Traditional, State-of-the-Art and Future Thermal Building Insulation Materials and Solutions - Properties, Requirements and Possibilities

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Abstract

The advantages and disadvantages of the thermal building insulation materials and solutions have been treated. Both traditional, state-of-the-art and possible materials and solutions beyond these have been investigated. Examples of these may be mineral wool, expanded polystyrene, extruded polystyrene, polyurethane, vacuum insulation panels, gas insulation panels, aerogels, and future possibilities like vacuum insulation materials, nano insulation materials and dynamic insulation materials. Various properties, requirements and possibilities have been compared and studied. Among these are thermal conductivity, perforation vulnerability, building site adaptability and cuttability, mechanical strength, fire protection, fume emission during fire, robustness, climate ageing durability, resistance towards freezing/thawing cycles, water resistance, costs and environmental impact.

Currently, there exist no single insulation material or solution capable of fulfilling all the requirements with respect to the most crucial properties. That is, for the buildings of today and the near future, several insulation materials and solutions are used and will have to be used depending on the exact circumstances and specifications. As of today, new materials and solutions like e.g. vacuum insulation panels are emerging, but only slowly introduced in the building sector partly due to their short track record. Therefore it will be of major importance to know the limitations and possibilities of all the insulation materials and solutions, i.e. their advantages and disadvantages. In this respect new conceptual thermal building insulation materials are also discussed.

KEYWORDS: Traditional, State-of-the-art, Future, Thermal insulation, Building insulation, Properties, Requirements, Possibilities, Thermal performance, Robustness.

Content

1. Introduction

As the energy use in the building sector accounts for a significant part of the world's total energy use and greenhouse gas emissions, there is a demand to improve the energy efficiency of buildings. Hence, in this respect, concepts like passive houses and zero emission buildings are being introduced. In order to meet the demands of an improved energy efficiency, the thermal insulation of buildings plays an important role. To achieve the highest possible thermal insulation resistance, new insulation materials and solutions with low thermal conductivity values have been and are being developed, in addition to using the current traditional insulation materials in ever increasing thicknesses in the building envelopes. However, very thick building envelopes are not desirable due to several reasons, e.g. considering space issues with respect to both economy, floor area, transport volumes, architectural restrictions and other limitations, material usage and existing building techniques. It should also be noted that recent studies (McKinsey 2009) point out that energy efficiency measures are the most cost-effective ones, whereas measures like e.g. solar photovoltaics and wind energy are far less cost-effective than insulation retrofit for buildings.

The objective of this work is to investigate and compare the various properties, requirements and possibilities for traditional, state-of-the-art and possible future thermal building insulation materials and solutions, their weaknesses and strengths, disadvantages and advantages.

2. Thermal background

The main key property of a thermal building insulation material or solution is the thermal conductivity, where the normal strategy or goal is to achieve as low thermal conductivity as possible. A low thermal conductivity (W/(mK)) enables the application of relatively thin building envelopes with a high thermal resistance (m^2K/W) and a low thermal transmittance U-value ($W/(m^2K)$). The total overall thermal conductivity λ_{tot}, i.e. the thickness of a material divided by its thermal resistance, is in principle made up from several contributions:

$$\lambda_{tot} = \lambda_{solid} + \lambda_{gas} + \lambda_{rad} + \lambda_{conv} + \lambda_{coupling} + \lambda_{leak} \qquad (1)$$

where

λ_{tot} = total overall thermal conductivity
λ_{solid} = solid state thermal conductivity
λ_{gas} = gas thermal conductivity
λ_{rad} = radiation thermal conductivity
λ_{conv} = convection thermal conductivity
$\lambda_{coupling}$ = thermal conductivity term accounting for second order effects between the various thermal conductivities in Eq.1
λ_{leak} = leakage thermal conductivity

In order to reach a thermal conductivity as low as possible, each of the above thermal contributions have to minimized. Normally, the leakage thermal conductivity λ_{leak}, representing an air and moisture leakage driven by a pressure difference, is not considered as insulation materials and solutions are supposed to be without any holes enabling such a thermal leakage transport. The coupling term $\lambda_{coupling}$ can be included to account for second order effects between the various thermal conductivities in Eq.1. This coupling effect can be quite complex and will be neglected in the rest of this article. Theoretical approaches to thermal performance of vacuum insulation panels (VIP) usually assume this coupling effect to be negligible. For further information see e.g. Heinemann (2008). In general, another coupling term might also be included in Eq.1, i.e. the interaction between the gas molecules and the solid state pore walls. However, as we will see later this last coupling term is included through a factor in the expression for the gas conductivity as given in Eq.2 for the Knudsen effect.

The solid state thermal conductivity λ_{solid} is linked to thermal transport between atoms by lattice vibrations, i.e. through chemical bonds between atoms. The gas thermal conductivity λ_{gas} arise from gas molecules colliding with each other and thus transferring thermal energy from one molecule to the other. The radiation thermal conductivity λ_{rad} is connected to the emittance of electromagnetic radiation in the infrared (IR) wavelength region from a material surface. The convection thermal conductivity λ_{conv} comes from thermal mass transport or movement of air and moisture. All these thermal conductivity contributions is driven by or dependent upon the temperature or temperature difference. The various thermal insulation materials and solutions utilize various strategies to keep these specific thermal conductivities as low as possible.

The thermal building insulation materials and solutions also have to fulfil a series of requirements with respect to other properties than the thermal conductivity. These other requirements may put restrictions on or challenges to how low thermal conductivities it will be possible to obtain with the selected materials and solutions.

3. Traditional thermal building insulation

In the following there is given a short description of the most common traditional thermal building insulation materials of today with a relatively low thermal conductivity. An overview of traditional thermal insulation materials may be found in the works by Al-Homoud (2005) and Papadopoulos (2005).

3.1 Mineral wool

Mineral wool covers glass wool (fibre glass) and rock wool, which normally is produced as mats and boards, but occasionally also as filling material. Light and soft mineral wool products are applied in frame houses and other structures with cavities. Heavier and harder mineral wool boards with high mass densities are used when the thermal insulation is intended for carrying loads, e.g. on floors or roofs. Mineral wool may also be used as a filler material to fill various cavities and spaces. Glass wool is produced from borosilicate glass at a temperature around 1400ºC, where the heated mass is pulled through rotating nozzles thus creating fibres. Rock wool is produced from melting stone (diabase, dolerite) at about 1500ºC, where the heated mass is hurled out from a wheel or disk and thus creating fibres. In both glass wool and rock wool dust abatement oil and phenolic resin is added to bind the fibres together and improve the product properties. Typical thermal conductivity values for mineral wool are between 30 to 40 mW/(mK).

