2O} = \frac{u_0}{\alpha \varphi_e} (\alpha \varphi_e - u) \quad (45)$$

where Δp is the difference in pressure between outside and inside the panel and where Q_g and Q_{H_2O} can be defined with the WVTR and GTR of the VIP (Simmler & Brunner 2005a, Schwab 2004, Schwab et al. 2005b). As a result, we come to the proposed analytical model of Tenpierik et al. (2007a):

$$\Delta \lambda_c(t) \approx \frac{\partial \lambda_c}{\partial p_g} p_{g,e} \left(1 - e^{-\frac{t}{\tau_g}} \right) + \frac{\partial \lambda_c}{\partial p_{wv}} p_{wv,e} \left(1 - e^{-\frac{t}{\tau_w}} \right) + \frac{\partial \lambda_c}{\partial u} \frac{du}{d\varphi} \varphi_e \left(1 - e^{-\frac{t}{\tau_w}} \right) \quad (46)$$

where τ_g and τ_w are (temperature and relative humidity dependent) time constants, defined as

$$\tau_g = \frac{\varepsilon V}{GTR(T, \varphi)} \frac{T_0}{p_0 T} \quad \text{and} \quad \tau_w = \frac{\rho_{dry} V}{WVTR(T, \varphi)} \frac{1}{p_{sat}(T)} \frac{du}{d\varphi} \quad (47)$$

where ε is the porosity of the core material, V the total volume of the core material, T_0 a reference temperature, p_0 a reference pressure, p_{sat} the water vapour saturation pressure of the air and where ρ_{dry} is the

dry density of the core material. This increase of thermal conductivity as in Eq.46 due to the intake of moisture and gas is expressed graphically in Fig.16 for three different foil types.

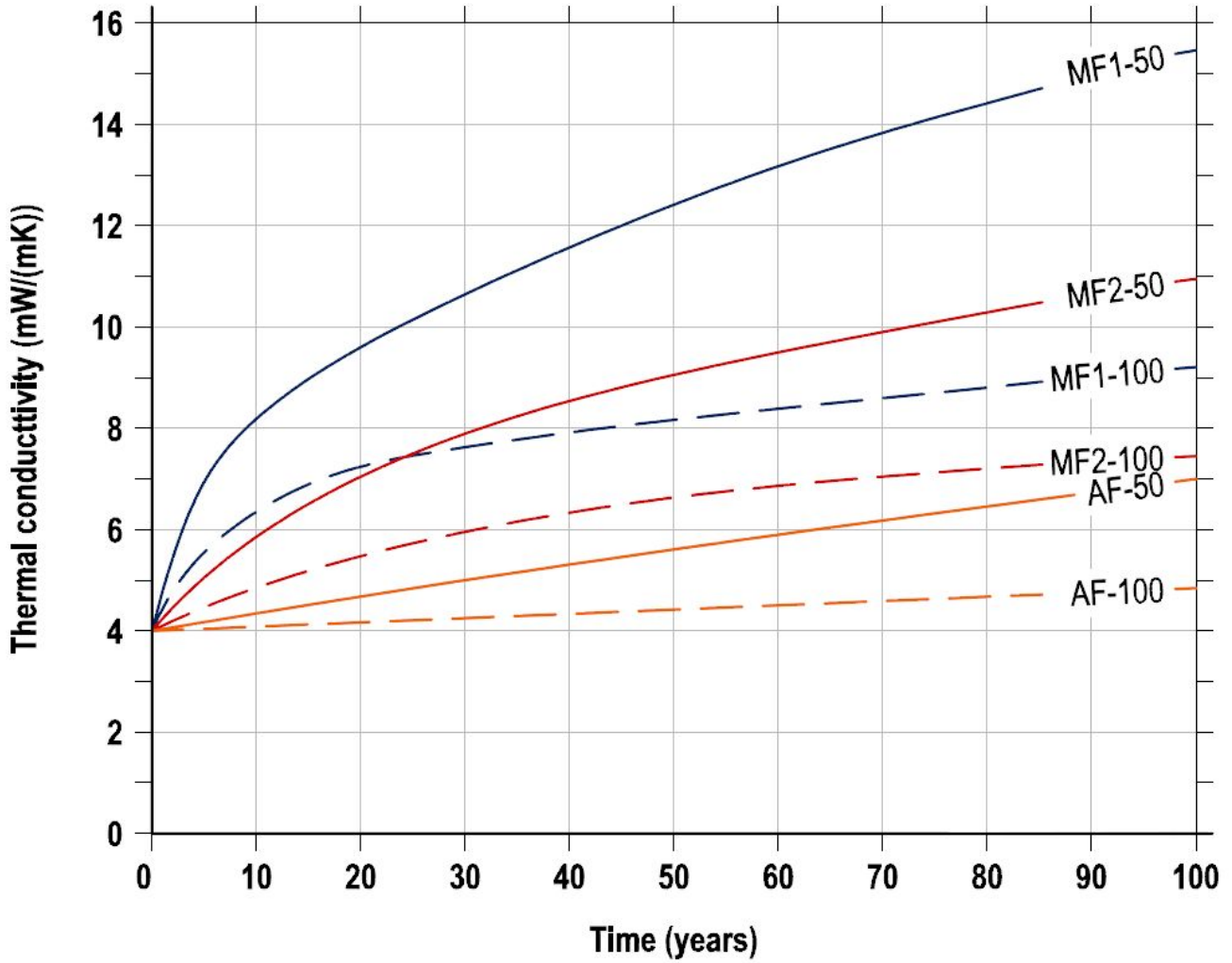


Fig.16. Centre-of-panel thermal conductivity for VIPs with a fumed silica core defined using Eqs.46-47, for panel sizes of 50 by 50 by 1 cm³ and 100 by 100 by 2 cm³ and for three different foil types AF, MF1 and MF2 (see Fig.7). The graph is calculated with values for the envelope WVTR and GTR determined at 23°C and 75 % relative humidity as mentioned in Table 4 (Schwab *et al.* 2005b), a porosity of 90 % a dry core density of 200 kg/m³, $u(\varphi)$ as defined in Eq.8, $\partial\lambda_c/\partial u$ as defined in Eq.13, $\partial\lambda_c/\partial p_g$ as calculated from Eq.4 and 5, and p_{sat} as defined in Fig.5, and matches the short-term increase of thermal conductivity as defined by Schwab *et al.* (2005b). The second term in Eq.46 (containing p_{wv}) is neglected. The inner air pressure is assumed to be zero at $t_0 = 0$ years whereas commercial products have an inner air pressure between 0.5 and 5 mbar and no getters and desiccants have been taken into account. One assumes that the VIP envelope properties remain the same, i.e. that no degradation will occur through time, which is unlikely (see Ch.3.5).

Equation 46 can be adapted to the retardation due to the getters and desiccants, that are added to the vacuum insulation core of fumed silica, by replacing the term t with respectively $(t-t_{get})$ and $(t-t_{des})$:

$$\Delta\lambda_c(t) \approx \frac{\partial\lambda_c}{\partial p_g} p_{g,e} \left(1 - e^{-\frac{-(t-t_{get})}{\tau_g}} \right) + \frac{\partial\lambda_c}{\partial p_{wv}} p_{wv,e} \left(1 - e^{-\frac{-(t-t_{des})}{\tau_w}} \right) + \frac{\partial\lambda_c}{\partial u} \frac{du}{d\varphi} \varphi_e \left(1 - e^{-\frac{-(t-t_{des})}{\tau_w}} \right) \quad (48)$$

where t_{get} and t_{des} are the time shifts due to getters and desiccants, calculated as

$$t_{get} = \frac{c_{get} m_{get}}{(p_{g,e} - p_{g,i,0}) GTR(T, \varphi)} \quad \text{and} \quad t_{des} = \frac{c_{des} m_{des}}{(p_{wv,e} - p_{wv,i,0}) WVTR(T, \varphi)} \quad (49)$$

where c_{des} [kg/kg] is the maximum capacity of the desiccant, m_{des} the mass of the added desiccants, c_{get} [m³/kg] the maximum capacity of the getter and m_{get} the mass of the added getters. However, it must be noticed that Eq.48 is only correct for $t > t_{des}$ and $t > t_{get}$. If t is smaller than one of those (or both), the corresponding term has to be equalled with zero. This means that as long as the getters and/or desiccants did not yet reach their maximum capacity, the pressure and/or moisture content in the vacuum insulation panels will not yet start to raise.