The thermal conductivity of mineral wool varies with temperature, moisture content and mass density. As an example, the thermal conductivity of mineral wool may increase from 37 mW/(mK) to 55 mW/(mK) with increasing moisture content from 0 vol% to 10 vol%, respectively. Mineral wool products may be perforated, and also cut and adjusted at the building site, without any loss of thermal resistance.

3.2 Expanded polystyrene (EPS)

Expanded polystyrene (EPS) is made from small spheres of polystyrene (from crude oil) containing an expansion agent, e.g. pentane C_6H_{12}, which expand by heating with water vapour. The expanding spheres are bond together at their contact areas. The insulation material is casted as boards or continuously on a production line. EPS has a partly open pore structure. Typical thermal conductivity values for EPS are between 30 to 40 mW/(mK).

The thermal conductivity of EPS varies with temperature, moisture content and mass density. As an example, the thermal conductivity of EPS may increase from 36 mW/(mK) to 54 mW/(mK) with increasing moisture content from 0 vol% to 10 vol%, respectively. EPS products may be perforated, and also cut and adjusted at the building site, without any loss of thermal resistance.

3.3 Extruded polystyrene (XPS)

Extruded polystyrene (XPS) is produced from melted polystyrene (from crude oil) by adding an expansion gas, e.g. HFC, CO_2 or C_6H_{12}, where the polystyrene mass is extruded through a nozzle with pressure release causing the mass to expand. The insulation material is produced in continuous lengths which are cut after cooling. XPS has a closed pore structure. Typical thermal conductivity values for XPS are between 30 to 40 mW/(mK).

The thermal conductivity of XPS varies with temperature, moisture content and mass density. As an example, the thermal conductivity of XPS may increase from 34 mW/(mK) to 44 mW/(mK) with increasing moisture content from 0 vol% to 10 vol%, respectively. XPS products may be perforated, and also cut and adjusted at the building site, without any loss of thermal resistance.

3.4 Cellulose

Cellulose (polysaccharide, $(C_6H_{10}O_5)_n$) comprises thermal insulation made from recycled paper or wood fibre mass. The production process gives the insulation material a consistence somewhat similar to that of wool. Boric acid (H_3BO_3) and borax (sodium borates, $Na_2B_4O_7\cdot 10H_2O$ or $Na_2[B_4O_5(OH)_4]\cdot 8H_2O$) are added to improve the product properties. Cellulose insulation is used as a filler material to fill various cavities and spaces, but cellulose insulation boards and mats are also produced. Typical thermal conductivity values for cellulose insulation are between 40 to 50 mW/(mK).

The thermal conductivity of cellulose insulation varies with temperature, moisture content and mass density. As an example, the thermal conductivity of cellulose insulation may increase from 40 mW/(mK) to 66 mW/(mK) with increasing moisture content from 0 vol% to 5 vol%, respectively. Cellulose insulation products may be perforated, and also cut and adjusted at the building site, without any loss of thermal resistance.

3.5 Cork

Cork thermal insulation is primarily made from the cork oak, and can be produced as both a filler material or as boards. Typical thermal conductivity values for cork are between 40 to 50 mW/(mK).

Cork insulation products may be perforated, and also cut and adjusted at the building site, without any loss of thermal resistance.

3.6 Polyurethane (PUR)

Polyurethane (PUR) is formed by a reaction between isocyanates and polyols (alcohols containing multiple hydroxyl groups). During the expansion process the closed pores are filled with an expansion gass, HFC, CO_2 or C_6H_{12}. The insulation material is produced as boards or continuously on a production line. PUR may also be used as an expanding foam at the building site, e.g. to seal around windows and doors and to fill various cavities. Typical thermal conductivity values for PUR are between 20 to 30 mW/(mK), i.e. considerably lower than mineral wool, polystyrene and cellulose products.

The thermal conductivity of PUR varies with temperature, moisture content and mass density. As an example, the thermal conductivity of PUR may increase from 25 mW/(mK) to 46 mW/(mK) with increasing moisture content from 0 vol% to 10 vol%, respectively. PUR products may be perforated, and also cut and adjusted at the building site, without any loss of thermal resistance.

It should be noted that even if PUR is safe in its intended use it rises serious health concerns and hazards in case of a fire. During a fire PUR will when burning release hydrogen cyanide (HCN) and isocyanates, which are very poisonous. The HCN toxicity stems from the cyanide anion (CN^-) which prevents cellular respiration. Generally, hydrogen cyanide may be found in the smoke from nitrogen (N) containing plastics.

3.7 Other building materials

The thermal conductivities of other building materials, including the load-bearing ones, are normally considerably higher than the thermal conductivity values of the thermal building insulation materials, i.e. the very reason for the need and application of thermal building insulation materials. As a comparison, typical examples may be wood (100-200), carbon steel (55 000), stainless steel (17 000), aluminium (220 000), concrete (150-2 500), lightweight aggregate (100-700), brick (400-800), stone (1 000-2 000) and glass (800), all values in brackets given in mW/(mK).

4. State-of-the-art thermal building insulation

Below there is given a short description of the state-of-the-art thermal building insulation materials and solutions of today. That is, the materials and solutions which are, or which are considered to be, the thermal building insulations with the lowest thermal conductivity today.

4.1 Vacuum insulation panels (VIP)

Vacuum insulation panels (VIP) consist of an open porous core of fumed silica enveloped of several metallized polymer laminate layers, see Fig.1 and Fig.2. The VIPs represent today's state-of-the-art thermal insulation with thermal conductivities ranging from between 3 to 4 mW/(mK) in fresh condition to typically 8 mW/(mK) after 25 years ageing due to water vapour and air diffusion through the VIP envelope and into the VIP core material which has an open pore structure. Depending on the type of VIP envelope, the aged thermal conductivity after 50 and 100 years will be somewhat or substantially higher than this value (see e.g. Fig.3). This inevitable increase of thermal conductivity represents a major drawback of all VIPs. Puncturing the VIP envelope, which might be caused by nails and similar, causes an increase in the thermal conductivity to about 20 mW/(mK). As a result, VIPs can not be cut for adjustment at the building site or perforated without loosing a large part of their thermal insulation performance. This represents another major disadvantage of VIPs.