With these equations given for the increase of the thermal conductivity of the core, an equation for the service life time t_{SL} of a vacuum insulation panel can be derived (Tenpierik et al. 2007a):

$$\Delta\lambda_c(t) \approx \frac{\partial\lambda_c}{\partial p_g} p_{g,e} \left(1 - e^{-\frac{-(t_{SL}-t_{get})}{\tau_g}} \right) + \frac{\partial\lambda_c}{\partial p_{wv}} p_{wv,e} \left(1 - e^{-\frac{-(t_{SL}-t_{des})}{\tau_w}} \right) + \frac{\partial\lambda_c}{\partial u} \frac{du}{d\phi} \varphi_e \left(1 - e^{-\frac{-(t_{SL}-t_{des})}{\tau_w}} \right) \quad (50)$$

If no getters and desiccants time shifts are assumed, the service life can be solved from Eq.50. For VIPs with a core of fumed silica, an analytical estimation can be made as in Eq.51 with a difference of maximum 17 % compared to the result of the differential Eq.50 (Tenpierik et al. 2007a):

$$t_{SL} \approx a e^{b(\lambda_{lim}-\lambda_0-\lambda_w)} d_{vip} \left(\frac{l_{vip}}{S_{vip}} \right)^c \frac{T_0}{T} e^{\left[\frac{E_a}{R} \left(\frac{1}{T} - \frac{1}{T_0} \right) \right]} \quad (51)$$

where a [sm^{-(1+c)}], b [mK/W] and c [-] are regression parameters defined in Table 5, d_{vip} the VIP thickness, E_a the activation energy, R the gas constant and λ_w the thermal conductivity of liquid water and water vapour at equilibrium with ambient conditions which can be determined (Schwab 2004) as:

$$\lambda_w = 0.029u(\varphi_e) + \frac{\lambda_{wv,0}}{1 + \frac{P_{1/2}}{\varphi_e P_{sat}}} \quad (52)$$

The regression parameters a and b in Eq.51 are parameters depending on the combination of envelope and core material, while the parameter c is a quadratic regression function depending on the temperature:

$$c = c_0 + c_1 \left(\frac{T_0}{T} \right) + c_2 \left(\frac{T_0}{T} \right)^2 \quad (53)$$

where c_0 , c_1 and c_2 have to be derived from experimental results. All these parameters a , b and c_x have been investigated (Schwab et al. 2005b, Simmler & Brunner 2005a) for panel thicknesses between 10 and 50 mm, temperatures between -5 and 45°C and for panels with a l_{vip}/S_{vip} in the range of 2 to 10 m⁻¹ for MF3- and AF-covered VIPs with a core of fumed silica. Within this range, the parameters can be assumed to have the value as mentioned in Table 5.

Table 5. Regression parameters for Eq.51. (Tenpierik & Cauberg 2007a). The values obtained by Tenpierik et al. (2007a) with a regression analysis on the data of Schwab (2005c) and Simmler & Brunner (2005a)

Core	Envelope	a [m ^{-(c+1)} yr]	b [mK/W]	E _a [J/mol]	c ₀ [-]	c ₁ [-]	c ₂ [-]
SiO _x	MF3	(5.17 ± 0.80) · 10 ³	333 ± 1	50 ± 2	15.4 ± 2.6	-31.3 ± 5.3	15.1 ± 2.6
	AF	(3.61 ± 0.39) · 10 ³	270	26 ± 2	8.8 ± 1.4	-17.8 ± 2.8	8.2 ± 1.4

With these values, a service life in the range of 18 to 40 years is found for MF3-VIPs panels with a l_{vip}/S_{vip} between 2 and 10 m⁻¹ at 23°C. For the same conditions, a service life between 60 and 160 years is found for AF-VIPs. Analogue values are found according to older studies and models (Schwab et al. 2005b). In these models, similar values are found for MF2-VIPs as the MF3-VIPs, while for MF1-VIPs an unacceptable service life of less than 10 years was found.

3.5. Other ageing factors

Other climate factors can age building materials and building components. These climate factors may be divided into ultraviolet, visible and near infrared solar radiation, ambient infrared heat radiation, temperature changes or freezing/thawing cycles, water (e.g. moisture, relative air humidity, rain and wind-driven rain), wind, erosion, pollutions, micro-organisms, oxygen and time determining the effect for all the previous mentioned factors to work (Jelle et al. 2008). The ageing factors on polymer degradation for VIP envelopes are expressed by Thorsell (2006), divided in four main groups: The chemical environment, thermal shocks, ultraviolet light and high energy radiation. However, the real effect of chemicals and radiation on VIPs is unknown and it is unclear what is meant with 'high energy radiation' by Thorsell (2006) in this context. One possibility might be 'shortwave visible radiation' which is the visible radiation with the highest photon energy, also taking part in the degradation of several materials (e.g. Jelle et al. (2007)).

Furthermore, accelerated ageing of the envelope material by high temperatures and damaging by mechanical loads is mentioned. These mechanical loads can be a nail penetrating the envelope with immediate pressurization as consequence or a worker stepping on the VIPs on the construction site without any visible damage. A VIP is such a fragile material that one has to assume proper and careful handling at both the manufacturing and construction site. The best way to ensure safe handling would be to never allow the bare VIPs at the construction site but supplying them integrated into more durable building components. (IEA/ECBCS 2005b, Thorsell 2006)

4. Acoustical properties of applied VIPs

The hygro-thermal properties of vacuum insulation panels have been previously discussed in Chs.1-3. A large potential in decreasing the thickness of the thermal layer due to the high insulation value has been noticed here. However, also the sound insulation properties of VIPs are important if they are used as building insulation. Research on these properties started by Lenz et al. (2005) and was continued by Cauberg & Tenpierik (2007) and Maysenholder (2008). However, there is not much known on the acoustical properties besides these three articles.

The acoustical knowledge or properties of VIPs can be divided in three groups: The acoustical properties of a single vacuum insulation panel, the properties of with VIPs insulated sandwich elements and the properties of insulated massive walls with VIPs. Important here for are three factors which determine the acoustical quality. These are noise banning and sound absorption for façades and the dynamic modulus for sprung floors.

4.1. Acoustical properties of a single VIP

The sound insulation of a material or structure is in the first place determined by the law of mass, in which the weighted sound reduction index R_w is expressed as $R_w \approx 20 \cdot \log(1+3.4m)$ where m [kg/m^2] is the mass per area. With a bulk density of $2.2 \text{ kg}/\text{m}^2$ for 10 mm VIPs and $5.7 \text{ kg}/\text{m}^2$ for 33 mm VIPs, a theoretical weighted sound reduction index in the range of 19 to 26 dB can be found (Maysenholder 2008). An other important property is the E-modulus: A value of 0.25 MPa for a VIP is found according to the international standard ISO 9052-1:1989, while a value of 0.49 MPa is found for the core material fumed silica.

The same acoustical performance are found in measurements by Maysenholder (2008) while much lower values are found for perforated VIPs. The general behaviour of single VIPs is here described as "according to mass law, followed by a coincidence dip". The weighted sound reduction index R_w drops with 10 to 15 dB at this coincidence frequency. The aim in building acoustics is not to have this coincidence dip in the range of traffic noise ($\sim 1 \text{ kHz}$), but it is found for VIPs with a fumed silica core in a disturbing zone between 1 kHz and 2 kHz (Lenz et al. 2005, Maysenholder 2008) (see Fig.17).

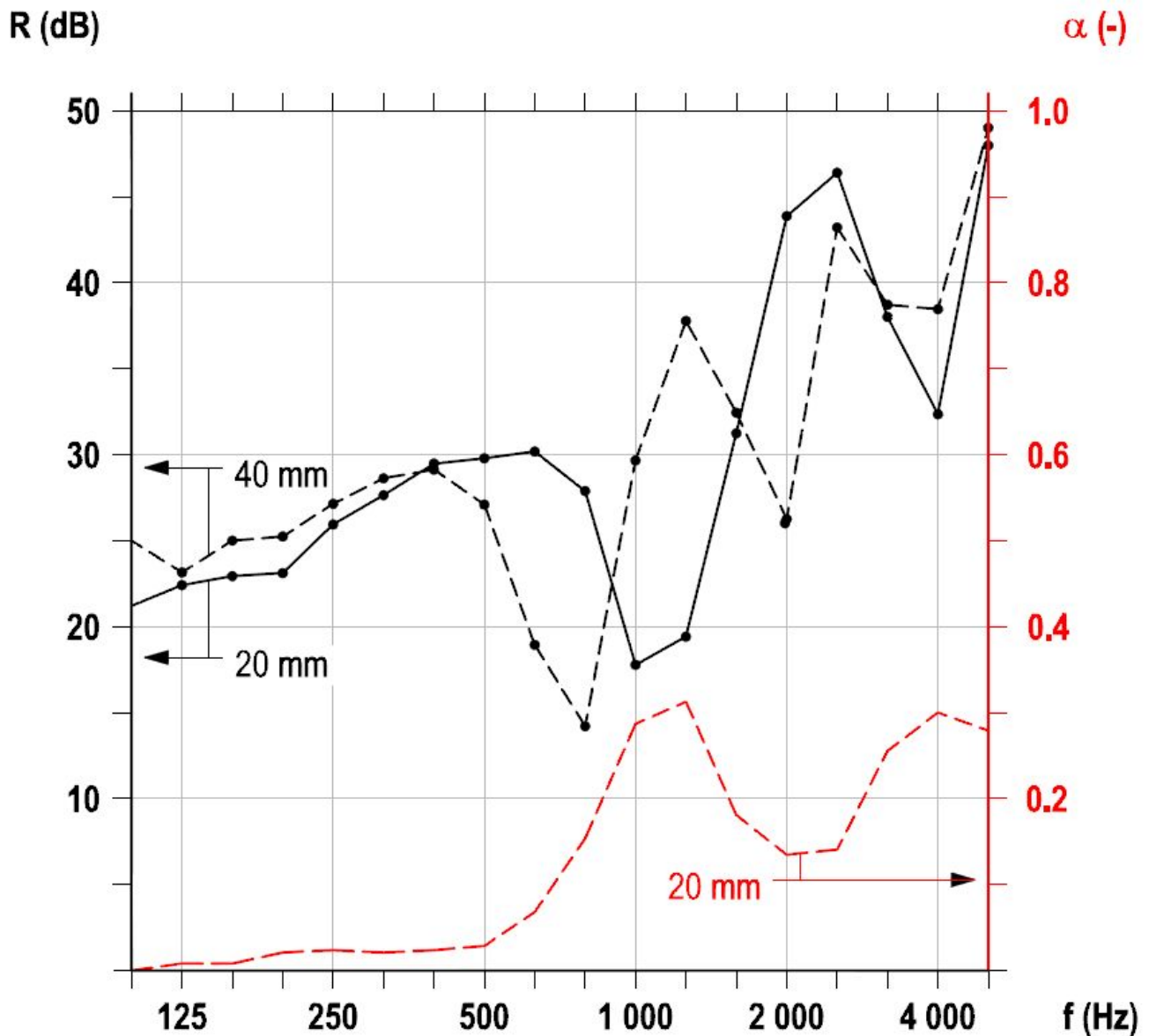


Fig.17. Sound reduction R (dB) of VISs with 15 kg/m^2 facings and absorption coefficient α (-) of a VIP under vacuum condition as function of frequency (redrawn from [Lenz et al. 2005](#) and [Cauberg & Tenpierik 2007](#)).

It becomes clear that due to the strong reduction in thickness (and as consequence also due to the high thermal properties) the acoustic performance will have to be corrected with thicker and heavier facings in vacuum insulated sandwich elements.

4.2. Acoustical properties of VIP insulated structures

4.2.1. Vacuum insulated sandwiches VISs

The acoustical properties can be improved by applying VIPs in sandwich elements, a common application of vacuum insulation panels. As result, the R_w value will increase due to a higher mass per surface, but dilatational resonances will occur due to mass-spring-mass system with the VIP as the spring and the facings as mass.

These VISs have been investigated: Sandwich elements with TRESPA facings by [Cauberg & Tenpierik \(2007\)](#) and with steel facings in [Maysenholder \(2008\)](#). Comparable data are found in both studies: A weighted sound reduction index $R_w \approx 28 \pm 1 \text{ dB}$ and a value of 4 dB lower for traffic noise. This value R_w can be improved strongly by adding two rubber layers of 1 mm between the (metal) facings and the vacuum

insulation panel: The coincidence frequency will move out of the disturbing zone to 3 kHz and the weighted sound reduction index will follow the mass law $R_w = 34$ dB.

4.2.2. VIP insulated cavity wall

VIPs applied as cavity insulation in a massive wall will not improve the acoustical performance of the wall: The vacuum insulation panels have a sound absorption coefficient of 0.0 up to 500 Hz and an absorption coefficient of 0.2 ± 0.05 at higher frequencies, as determined by [Cauberg & Tenpierik \(2007\)](#).

5. Building applications of VIPs

One main benefit with VIPs is the reduction of the required thickness of the insulation layers compared to traditional thermal insulation materials in building applications due to the much lower thermal conductivity of VIPs, i.e. approximately 5 to 10 times lower. As a result, the necessary building insulation thickness may be decreased with a factor of 5 up to 10, which is depicted in [Fig.1](#) and [Fig.18](#). However, for the application of VIPs, one has to pay attention to certain disadvantages compared to the conventional insulation materials (see [Table 6](#)).

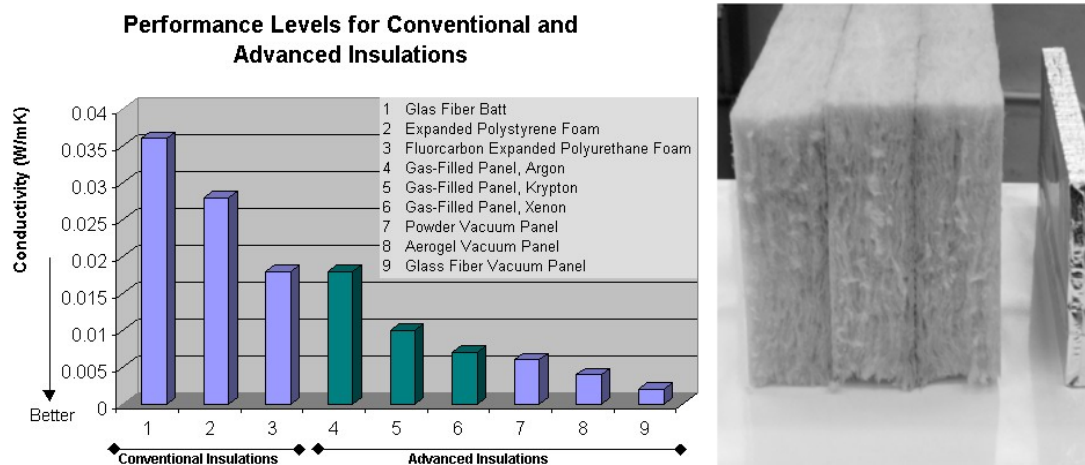


Fig.18. Comparison [left] between the thermal conductivities of conventional and advanced insulation materials and solutions (<http://gfp.lbl.gov/>) and [right] between the required thicknesses for conventional insulation (e.g. glass wool) and a VIP ([Cauberg & Tenpierik 2005b](#)).

Table 6. Summary of the advantages and disadvantages of vacuum insulation panels for building purposes.

Advantages	Disadvantages
<ul style="list-style-type: none"> - High performance thermal insulating - Increased floor area - Appropriate refurbishing of existing buildings with high restrictions. - Can be used as ‘thermal-bridge-insulation’ on places where not much space is available. - Up to now the only material for which 4 cm is enough to meet (most of) national building regulations. - Lower operating temperature increases thermal performances, which is beneficial in Nordic countries. 	<ul style="list-style-type: none"> - Very fragile and protection for puncture of the foil is necessary. - Reducing thermal performances through time. - Limited service life may require replacement. - Effective thermal performance will be reduced by thermal bridging of the VIP envelope. - Increased structural thermal bridging due to the envelope. - Less suitable for traditional timber wall structures. - Inflexible: On-site adaptations (cutting of panels) are not possible. - Production inaccuracy of the panel sizes

Vacuum insulation panels are already introduced to the market in large-scale production. However the manufacturing is still mainly hand-labour. The last decades, several building applications for VIPs have been proposed and/or tested and a large-scale study has been carried out on the possibilities of VIP insulated building envelopes ([Cremers 2006](#)). Example building applications in papers may be divided in several groups:

A first application method consists of insulating existing buildings on the inside (Bundi et al. 2003, Binz et al. 2002, Ghazi et al. 2005) or on the outside (Schwab et al. 2003, IEA/ECBCS 2005b, Willems & Schild 2005, Winkler & Mainka 2005, Zwerger & Klein 2005, ZAE Bayern 2008) of the existing building envelope. Installing additional insulation on the inside results mostly in a great loss of floor space, therefore VIPs are of interest for renovations. Special attention has to be paid on low surface temperatures and possible condensation damages at connections to surrounding compounds.

A second current common application method is applying VIPs as vacuum insulated sandwich elements (VISs) in door & window frames, in curtain walls and in non-load bearing walls (van Went 2002, Schwab et al. 2003, Binz & Steinke 2005, Willems & Schild 2005, Ogden & Kendrick 2005, Nussbaumer et al. 2005, Winkler & Mainka 2005, Cremers 2006, Tenpierik & Cauberg 2007b, ZAE Bayern 2008). In the studies on window and door frames, an improvement up to 50 % of energy transmittance is noticed for the overall frame system if the performance of the overall system is not comprised by an adapted frame design.

A third application group can be found in insulating flat roofs, loggias, terraces and internal floors, where the small thickness of the needed insulation layer enables a simple construction for a stepless transition between the interior and exterior space (Schwab et al. 2003, Binz & Steinke 2005, Cauberg & Tenpierik 2005b, Willems & Schild 2005, Brunner & Simmler 2007, Brunner & Simmler 2008, ZAE Bayern 2008) (see Fig.19). Measurements have been performed on VIP insulated flat roofs and have shown that a service life of several decades is very likely. It has also been shown that the moisture load of flat roofs can strongly influence the effective thermal conductivity.

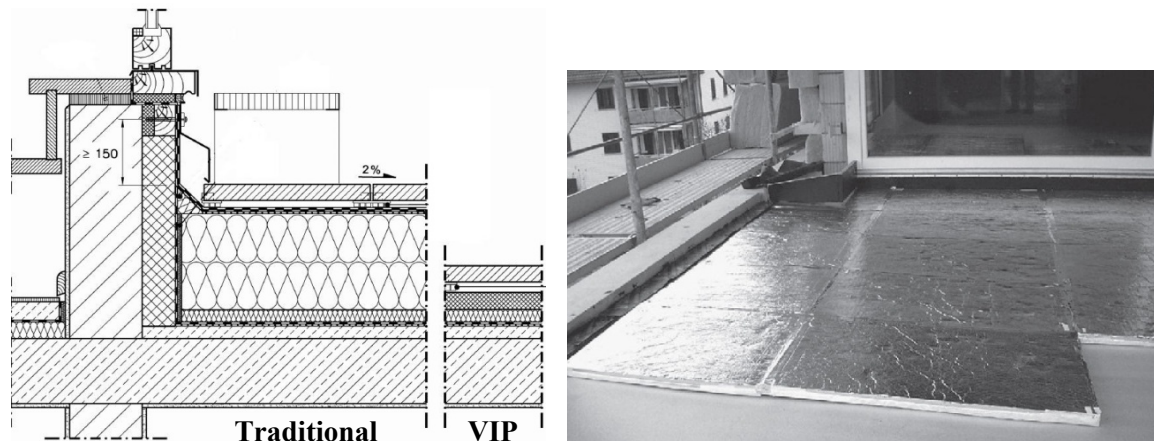


Fig.19. [left] Comparison between a vertical cross section of a connection of a conventional insulated terrace and a construction with a comparable with VIS insulated terrace construction (Willems & Schild 2005) and [right] an example of a slim balcony construction (Brunner & Simmler 2007).