Several authors have been studying various aspects of VIPs, ranging from analytical models, thermal bridges and conductivity, air and moisture penetration, ageing and service life, quality control and integration of VIPs in building construction, e.g. Beck et al. (2007), Brunner and Simmler (2007, 2008), Caps and Fricke (2000), Caps (2005), Caps et al. (2008), Fricke (2005), Fricke et al. (2006), Grynning et al. (2011), Schwab et al. (2005abcde), Simmler and Brunner (2005ab), Simmler et al. (2005c), Sveipe et al. (2011), Tenpierik and Cauberg (2007a), Tenpierik et al. (2007bc, 2008), Wegger et al. (2011) and Zwerger and Klein (2005), where comprehensive reviews on VIPs for building applications have been made recently by Tenpierik (2009) and Baetens et al. (2010a).

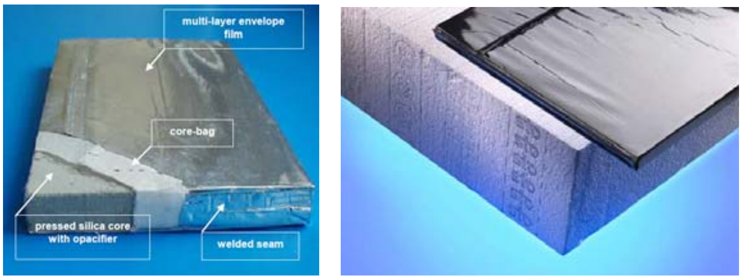

Figure 1. (left) Typical VIP structure showing the main components (Simmler et al. 2005c) and (right) a comparison of equivalent thermal resistance thickness of traditional thermal insulation and VIP (Zwerger and Klein 2005).

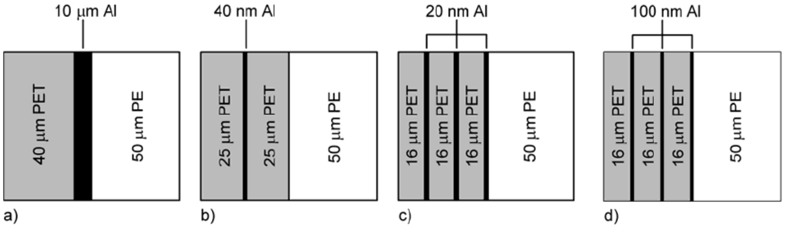

Figure 2. Cross-sections of typical envelope materials for VIPs: (a) Metal film, (b) Single layer metallized film and (c,d) Three layer metallized films. The four foil types are commonly named (a) AF, (b) MF1, (c) MF2 and (d) MF3 in literature (Willems and Schild 2006). Note that different types of foil with the same name are used in literature (Heineman et al. 2005, Brunner et al. 2006).

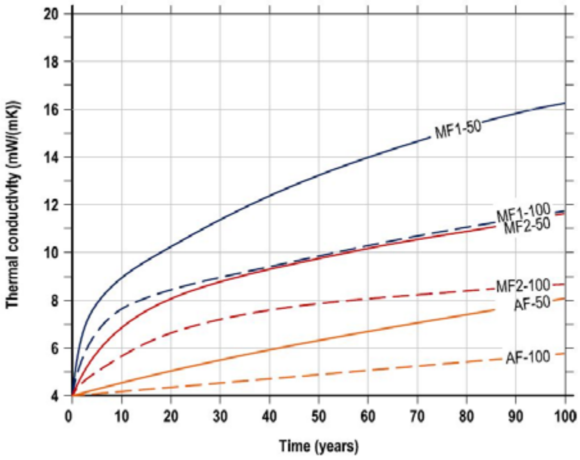

Figure 3. Centre-of-panel thermal conductivity for VIPs with a fumed silica core as function of elapsed time. For two different panel sizes of 50 cm x 50 cm x 1 cm and 100 cm x 100 cm x 2 cm, and for three different foil types AF, MF1 and MF2 (Baetens et al. 2010a).

Despite of the large disadvantages of VIPs, including their relatively high costs, they do represent a large leap forward in thermal insulation for building applications. Thermal conductivities between 5 to 10 times, depending on ageing time, lower than traditional thermal insulation materials like mineral wool and polystyrene products will especially be important when trying to achieve the standard and requirements of passive houses and zero energy or zero emission buildings. Thermal insulation thicknesses up to 50 cm or more in walls and roofs are not desired (see Fig.1 for a visual thickness comparison). Such thick building envelopes might require new construction techniques and skills. In addition, transport of thick building elements leads to increased costs. As an example, height restrictions may apply for passing under several bridges and through tunnels, i.e. thinner elements will bring about a more efficient transport to a reduced cost. Building restrictions during retrofitting of existing buildings, e.g. by the lawful authorities or practical restrictions concerning windows and other building parts, may also require thinner high performance thermal insulation thicknesses than traditional insulation would be able to solve. Furthermore, in areas with a high living area market value per square meter, a reduced wall thickness may involve large area savings and thus a higher value of the real estate. Simple calculations show that for such areas the application of VIPs may actually result in an economic profit (ch. 7.7).

Thus, even if the VIPs are not the ultimate solution for the future, they may be the best solution for many thermal building envelopes today and in the near future, both from a thermal energy savings and an economical point of view. VIP research and advances should be concentrated towards developing VIP envelopes capable of preventing far better air and water vapour from entering into the VIP core for longer time periods up to at least 50 to 100 years. Besides, the research on and application of VIPs contribute to increased knowledge and idea generation about the thermal insulation solutions of tomorrow.

4.2 Gas-filled panels (GFP)

Close to VIPs, in principle, is the technology of gas-filled panels (GFP), studied by Griffith et al. (1993, 1995) and Mills and Zeller (2008) among others. A recent review of GFPs for building applications is given by Baetens et al. (2010c). The GFPs apply a gas less thermal conductive than air, e.g. argon (Ar), krypton (Kr) and xenon (Xe), instead of vacuum as in the VIPs. The barrier foil and baffle structure inside a GFP are shown in Fig.4. To maintain the low-conductive gas concentration inside the GFPs and avoid air and moisture penetration into the GFPs are crucial to the thermal performance of these panels. Vacuum is a better thermal insulator than the various gases employed in the GFPs. On the other hand, the GFP grid structure does not have to withstand an inner vacuum as the VIPs. Low emissivity surfaces inside the GFPs decreases the radiative heat transfer. Thermal conductivities for prototype GFPs are quite high, e.g. 40 mW/(mK), although much lower theoretical values have been calculated. Hence, the GFPs hold many of the VIPs advantages and disadvantages.