A fourth group of building applications is VIPs as main insulation of the building envelope for new buildings (Willems & Schild 2005, Cremers 2006, Platzer 2007, Simmler & Brunner 2005a, Brunner & Simmler 2008). Adapted wall constructions are shown/proposed for integrating VIPs in a sustainable solution (Cauberg & Tenpierik 2005b, Jordi 2008) to come to average thermal performances of $U_{\text{wall}} \approx 0.1 \text{ W}/(\text{m}^2\text{K})$ with limited thicknesses. In such applications, it is always studied whether or not the complete envelope building components should be pre-assembled in advance, to ensure the proper handling of the VIPs.

A last group of VIP building applications can be found in building installations, e.g. pipe insulation (Kerspe & Zwarts 2007), insulation for hot water cylinders (Omer et al. 2007) or under-insulation of floor heating (Cauberg-Huyghen 2004, Cauberg-Huyghen 2006).

6. Other possible high performance thermal insulating materials and solutions

Vacuum technology is only one way to achieve a high performance thermal insulating solution. As comparison, a short extension towards gas-filled panels (GFPs) and aerogels will be made. Both GFPs and aerogels are new high performance thermal insulating solutions and materials developed in the last decade, introducing new technologies or possibilities which may be useful in the development of such new high performance thermal insulation materials.

6.1. Gas-filled panels

Gas-filled panels (GFPs) try to minimize all parameters of heat transfer by using a low-conductive gas as the main insulator to influence both the gaseous thermal conductivity λ_g and the thermal conductivity of the solid structure λ_{cd} . Because the gas is used at ambient pressure, a core material is no longer necessary to transfer forces as in vacuum insulation panels. To enclose the gas and to decrease the heat transfer due to radiation, GFPs use a low-emissivity surface baffle structure in a barrier envelope.

The thermal conductivity through the gas is the most important heat transfer in a GFP. High performance GFPs use gases which have a lower thermal conductivity than air. Two general rules (Griffith 1992) can be expressed to explain this lower thermal conductivity of a gas. Firstly, a gas with a higher molecular weight will have a lower thermal conductivity. Secondly, a mono-atomic gas (e.g. argon, krypton and xenon) will have a lower thermal conductivity compared to polyatomic gases with the same molecular weight. The reason for this is an extra possible energy transfer due to rotation and vibration of the gas molecules. Most attention is paid to the potential of GFPs with the inert noble gases argon, krypton and xenon as a gas-fill because these gases can be extracted from the atmosphere and as consequence have a global warming potential of zero.

Gas-filled panels are made of two types of polymer films: Metallized films are used in a tied assembly called 'the baffle', producing a cellular structure in the panel which suppress convection and radiation (see Fig.20). Low diffusion gas barrier foils are used in a hermetic 'barrier', keeping the panels gas-tight. Depending on the type of foils used for the structure, these panels may be made as stiff or flexible insulation panels. As a result of the structure, the total panel will have a thermal conductivity close to the still-gas thermal conductivity of the fill (see Table 7).



Fig.20. View of the barrier foil and the baffle structure inside a gas-filled insulation panel (<http://gfp.lbl.gov/>).

The barrier is a hermetically sealed enclosure to maintain the gas-fill and a critical component for the GFPs. The foil will have to act as an effective gas barrier in two directions: Moisture and air gases are driven into the panel and the gas-fill is driven out of the panel. Similar to the envelope foil for vacuum insulation panels will the quality of GFP barriers be quantified by their gas transmission rate. However, a distinction will be made for each type of gas because of the specific gas content of the panel. A gas loss of 0.1 vol% is acceptable for GFPs. Within this limitation, a variety of films and foil configurations are commercially available. A first group includes all foils of vacuum applications with very thin layers of aluminium such as vacuum insulation panels. A second group is polymer barrier resins, including ethylene-vinyl-alcohol, polyvinylidene-chloride and polyvinyl-alcohol (Griffith 1992).

Table 7. The effective thermal conductivity for an optimum number of cavities, based on the lowest marginal cost of the fabrication of the gas-filled panels (Griffith 1993).

Panel thickness	Effective thermal conductivity λ_e [W/(mK)]		
	Air	Argon	Krypton
25 mm	0.0350	0.0213	0.0106
50 mm	0.0380	0.0226	0.0106

The baffles are necessary to suppress convection and radiation. Making compartments by constructing the baffle out of a solid material minimizes the convective heat transport of the gas. For this gas division into

compartments, thin sheets are assembled in a three-dimensional form of multiple layers of cavities. The radiation heat transfer is decreased by using low-emissivity cavity surfaces, which are inexpensive and available as metallized thin polymer films. The dimensions of the foil and the formed cavities are selected to minimize the gas convection in these cavities, to reduce the solid conduction and to minimize the economic cost. There is an optimal number of baffle layers (Griffith 1995) to use in a GFP with its specific thickness, gas-fill and temperature difference regarding the economic cost and the thermal performance.

6.2. Aerogels

The remarkable properties of aerogel result from its extraordinary physical and chemical structure. Silica aerogels consist of a cross-linked internal structure of SiO_2 -chains with a large number of air filled pores. These pores of aerogel are very small: Pure aerogel has an average pore diameter between 10 and 100 nm (Zeng et al. 1994). However, aerogels in general will have pore sizes between 5 and 100 nm, depending on the purity and the fabrication method (van Bommel et al. 1997). These pores will take 85 up to 99.8 % of the total aerogel volume. Due to its extraordinary pore sizes and the high porosity achieves aerogel remarkable physical, thermal, optic and acoustic properties. However, this also results in a very low mechanical strength. The high porosity makes aerogels the lightest solid material know at present: However it has a skeleton density of $\sim 2\,200\text{ kg/m}^3$, the high porosity results in a bulk density up to as low as 3 kg/m^3 whereas e.g. the density of air is 1 kg/m^3 (Smirnova 2002, Richter 1995, Hüsing 1998).

Silica aerogels have an overall thermal conductivity of $\sim 0.017\text{ W/(mK)}$ at ambient pressure. The solid thermal conductivity of dense silica is relatively high, but silica aerogels have such a small fraction of solid silica. Furthermore, the inner skeleton structure has many ‘dead-ends’ resulting in an ineffective and tortuous path of thermal transport. Lower density aerogels can be made to decrease the solid conductivity, but this may result in mechanically weaker properties and in wider pores, i.e. less optimal thermal properties.

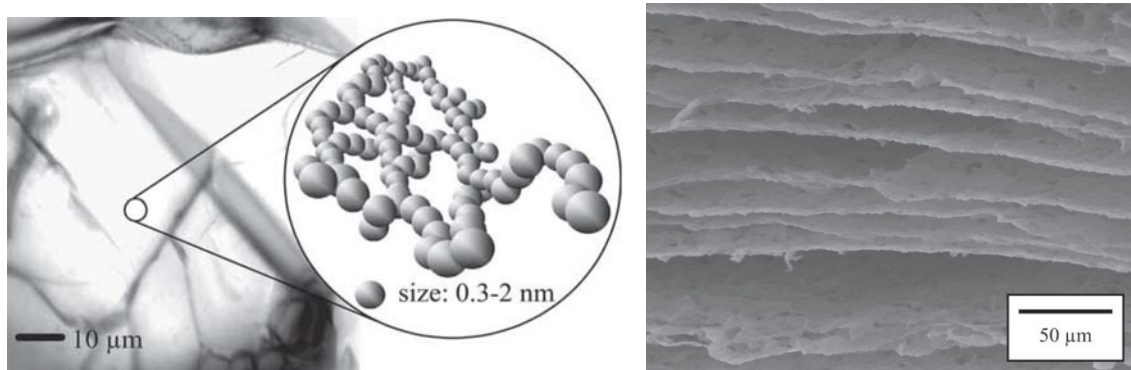


Fig. 21. Structure of the nano-porous SiO_2 network of silica aerogel (Reim et al. 2005) and a Scanning Electron Microscopy SEM image of the structure of clay aerogel (Hostler 2008).

The low gaseous thermal conductivity may be explained using Eq.6: Silica aerogels have both an intrinsic low characteristic pore size δ and a very high porosity. As a result, the gaseous thermal conductivity will have a large influence on the overall thermal conductivity of aerogels, but will at the same time be strongly reduced due to the Knudsen effect at ambient pressure. As brought up before, the gaseous thermal conductivity can be further reduced by filling the aerogel with a gas, by decreasing the maximum pore size and by applying a vacuum in the aerogel. An overall thermal conductivity of 0.008 W/(mK) can be reached for silica-aerogels by applying a pressure of $\sim 50\text{ mbar}$ or less if no attempts are made to decrease the radiation transfer (Smith et al. 1998, Zeng et al. 1994, Richter 1995, Hüsing 1998, Ramakrishnan et al. 2007).

Silica-aerogels are reasonable transparent in the infrared. The radiative transfer will become a dominant factor of thermal conductivity at higher temperatures ($> 200^\circ\text{C}$), but will represent no problem at low temperatures. Radiative transfer can be suppressed by adding an additional component to the aerogel (before or after the critical drying) that either absorbs or scatters infrared radiation, e.g. carbon black. In this way, the overall thermal conductivity at ambient pressure can be decreased to a value of 0.0135 W/(mK) at ambient pressure and to 0.004 W/(mK) at a pressure of $\sim 50\text{ mbar}$ or less.

Silica aerogels have interesting optical properties. It has a high transmittance of radiation within the range of visible light. However, reflected light appears bluish and transmitted light appears slightly yellow. The scattering of the light can be explained by bulk or Rayleigh scattering and by exterior surface scattering. This Rayleigh scattering is caused by interaction with in-homogeneities in solids, liquids or gases (e.g. dust particles in atmosphere) and becomes more effective when the size of the particles is similar to the wavelength of the incident light (380 up to 780 nm for visible light). The presence of a certain number of pores within this range can act as so-called 'scattering centres'. The efficiency of scattering will depend on the size of the scattering centres, while different wavelengths of radiation will scatter with different magnitudes. A heating-treatment of the aerogels can increase their transparency furthermore with ~ 6 % to a value of 76 % (Jensen et al. 2004) due to water desorption and burning of organic components. Furthermore, the optical properties can be influenced by parameters of the sol-gel process by selecting optimal synthesis parameters (Smirnova 2002, Ramakrishnan et al. 2007).

7. Beyond vacuum insulation panels

The reduction of the gaseous conductivity of a material using vacuum technology and low conductivity gases has meant a big leap in thermal insulation. While the traditional insulation materials developed before the 1960s had a theoretical minimum thermal conductivity equalling the thermal conductivity of air, the new developed insulation materials have initial thermal conductivities up to 10 times lower than this limit.

But also for these new high performance insulating solutions, strong restrictions were found: Although current vacuum insulation panels seem highly promising with their thermal conductivities between 0.004 and 0.008 W/(mK), it became clear that VIPs are a very delicate system. Damaging the envelope can severely and rapidly increase the thermal transmittance of a large area. Such a process will slowly occur anyway because of gas and water vapour intake through time, while also the need for metals in the common VIP envelope increases the overall thermal conductivity, compared to the remarkable low centre-of-panel conductivity of VIPs.

7.1 Possible improvements for current VIPs

Based on previous chapters, some possible improvements could be brought up to reduce the effective thermal conductivity or to prolong service life of currently common VIPs. The development of a core material with a lower solid core conduction could bring the centre-of-panel thermal conductivity of a VIP further down. Also the development of a polymer envelope material that no longer needs metal layers to maintain the inner lower pressure may result in a lower effective heat transmittances. The development of a higher quality of air and moisture tight envelope could extend the service life of current VIPs for the same defined criteria, while also a core material with smaller pores could prolong the service life, when a high quality vacuum is no longer necessary due to the Knudsen effect.

Such improvements are likely to occur in the coming decade(s), but it might be questionable if they would mean a new big leap forward in high performance thermal insulating materials.

7.2 New high performance thermal insulation materials

To come to such a new big leap in high performance thermal insulating materials, different question may be asked:

- *Is it possible to develop a vacuum insulation material or gas insulation material based on the same principles but without its disadvantages?*
- *May we develop a material that does not need an envelope or that is not affected by gas and water vapour intake over time?*
- *May we combine both the technology of VIPs and GFPs to achieve a more robust high performance thermal insulating material?*

Based on the above asked question, a possible division may be made in potential new high performance insulation materials: A first group can be found in *core-based materials with no envelope* using vacuum-technology to achieve high performance thermal properties, resulting in a material that can be cut, placed and handled on-site like traditional insulation materials, e.g. mineral wool, expanded polystyrene (EPS) and extruded polystyrene (XPS). A second group can be found in *envelope-based solutions with no core*, i.e. a surrounded vacuum space. Such solutions, e.g. as a special case small vacuum spheres, may then be applied as loose-fill insulation in building envelopes. Both groups of potential VIMs deal on their own way with the current limitations in vacuum technology in order to achieve a high performance thermal material or solutions. Both options will be questioned in the next chapters.

One of the main issues for common VIPs is the vacuum-maintaining envelope around the core material, putting strong limitations on the application of it in building envelopes. Where traditional insulation materials can be ordered en-masse, the envelope of VIPs makes it necessary to pre-calculate and fabricate every single vacuum panel since on-site adaptation is impossible. Can we develop a high performance thermal insulation material that no longer needs this envelope, leaving only the core material while still applying vacuum technology to come to a high performance thermal insulation material? Three possibilities to come to such a material can be concluded from previous Chs.1-4: A first possibility can be found in the pore construction. The core material of current VIPs is 100 % open porous, where a possible solution can be found in porous materials with 100 % closed pores, maintaining the vacuum on the level of the pores. A second possibility may be found in the so-called 'Knudsen effect', where the need of a vacuum is expressed as function of the pore sizes. Influencing the pores sizes and pore size distribution can lead to the need for a vacuum of much lower quality or even evolve in a material that no longer needs a vacuum but that is still based on the principles of vacuum technology. A third possibility may be found in the combination of both possibilities. All three possibilities will be addressed.

Another option was proposed combining the structure of GFPs with vacuum technology, leaving the core material behind and resulting in only a stiffened vacuum envelope. In this way, the two main factors (solid thermal conduction λ_{cd} and gaseous thermal conductivity λ_g) are almost completely excluded, leaving only radiation as the main heat transfer. However, the structure of GFPs result from the fact that gasses are applied at atmospheric pressure and that no forces have to be transferred, where in VIPs the forces up to 1 bar (100 kPa) due to the vacuum are transferred by the core material. A solution can be found in the shape of the vacuum envelope: It is commonly known that spheres are most resistant to vacuum or high gas pressures in such a way that an internal pressure of 1.5 mbar is no problem. However, these solutions consist mostly of heavy metal spheres to prevent the sphere from collapsing. They can still form a solution if the size of the spheres can be kept in the range of millimetres or micrometres to reduce forces in such way that a low-conductivity material can be used to form the spheres. Such spheres can then be applied in buildings as loose-fill insulation or repacked in panels.

7.3 Vacuum insulation materials (VIM)

As previously brought up, a closed-porous material could have a high potential as possible vacuum insulation material or VIM which no longer requires a panel envelope to maintain an inner vacuum. Such a vacuum insulation material (VIM) can be defined as *a material that is basically homogenous and which achieves its high performance thermal insulating qualities due to vacuum technology in its closed-porous structure.*

A first requirement for such a VIM are pores closed for air which maintain a vacuum on the scale of the pores and making an envelope no longer necessary. This would result in a material that can be cut on-site and for which damaging by perforation with a nail only would lead to a local thermal bridge. On such places, only a certain limited amount of pores will be ventilated, instead of a whole large region as for VIPs. A closed-porous material may even have other advantages compared to open-porous materials: An open-porous structure could result in capillary condensation of water after a long exposure to humid circumstances. Here, materials with closed pores are more desirable because of its useful properties as mechanical strength and resistance to humidity (Pei et al. 2004).

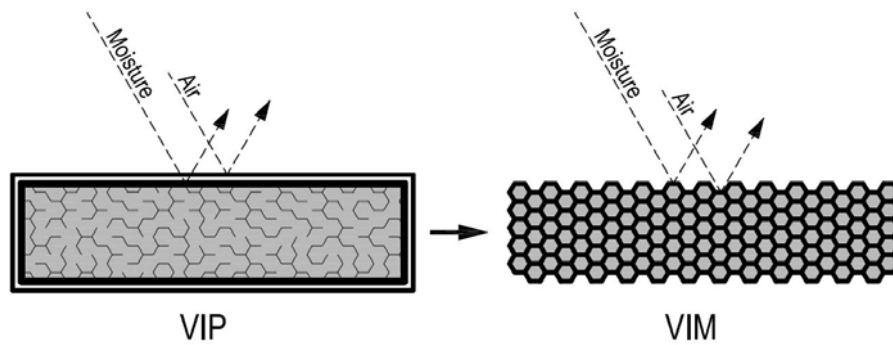


Fig.22. Closed-porous materials may make it possible to avoid the envelope necessary to maintain the inner vacuum in the material, i.e. making a so-called vacuum insulation material (VIM).

However, one of the restrictions stated for VIP core materials is a 100 % open-porous structure. This is necessary to be able to evacuate the material. A closed porous material where intake of air does not occur through time, means on the same time that a vacuum can not be achieved in the pores by evacuation as in common VIPs because both are based on the same principles. Solutions for this problem may be found in the production of the material under vacuum conditions (or only for the production stage where the closed-pores are formed) or in chemical binding of the air in the pores.

The synthesis of closed porous silica has been studied recently (Pei et al. 2004, Pei et al. 2005) in order to develop an increased resistance to humidity and mechanical strength. The closed-pores were synthesized by incorporating rapid drying with the sol-gel process (see Ch.3.1.1 on the production of aerogel) and the effect of the drying temperature on the closed porosity of the silica has been studied.