Nevertheless, the future of GFPs as thermal building insulation may be questioned or even doubtful, as compared to them the VIPs seem to be a better choice both for today and tomorrow.

Figure 4. Barrier foil and baffle structure inside a GFP (LBNL 2008).

4.3 Aerogels

Aerogels (Fig.5) represent a state-of-the-art thermal insulation solution, and maybe the most promising with the highest potential of them all at the moment, studied by Baetens et al. (2011), Hostler et al. (2008), Schultz et al. (2005) and Schultz and Jensen (2008) among several others. Using carbon black to suppress the radiative transfer, thermal conductivities as low as 4 mW/(mK) may be reached at a pressure of 50 mbar. However, commercially available state-of-the-art aerogels have been reported to have thermal conductivities between 13 to 14 mW/(mK) at ambient pressure (Aspen Aerogels 2008ab). The production costs of aerogels are still very high. Aerogels have a relatively high compression strength, but is very fragile due to its very low tensile strength. The tensile strength may be increased by incorporation of a carbon fibre matrix. A very interesting aspect with aerogels is that they can be produced as either opaque, translucent or transparent materials, thus enabling a wide range of possible building applications. For aerogels to become a widespread thermal insulation material for opaque applications, the costs have to be lowered substantially.

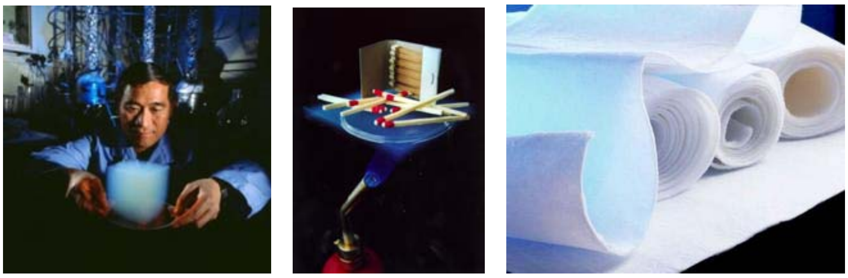

Figure 5. (left) Peter Tsou from NASA with a translucent aerogel sample developed for space missions (NASA 2010), (middle) matches on top of aerogel are protected from the flame underneath (NASA 2010) and (right) an example of aerogel as a high performance thermal insulation material (Aspen Aerogels 2009).

4.4 Phase change materials (PCM)

Phase change materials (PCMs) are not really thermal insulation materials, but since they are interesting for thermal building applications, they are mentioned within this context. PCMs change phase from solid state to liquid when heated, thus absorbing energy in the endothermic process. When the ambient temperature drops again, the liquid PCMs will turn into solid state materials again while giving off the earlier absorbed heat in the exothermic process. Such a phase change cycle stabilizes the indoor building temperature and decreases the heating and cooling loads. Various paraffins are typically examples of PCMs, but a low thermal conductivity (Farid et al. 2004) and a large volume change during phase transition (Hasnain 1998) limit their building application. An overview of the main PCMs has been given by Demirbas (2006), whereas other reviews on PCMs may be found in works by Baetens et al. (2010b), Farid et al. (2004), Hasnain (1998) and Khudhair and Farid (2004). A suitable phase change temperature range, depending on climatic conditions and desired comfort temperatures, as well as an ability to absorb and release large amounts of heat, are important properties for the selection of a specific PCM for building applications. Corresponding melting enthalpies and melting temperatures are depicted for various groups of PCMs in the work by Dieckmann (2006).

5. Nanotechnology and thermal insulation

Shortly we will be seeing that nanotechnology may be applied as a scientific tool to make high performance thermal insulation materials. The normal focus in nanotechnology is to control matter, typical particles, of dimensions between 0.1 nm and 100 nm, i.e. at an atomic and molecular scale. However, for nanotechnology applied for making thermal insulation materials, the focus is shifted from particles to pores in the nano range. These aspects are visualized in Fig.6.

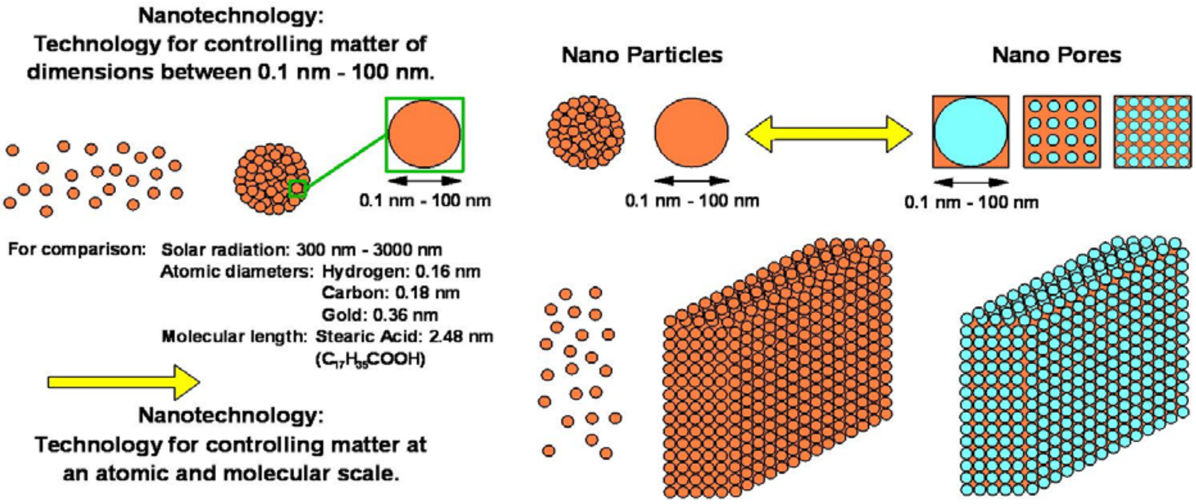

Figure 6. Nanotechnology and its application on high performance thermal insulation materials.

6. Possible future thermal building insulation

Below there is given a short description of possible future thermal building insulation materials and solutions. That is, possible materials and solutions which are thought to may become the high performance thermal building insulation materials and solutions of tomorrow, i.e. the future.

6.1 Vacuum insulation materials (VIM)

A *vacuum insulation material* (VIM) is basically a homogeneous material with a closed small pore structure filled with vacuum with an overall thermal conductivity of less than 4 mW/(mK) in pristine condition (Fig.7). The VIM can be cut and adapted at the building site with no loss of low thermal conductivity. Perforating the VIM with a nail or similar would only result in a local heat bridge, i.e. no loss of low thermal conductivity. For further details on VIMs it is referred to Jelle et al. (2010a).

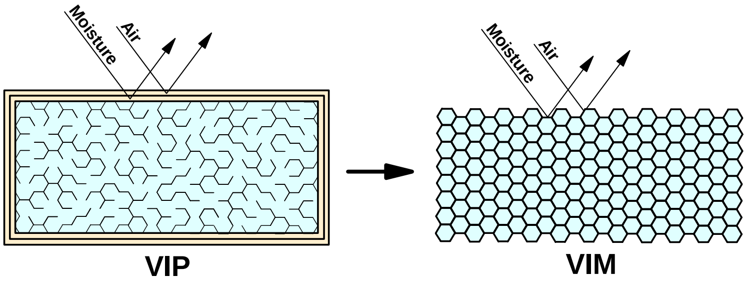

Figure 7. The development from VIPs to VIMs (Jelle et al. 2010a).

6.2 Gas insulation materials (GIM)

A *gas insulation material* (GIM) is basically a homogeneous material with a closed small pore structure filled with a low-conductance gas, e.g. argon (Ar), krypton (Kr) or xenon (Xe), with an overall thermal conductivity of less than 4 mW/(mK) in the pristine condition. That is, a GIM is basically the same as a VIM, except that the vacuum inside the closed pore structure is substituted with a low-conductance gas. For further details on GIMs it is referred to Jelle et al. (2010a).

6.3 Nano insulation materials (NIM)

The development from VIPs to *nano insulation materials* (NIM) is depicted in Fig.8. In the NIM the pore size within the material is decreased below a certain level, i.e. 40 nm or below for air, in order to achieve an overall thermal conductivity of less than 4 mW/(mK) in the pristine condition. That is, a NIM is basically a homogeneous material with a closed or open small nano pore structure with an overall thermal conductivity of less than 4 mW/(mK) in the pristine condition.

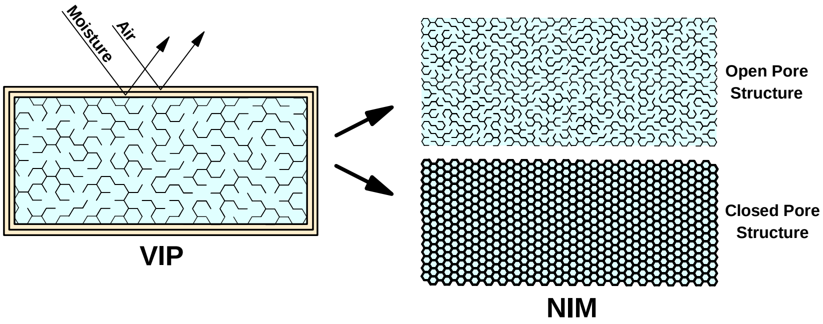

Figure 8. The development from VIPs to NIMs (Jelle et al. 2010a).

The grid structure in NIMs do not, unlike VIMs and GIMs, need to prevent air and moisture penetration into their pore structure during their service life for at least 100 years. The NIMs achieve their low thermal conductivity without applying a vacuum in the pores by utilizing the Knudsen effect. The gas thermal conductivity λ_{gas} taking into account the Knudsen effect may be written in a simplified way as (Baetens et al. 2010a, Jelle et al. 2010a):

$$\lambda_{gas} = \frac{\lambda_{gas,0}}{1 + 2\beta Kn} = \frac{\lambda_{gas,0}}{1 + \frac{\sqrt{2}\beta k_B T}{\pi d^2 p \delta}} \tag{2}$$

where

$$Kn = \frac{\sigma_{mean}}{\delta} = \frac{k_B T}{\sqrt{2}\pi d^2 p \delta} \tag{3}$$

where

λ_{gas} = gas thermal conductivity in the pores (W/(mK))
$\lambda_{gas,0}$ = gas thermal conductivity in the pores at STP (standard temperature and pressure) (W/(mK))
β = coefficient characterizing the molecule-wall collision energy transfer efficiency (between 1.5 – 2.0)
k_B = Boltzmann's constant ≈ $1.38 \cdot 10^{-23}$ J/K
T = temperature (K)
d = gas molecule collision diameter (m)
p = gas pressure in pores (Pa)
δ = characteristic pore diameter (m)
σ_{mean} = mean free path of gas molecules (m)

Decreasing the pore size within a material below a certain level, i.e. a pore diameter of the order of 40 nm or below for air, the gas thermal conductivity, and thereby also the overall thermal conductivity, becomes very low (< 4 mW/(mK) with an adequate low-conductivity grid structure) even with air-filled pores. This is caused by the Knudsen effect where the mean free path of the gas molecules is larger than the pore diameter. That is, a gas molecule located inside a pore will hit the pore wall and not another gas molecule. The resulting gas thermal conductivity λ_{gas} versus pore diameter and gas pressure in pores is depicted in Fig.9. For further details it is referred to the work by Baetens et al. (2010a) and Jelle et al. (2010a).

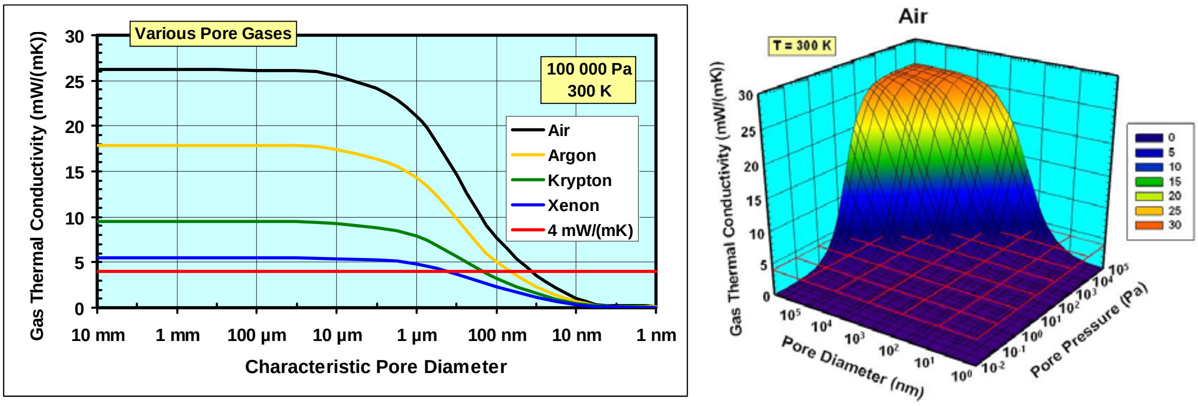

Figure 9. Gas thermal conductivity and a (left) 2D-plot depicting the effect of pore diameter for air, argon, krypton and xenon and a (right) 3D-plot depicting the effect of pore diameter and gas pressure in pores for air (Jelle et al. 2010a).