“Closed porous silica were synthesized (...) from starting agents with the molar ratio of 0.04 TEOS, 1 H₂O, 0.022 ethanol and 0.001 HCl. These were mixed and stirred at room temperature until a transparent solution was obtained after the completion of hydrolysis of TEOS in the acidic condition. Then pluronic® F127 is dissolved (...) with a weight fraction to that of water of 0.1. The solution was rapidly dried (...) and a complete desiccation was carried out using a drying over for a few hours. The final calcinations was carried out at 600°C for 5 h in air to completely remove the copolymer as the structure-directing agent.” (Pei et al. 2004, pp.663-664)

The effect of closed pores can be forced by controlling the temperature of the rapid drying. Higher temperatures, which cause more rapid drying, are expected to promote the formation of the closed pores due to the more instant solidification (see Fig.23). So far, silica with a closed-porosity up to 48 % has been obtained at a drying temperature of 200°C (Pei et al. 2005). However, it can be stated that higher temperatures above 150°C also promote the formation of the open pores (Pei et al. 2004). However the development of partial closed-porous silica do not seem to be a problem with current technology, no information is found on full-closed-porous materials or the application of vacuum within these pores.

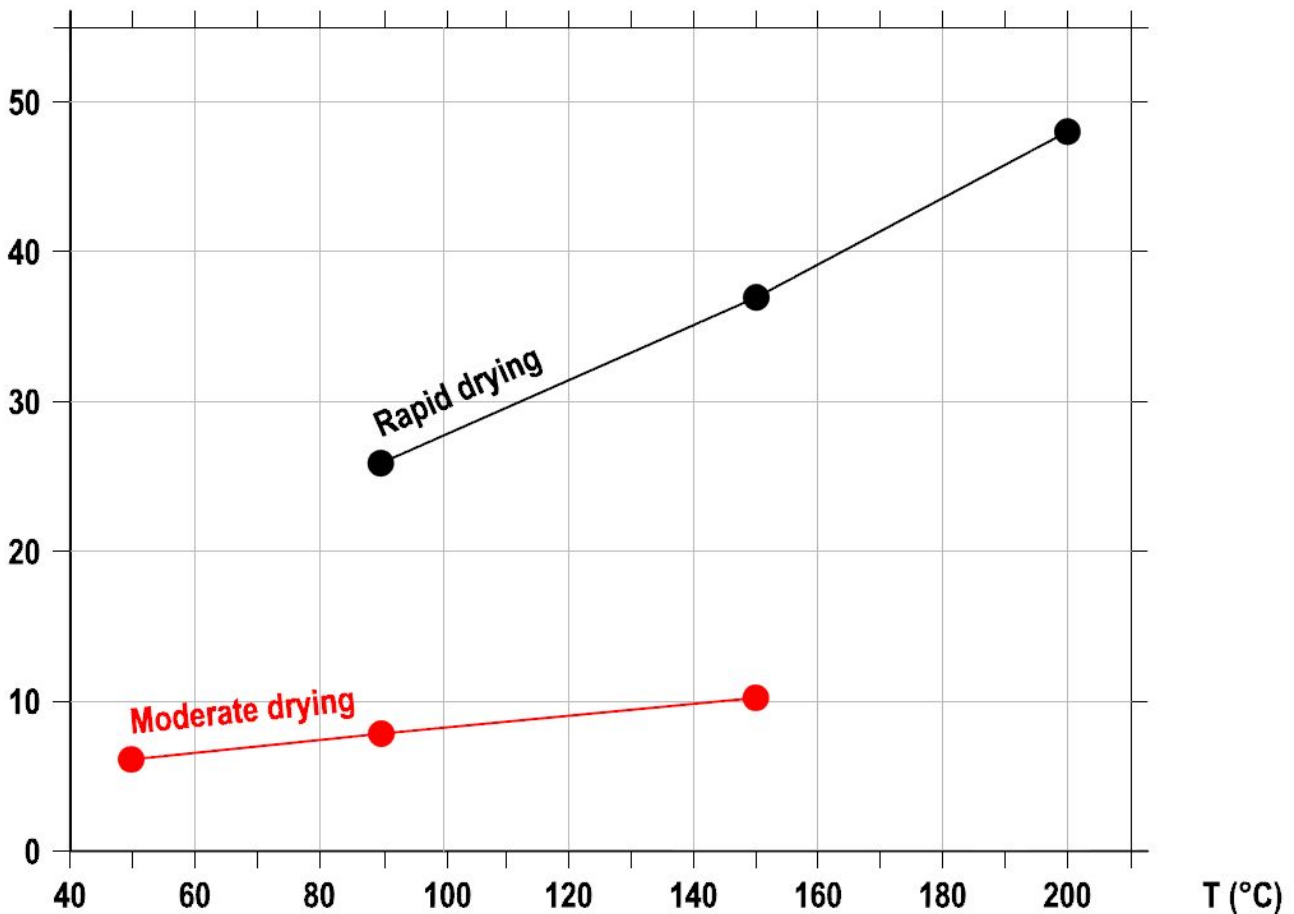
Closed porosity (%)

Fig.23. Dependence of closed porosity on the drying temperature for silica (redrawn from Pei et al. 2005).

7.4 Nano insulation materials (NIM)

A nano insulation material or NIM may be defined as *a material that is basically homogeneous and which achieves high performance thermal insulating qualities mainly due to its open or closed nanoporous structure.*

The principle of vacuum insulation panels is based on the Knudsen effect, generally describing that the gaseous thermal conductivity λ_g can be influenced by controlling both the mean free path l_{mean} of the gas and maximum pore size δ of the medium. While reducing the gas pressure in a material, the gas conductivity remains almost unaffected until the mean free path of the gas molecules reaches values in the same order of size as the largest pores in the medium. When the pore diameter of the material becomes less than the average free length of path of gas molecules, the air molecules will only collide with the pore surfaces without transferring energy by this elastic impact.

It could be stated that a certain vacuum is no longer required if a material is used with a maximum pore size much smaller than l_{mean} of free air. Such so-called 'mesoporous materials' with a pore size δ of 50 nm or less or 'microporous materials' with a pore size δ of 2 nm or less, could reduce the gaseous thermal conductivity without applying a vacuum, thus achieving a nano insulation material (NIM). A gaseous thermal conductivity of 0.2 mW/(mK) can be found for pore sizes of 2 nm according to Eq.4. Furthermore, degradation of the overall thermal conductivity because of gas penetration can be neglected because air is allowed in the pores and an air-tight envelope is no longer necessary.

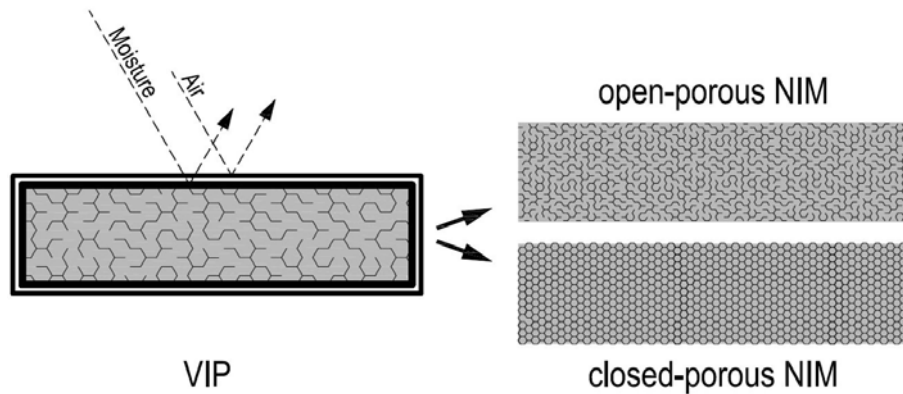


Fig.24. Manufacturing materials with a low-conductivity solid state lattice filled with tiny nano pores may make it possible to avoid the envelope necessary to maintain the inner vacuum in a VIP (as a vacuum is no longer necessary to reduce the gaseous thermal conductivity to a minimum), resulting in a nano insulation material (NIM) with an open pore structure. In addition, nano structures may also be used to make a closed-porous NIM with or without vacuum in the pores.

Aerogel is one of the materials that has a low thermal conductivity at ambient pressure partly because of the Knudsen effect. Common aerogels have mean pore sizes between 10 and 40 nm, but will furthermore also have pores with sizes up to 100 nm. The development of such a new material can be positioned at the branch of nanotechnology, a technology generally described as ‘dealing with structures of 100 nm or smaller’.

Most well-known mesoporous materials are aluminium oxide or oxides of the metals ^{41}Nb , ^{73}Ta , ^{22}Ti , ^{40}Zr and ^{50}Sn with high thermal conductivities. However, a mesoporous silica was developed in the early 1990s by the oil company ‘Mobil’, resulting in materials called MCM-41 with pore sizes between 1.5 and 10 nm (Beck et al. 1992) and SBA-15 with pore sizes between 4.6 and 30 nm (Zhao et al. 1998) (see Fig.25). Since then, much research has been done on the development of mesoporous materials, proved by the appearance of the journal ‘Microporous and Mesoporous Materials’ of Elsevier. The pore size of the materials can be modulated during the synthesis by controlling the reaction time and temperature, by using swelling organic molecules, by adjusting the surfactant, by post-synthesis or changing the calcinations conditions (Giraldo et al. 2007).