Applying the Stefan-Boltzmann relationship it may be shown that the radiation thermal conductivity decreases linearly with decreasing pore diameter, where the emissivity of the inner pore walls determine the slope of the decrease. That is, the smaller the pores, and the lower the emissivity, the lower the radiation thermal conductivity will be. However, various works (e.g. Joulain et al. 2005, Mulet et al. 2002, Zhang 2007) describe a large increase in the thermal radiation as the pore diameter decreases below the wavelength of the thermal (infrared) radiation (e.g. 10 μm), where tunneling of evanescent waves may play an important role. The work by Mulet et al. (2002) and Joulain et al. (2005) indicate that the large thermal radiation is only centered around a specific wavelength (or a few). That is, this might suggest that the total thermal radiation integrated over all wavelengths is not that large. How much this actually contributes to the total (overall) thermal conductivity is not known by the authors at the moment, although we believe it is at least rather moderate. Nevertheless, these topics are currently being addressed in on-going research activities. The work by Jelle et al. (2010a) elaborates more on these thermal radiation issues.

The solid state lattice conductivity in the NIMs has to be kept as low as possible in order to obtain the lowest possible overall thermal conductivity. If a low-conductivity solid state lattice and a low gas thermal conductivity are achieved, and which still dominate the thermal transport, i.e. larger than the thermal radiation part, then NIMs may become the high performance thermal insulation material of tomorrow and the future.

6.4 Dynamic insulation materials (DIM)

A *dynamic insulation material* (DIM) is a material where the thermal conductivity can be controlled within a desirable range. The thermal conductivity control may be achieved by being able to change in a controlled manner:

- The inner pore gas content or concentration including the mean free path of the gas molecules and the gas-surface interaction.
- The emissivity of the inner surfaces of the pores.
- The solid state thermal conductivity of the lattice.

Two models exist for describing solid state thermal conductivity. That is, the phonon thermal conductivity, i.e. atom lattice vibrations, and the free electron thermal conductivity. One might ask if it could be possible to dynamically change the thermal conductivity from very low to very high, i.e. making a DIM? Furthermore, could other fields of science and technology inspire and give ideas about how to be able to make DIMs, e.g. from the fields?:

- Electrochromic materials, e.g. smart windows (Baetens et al. 2010d).
- Quantum mechanics.
- Electrical superconductivity.
- Others?

The thermal insulation regulating abilities of DIMs give these conceptual materials a great potential. However, first it has to be demonstrated that such robust and practical DIMs can be manufactured. It is referred to Jelle et al. (2010a) for further details and elaborations concerning DIMs.

6.5 Concrete and applications of NIMs

With decreasing thermal conductivities of insulation materials, new solutions should also be sought for the load-bearing elements of the building envelope. Using concrete as an example, one might envision to mix NIMs into the concrete, thereby decreasing the thermal conductivity of the structural construction material substantially, while maintaining most or a major part of the mechanical strength and load-bearing capabilities of concrete. As concrete has a high thermal conductivity (1700 – 2500 mW/(mK), without and with rebars) a concrete building envelope always has to utilize various thermal insulation materials in order to achieve a satisfactory low thermal transmittance (U-value). That is, the total thickness of the building envelope will often become unnecessary large, especially when trying to obtain passive house or zero energy building standards. Furthermore, the large CO_2 emissions connected to the production of cement, imply that concrete has a large negative environmental impact with respect to global warming due to the man-made CO_2 increase in the atmosphere (McArdle and Lindstrom 2009, World Business Council for Sustainable Development 2002). In fact, the cement industry produces 5 % of the global man-made CO_2 emissions of which (World Business Council for Sustainable Development 2002):

- 50 % from the chemical process
  e.g.: $3CaCO_3 + SiO_2 \rightarrow Ca_3SiO_5 + 3CO_2$
  $2CaCO_3 + SiO_2 \rightarrow Ca_2SiO_4 + 2CO_2$
- 40 % from burning fossil fuels
  e.g. coal and oil
- 10 % from electricity and transport uses

Various applications of NIMs as thermal insulation for concrete are given in Fig.10, i.e. NIM as outdoor and/or indoor retrofitting of concrete, NIM applied in the midst of concrete and NIM mixed together with concrete. As noted above, when mixing NIMs with the concrete, it will be important to maintain a major part of the structural construction capabilities of concrete.

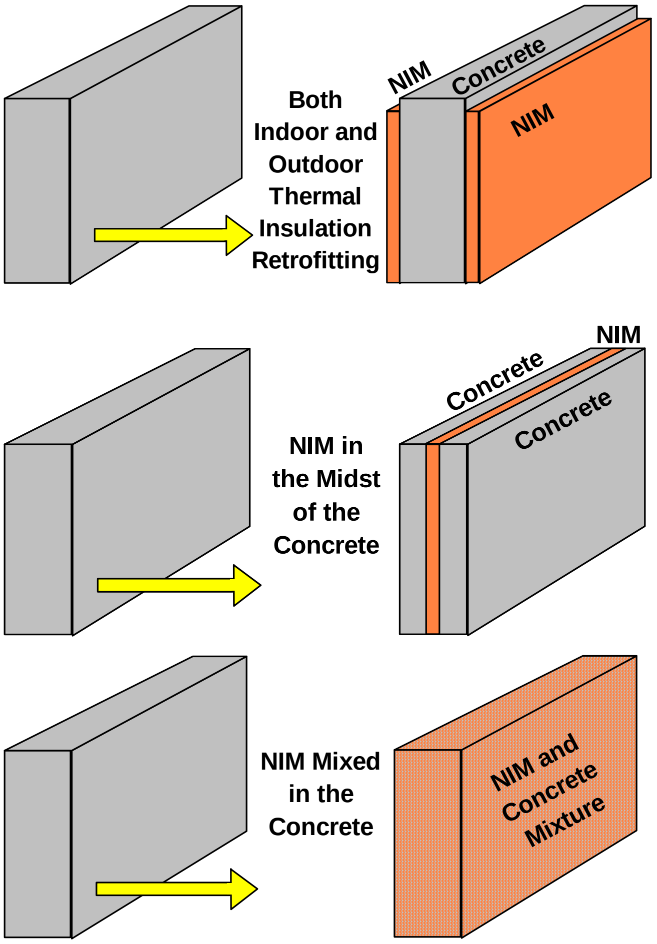

Figure 10. NIMs as thermal insulation for concrete, i.e. (top) NIM as outdoor and/or indoor retrofitting of concrete,(middle) NIM applied in the midst of concrete and (bottom) NIM mixed together with concrete.