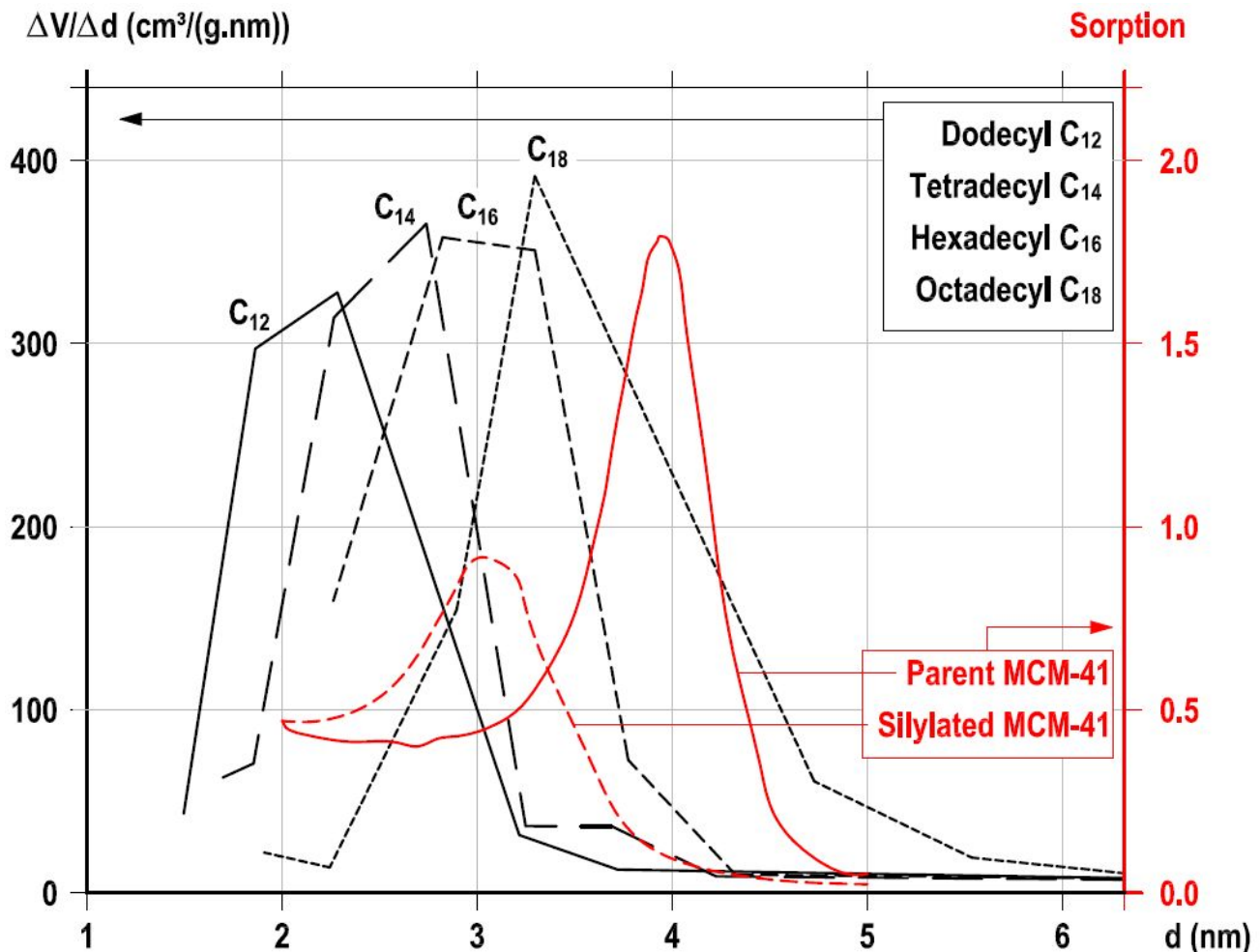


Fig.25. Pore size distribution of MCM-41 (redrawn from Beck et al. 1992) and of (mesoporous) calcinated products (redrawn from Kuroda 1996) with even smaller pore sizes. The development of mesoporous materials do not seem to be a problem with current technology, though no information is found on the thermal conductivities of these materials.

As shown can both the Knudsen effect and a closed-porous material have a potential as high performance insulating material. However, a 100 % closed porous material is currently unlikely and as a result, intake of air and water vapour will occur as in the current VIPs due to the pressure differences. The combination of both ideas behind VIM and NIM could result in a material that will degrade through time, but prolonged in service life because the driving forces are reduced by the need for a low-quality vacuum resulting from the Knudsen effect. It was brought up before in Ch.7.3 that (partially) closed-porous silica have been developed by Pei et al. (2004, 2005). It was not mentioned that these developed materials were mesoporous and that (partially) closed-porous silica with a pore size ≤ 7 nm have been developed. However, a contradiction may be concluded: Rapid drying will increase the amount of closed pores, while in addition, rapid drying will result in the formation of larger pores. Although, the formed pores were still of moderate small size (≤ 12 nm).

7.5 Gas insulation materials (GIM)

Similar as for VIMs can a gas insulation material (GIM) be defined as *a material that is basically homogenous and which achieves its high performance thermal insulating qualities due to a low gas-fill in its closed-porous structure.*

The idea was brought up previously to apply a vacuum by binding the molecules of the present air. However, it was mentioned that air consists mainly of triple bond nitrogen, which is almost inert. Replacing the air molecules with other gas molecules during the production process of the material can make it possible to chemically bind these molecules (with the solid material) with vacuum as a result. However, the same problem may appear here: Most low-conductive gasses are noble gasses such as argon (see Fig. 26), krypton or

xenon, which may make it impossible to bind them. Other (non-inert) gases are needed here. If no vacuum is aimed at and the low gaseous conductivity is aimed based on the Knudsen-effect, replacing air molecules with a low thermal conductive gas can result faster in a high performance thermal insulation material.

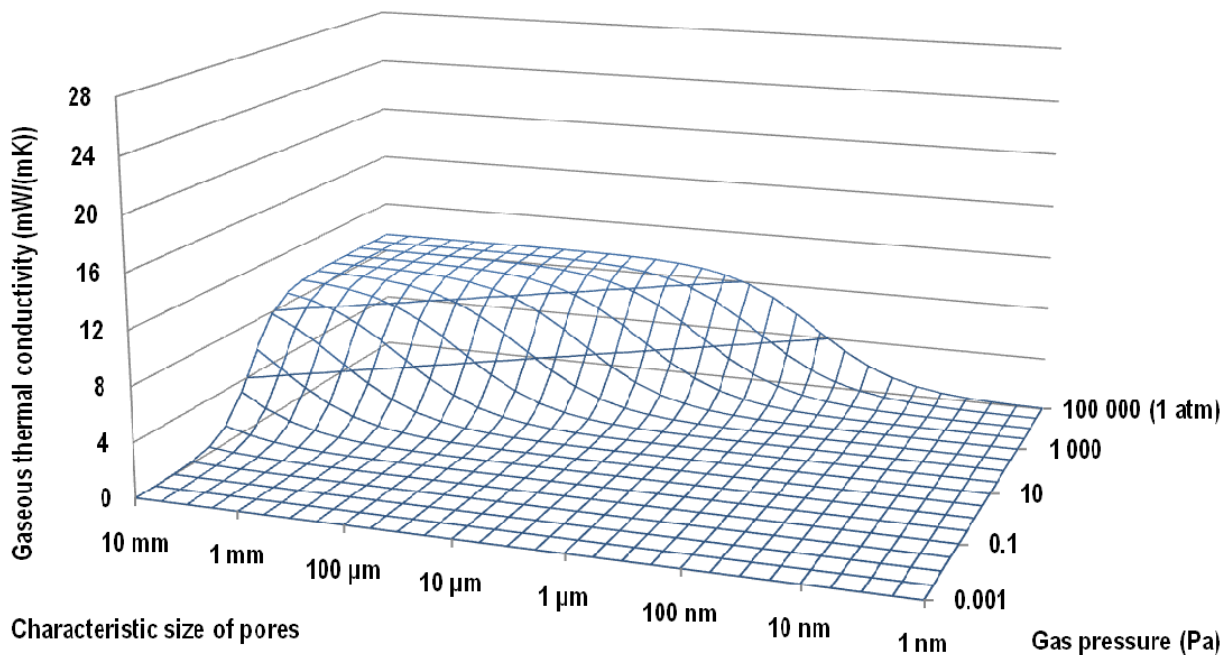


Fig. 26. Gaseous thermal conductivity of krypton (mW/(mK)) as function of the materials characteristic pore size and the gaseous pressure at a temperature of 300 K. The values have been retrieved from Eq.4-5 representing the Knudsen effect. Compare with Fig.3 (air).

7.6 Dynamic insulation materials (DIM)

Previous discussed possible solutions may lead to an insulation material with a very low thermal conductivity as based on the static definition of thermal insulation. *But can the future of high performance thermal insulation materials be found in such a static or single-value definition? Is it true that high thermal resistance is of great importance for building envelopes?* Introducing insulation layers with a high thermal resistance has strongly reduced the energy consumption during the heating season. However, an increasing use of home electrical equipment in combination with a high thermal resistance and a higher air-tightness of the building envelope have introduced the problem of cooling in many buildings. The high thermal resistance of the wall may in the cooling season indirectly be a reason for an increased energy consumption.