6.6 NanoCon

In principle, it is not the building material itself, i.e. if it is steel, glass, wood, mineral wool, concrete or another material, which is important. On the contrary, it is the property requirements or functional requirements which are crucial to the performance and possibilities of a material, component, assembly or building. Thus, one might ask if it is possible to invent and manufacture a material with the essential structural or construction properties of concrete intact or better, but with substantially (i.e. up to several decades) lower thermal conductivity? Furthermore, it would be beneficial if that new material would have a much lower negative environmental impact than concrete with respect to CO_2 emissions. Such a material may be envisioned with or without reinforcement bars, depending on the mechanical properties, e.g. tensile strength, of the material.

With respect to the above discussion a new material is introduced on a conceptual basis (Jelle et al. 2010b): *NanoCon* is basically a homogeneous material with a closed or open small nano pore structure with an overall thermal conductivity of less than 4 mW/(mK) (or another low value to be determined) and exhibits the crucial construction properties that are as good as or better than concrete (Fig.11).

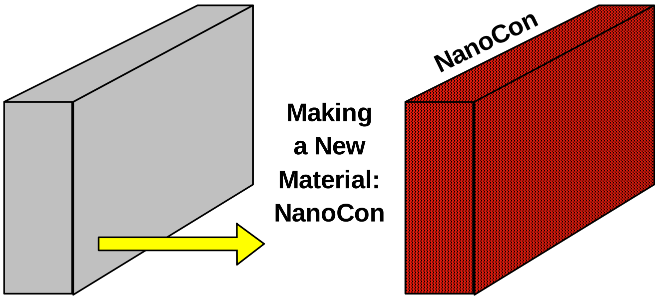

Figure 11. NanoCon is essentially a NIM with construction properties matching or surpassing those of concrete. (Jelle et al. 2010b).

The term ”Con” in NanoCon is meant to illustrate the construction properties and abilities of this material, with historical homage to concrete. Essentially, NanoCon is a NIM with construction properties matching or surpassing those of concrete. Depending on the mechanical or construction properties of NanoCon, it may be envisioned both with or without reinforcement or rebars. In the above definition of NanoCon, a homogeneous material is stated, although the first attempts to reach such a material might be tried by piecing or mixing several different materials together, i.e. with a final material product which on a nanoscale is not homogeneous. For example, joining NIM and carbon nanotubes in one single material might enable a very low thermal conductivity due to the NIM part and a very large tensile strength due to the carbon nanotube part. In this respect it should be noted that carbon nanotubes have a very large thermal conductivity along the tube axis. Furthermore, it is noted that the extremely large tensile strength of carbon nanotubes (63 000 MPa measured and 300 000 MPa theoretical limit) surpasses that of steel rebars (500 MPa) by more than two orders. As a comparison concrete itself without rebars has a tensile strength of 3 MPa and a compressive strength of 30 MPa. Thus, the potential impact of NanoCon is tremendously huge.

6.7 Other future materials and solutions?

The ultimate thermal solution will always be subject to change as time is progressing. That is, the thermal solution we are searching might very well, also for the near future, be found in solutions governed by hitherto unknown principles and which has yet to be discovered or invented. With other words, the thermal solution of tomorrow might be found in materials and solutions not yet thought of, which requires that we may have to *think thoughts not yet thought of* (Jelle et al. 2010a).

7. Comparison of weaknesses and strengths

Comparing the traditional, state-of-the-art and future thermal building insulation materials and solutions from the short descriptions given above (referral is made to the available literature for further details and in-depth knowledge), some general trends may be seen.

7.1 Robustness of traditional thermal insulation materials

The traditional insulation materials are the robust ones with respect to perforation vulnerability and flexibility issues like e.g. possible to adapt at the building site. However, the traditional insulation materials have relatively high thermal conductivity values which in cold climates may require all too thick building envelopes in order to reach the goals of passive houses and zero energy or emission buildings. In addition, the thermal conductivity increases substantially with increasing moisture content for the traditional thermal building insulation materials, i.e. a vulnerability towards moisture uptake. The traditional insulation material with the lowest thermal conductivity is polyurethane (PUR), with values down to 20 mW/(mK) compared to the others’ values typically ranging between 30-40 mW/(mK). However, the toxic gas release from PUR during a fire raises serious health hazard issues.

7.2 Thermal conductivity of state-of-the-art thermal insulation materials

The two most promising state-of-the-art insulation materials and solutions, i.e. vacuum insulation panels (VIP) and aerogels, have considerably lower thermal conductivity values than the traditional ones. The future of gas-filled panels (GFP) is considered to be doubtful, as VIPs seem to be a better choice with respect to attaining a very low thermal conductivity and being the most robust of the two, both for now and the foreseeable future. Comparing the miscellaneous traditional and state-of-the-art thermal insulation materials and solutions, the VIP solution has definitively the lowest thermal conductivity value of them all, i.e. typical around 4 mW/(mK) in the pristine non-aged condition, whereas the typical low value for aerogel is 13 mW/(mK). However, the VIP thermal conductivity increases with time due to moisture and air penetration by diffusion, attaining a value of 20 mW/(mK) in the non-vacuum or perforated condition. The aerogel conductivity on the other hand is not considered to be increasing substantially with time, and perforations represent no problem. Both VIPs and aerogels are very expensive, but it has been demonstrated that VIPs may be cost-effective (ch. 7.7), and aerogels in their transparent or translucent state offer application areas where one may be willing to accept higher costs.

7.3 Thermal conductivity of future thermal insulation materials

The conceptual future insulation materials have been designed, wisely enough, to have very low thermal conductivities and at the same time be very robust with respect to both ageing, perforation, building site adaptions and several other properties. If these thermal insualtion materials of beyond tomorrow may be conceived within a not too distant future remains to be seen, but nevertheless these materials give us something to strive at and a hope of a bright new day.