Building envelopes with variable properties seem in this point of view much more favourable to decrease the overall energy consumption of a building. Adapting the thermal performances to the (changing) environmental conditions and user needs can lead to energy savings. A similar approach is already noticed in building glazing: Where first only the U-value of a window was of great importance, this has changed by a desire for dynamically regulate terms as the solar factor, the visible transmittance, etc. leading to the development of electrochromic windows. Such windows are able to strongly control the daylight illuminance and the solar heat gains, resulting in stronger control of the cooling loads, the use of electrical light, comfort conditions, etc (Jelle & Hagen 1999, Jelle et al. 2007). It is maybe even not their annual energy impact that is of most importance, but their performance at peak times resulting in more economical performing and downsized heating, ventilating and air-conditioning (HVAC) systems.

Such a dynamic insulation material or DIM may be defined as *a material which has controllable thermal insulating properties within a desirable range.*

7.6.1 Dynamic vacuum

One question now is whether dynamic properties may also be introduced for insulation materials. Or in other words, *is it possible to come to an insulation material with a controllable thermal conductivity? And which advantages has such a material compared to static values?* Controllable thermal conductivity would suggest that we can control a certain (or multiple) mechanism(s) of heat transfer in such way that we can vary the total heat transfer through the material within a wide range. In theory, this varying of thermal conductivity is something that is already achieved and discussed in this review: By controlling the internal pressure, we are able to vary the gaseous component of the overall thermal conductivity of the material. In this way values between 0.004 and 0.020 W/(mK) may be obtained for fumed silica, or even higher values if inner overpressure is allowed. However, controlling the inner pressure in common VIPs would be unwieldy: Ventilating and evacuating such a large volume requests much electrical power. This stands in strong contrast with the principles of electrochromic glazing, where the control of irradiance is achieved with a minimum of electrical potential. *Is such an economic process also achievable for varying the thermal conductivity based on vacuum technology?*

A solution may be once more found in a so-called closed-porous vacuum insulation material VIM with chemical binding of the gasses. *What if the chemical binding of the inner gasses (with the solid structure) can be achieved by applying a relative small electrical potential? What if the balance between binding and releasing the gas molecules can be achieved within a small range of different electrical potentials?* However, it can be questioned now whether chemical binding of the gasses is necessary. *What if we, instead of chemically binding the gas molecules, make them immobile for heat transfer?* Electrically charged gas molecules could be immobilized by applying a potential, making them physical attracted by the opposite charged pore structure without chemical binding.

Such a dynamic vacuum has been yet achieved in the nineties ([Patent DE 196 47 567 A 1](#)) by controlling the reversible properties of the applied getters and desiccants by applying an electrical potential, resulting in an electric consumption of about 5 W/m².

7.6.2 Dynamic emissivity of inner pore surfaces

It was found that the overall thermal conductivity could be controlled by adapting the inner gas pressure in the material. However, the gaseous thermal conductivity is only one term of the overall performance. Another possibility may be found in controlling the emissivity of the pore surfaces. However, in order to obtain reflection modulation of a material, the material has to be crystalline so injected or extracted electrons can be free. Changing the free electron density changes the plasma wavelength λ_p , making it possible to regulate the reflectance. Increasing the electron density results in an increasing λ_p , moving the reflectance edge to lower wavelengths (see [Fig. 27](#)) and vice versa. Materials with a high free electron density will be high reflecting materials, while a material with a low free electron density has a low reflectivity ([Jelle 1993](#)).

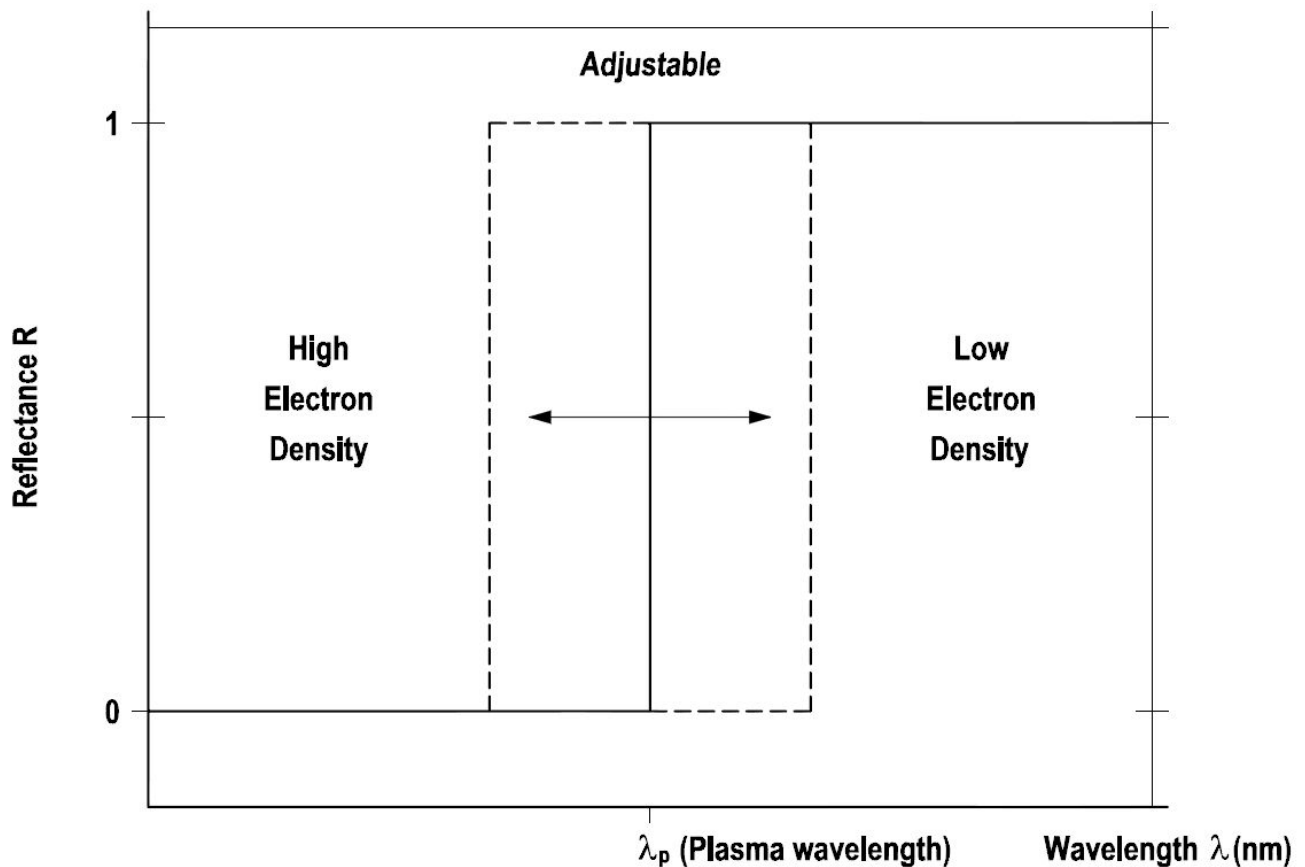


Fig. 27. Step-like variation of the reflectance R in an ideally electrochromic material as function of the wavelength λ (nm) (redrawn from Jelle 1993). The plasma wavelength may be defined as $\lambda_p = (2\pi c/q_e)(m_e \epsilon_0/n_e)^{1/2}$, where c , q_e , m_e , n_e and ϵ_0 denote the velocity of light, the electron charge, the free electron effective mass, the free electron density and the dielectric coefficient of vacuum, respectively.

7.6.3 Dynamic solid core thermal conductivity

One might also envision to be able to regulate the solid core thermal conductivity which may contribute to a fully dynamic controllable vacuum insulation material. Possible ways to accomplish this may be by application of electrical fields in order to change the structure, electron density, chemical bonds, etc. in the material lattice. The fundamental understanding of the thermal conductance has to be explored in order to achieve such a dynamic solid core conductivity.

7.7 New thoughts and ideas

The previously mentioned list of ideas ‘beyond VIPs’ is meant as a feasibility study for future insulation materials and is not exhaustive. The brought up concepts are still based on a classic point of view where thermal insulation materials mainly only have to fulfil their function of reducing heat transfer through a building envelope, while many other ideas, e.g. load bearing insulation materials, could be brought up to come back to “the building envelope as the climate regulating skin it once was” (Cohen & Heijnis 2007).

8. Conclusions

Vacuum insulation panels (VIPs) in their current form can result in a strong reduction of energy consumption if they are properly installed. It was even proven (IEA/ECBCS 2005) that the requirements of the Kyoto-

protocol are easily met if every non-insulated building currently existing in the European Union is insulated with a layer of only 2 cm thick VIPs. However, the proper application of VIPs is problematic because of factors as fragility, no possibilities for adaption at the building site, high cost, thermal bridges and decreasing thermal properties through time. It might also be difficult or challenging to introduce new solutions within existing building traditions.

Concepts for advancing beyond VIPs are investigated, where possible solutions such as e.g. vacuum insulation materials (VIMs) and nano insulation materials (NIMs) are introduced.

Acknowledgements

This work has been supported by the Research Council of Norway, AF Gruppen, Glava, Hunton Fiber as, Icopal, Isola, Jackson, maxit, Moelven ByggModul, Rambøll, Skanska, Statsbygg and Takprodusentenes forskningsgruppe through the SINTEF/NTNU research project "Robust Envelope Construction Details for Buildings of the 21st Century" (ROBUST).

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