7.4 Thermal conductivity and other properties

Future thermal insulation materials and solutions need to have as low thermal conductivity as possible. Furthermore, the thermal conductivity should not increase substantially over a 100 year or more lifetime span. In addition, these materials and solutions should also be able to maintain their low thermal conductivity even if they are perforated by external objects like nails and similar, except the increase due to the local heat bridges. Thus, technologies based on vacuum may have problems with maintaining a low thermal conductivity over a long time span stretching over several decades, due to loss of vacuum with air and moisture uptake during the years.

A major requirement for the future thermal insulation materials is that they can be cut for adaption at the building site without losing any of their thermal insulation resistance. The VIP solution with an envelope barrier around an open pore structure supposed to maintain a vacuum does not satisfy this specific requirement, as cutting a VIP will result in a total loss of vacuum and an increase of thermal conductivity up to typically 20 mW/(mK).

Several other properties also have to be addressed. These include mechanical strength, e.g. compression and tensile strength, fire protection issues either by the thermal insulation material itself or other protection means, fume emissions during fire where preferably no toxic gases should be released, climate ageing durability with various climate exposures, resistance towards freezing/thawing cycles and water in general, dynamic properties (i.e. the ability to regulate the thermal insulation level) and costs which should be competitive versus other thermal insulation materials.

7.5 Requirements of future thermal insulation materials and solutions

The thermal insulation materials and solutions of tomorrow have to satisfy several crucial requirements. Table 1 summarizes the various properties with their proposed requirements. As it can be seen, the proposed thermal conductivity requirement in the pristine condition is a conductivity less than 4 mW/(mK), which is the typical value for non-aged VIPs. Naturally, the thermal conductivity after a certain period of time or service life, is of vital importance. A conductivity less than 5 mW/(mK) after 100 years is proposed for the future thermal insulation materials and solutions to be developed. Thus, Table 1 represents an initial attempt to address the crucial properties and requirements of the future high performance thermal insulation materials and solutions, and will naturally be subject to change in the years to come.

Table 1. Selected and proposed requirements of the future high performance thermal insulation materials and solutions.

Selected properties	Requirement
Thermal conductivity – pristine	< 4 mW/(mK)
Thermal conductivity – after 100 years	< 5 mW/(mK)
Thermal conductivity – after modest perforation	< 4 mW/(mK)
Perforation vulnerability	not to be influenced significantly
Possible to cut for adaption at building site	yes
Mechanical strength (e.g. compression and tensile)	may vary
Fire protection	may vary, depends on other protection
Fume emission during fire	any toxic gases to be identified
Climate ageing durability	resistant
Freezing/thawing cycles	resistant
Water resistant	resistant
Water permeability	may vary
Dynamic thermal insulation	desirable as an ultimate goal
Costs vs. other thermal insulation materials	competitive
Environmental impact (including energy and material use in production, emission of polluting agents and recycling issues)	low negative impact

7.6 The potential of miscellaneous thermal insulation materials and solutions

Table 2 gives a short summary of the potential of the traditional, state-of-the-art and possible future thermal building insulation materials and solutions with respect to become the high performance thermal insulation of tomorrow.

Table 2. The potential of the traditional, state-of-the-art and possible future thermal building insulation materials and solutions of tomorrow.

Materials	Low pristine/aged thermal conductivity	Perforation robustness	Possible building site adaption cutting	Load-bearing capabilities	A thermal insulation material and solution of tomorrow ?
Traditional thermal insulation					
Mineral wool	no	yes	yes	no	no
EPS	no	yes	yes	no	no
XPS	no	yes	yes	no	no
Cellulose	no	yes	yes	no	no
Cork	no	yes	yes	no	no
PUR	no	yes	yes	no	no
State-of-the-art thermal insulation					
VIP	yes/maybe	no	no	no	today and near future
GFP	maybe	no	no	no	probably not?
Aerogel	maybe	yes	yes	no	maybe
PCM	-	-	-	-	heat storage and release
Possible future thermal insulation					
VIM	yes/maybe	yes	yes	no/maybe	yes
GIM	yes/maybe	yes	yes	no/maybe	maybe
NIM	yes	yes, excellent	yes, excellent	no/maybe	yes, excellent
DIM	maybe	not known	not known	no/maybe	yes, excellent
NanoCon	yes	yes	yes	yes	yes, excellent
Others?	-	-	-	-	maybe

In addition to being a summary, Table 2 may be utilized to initiate a chain of thoughts of how to proceed beyond today's state-of-the-art thermal solutions. Also note that Table 2 expresses the current status for the state-of-the-art solutions of today and the foreseen status for the beyond state-of-the-art solutions, where certain items in the table might be subject both to discussion and change. Currently, the NIM solution seems to represent the best high performance low conductivity thermal solution for the foreseeable future. DIMs and NanoCon represent two solutions with a huge potential, with thermal insulation regulating and load-bearing capabilities, respectively.

7.7 Potential cost savings by applying VIPs

Today's vacuum insulation panels (VIP) are relatively costly. Nevertheless, application of VIPs may actually be directly profitable compared to traditional thermal insulation. This potential profit is due to the very low thermal conductivity values of VIPs (e.g. compared to mineral wool) which make it possible to build considerably slimmer wall constructions. The higher the market value of living area (EUR/m^2 living area) the higher the potential profit is by the application of VIPs and reduction of the wall thickness which hence increases the living area.

Table 3 shows the available means for VIP purchase due to reduced wall thickness and thus increased living area, where the potential savings include the costs of traditional thermal insulation. In all the calculations shown here it is assumed that VIPs in a wall construction in average have a thermal resistance about 5-6 times higher than traditional thermal insulation during a given operation period, i.e. more specifically that 35 cm of mineral wool corresponds thermally to 6 cm VIPs over a given period. An interior floor to ceiling height of 2.5 m is assumed in the calculations. For example, if the market value at the construction site is 4 000 EUR/(m^2 living area), and the wall thickness is reduced with 20 cm (from 35 cm timber frame work with mineral wool to 15 cm timber frame work with VIPs), one may use up to 330 EUR/(m^2 living area) for VIP purchase before the VIP costs exceed the costs one would have had with traditional thermal insulation (Table 3). If one uses less than 330 EUR/(m^2 living area) for the actual VIP purchase, the difference will be a clean-cut profit in favour of VIPs. The costs of traditional thermal insulation constitute only a relatively small part of the total savings. In Table 3 there is given mineral wool costs of 15, 18, 20, 24 and 26 EUR/m^2 for mineral wool thicknesses of 25, 30, 35, 40 and 45 cm, respectively, for a corresponding wall thickness reduction of 10, 15, 20, 25 and 30 cm by application of VIPs. These mineral wool costs may be directly subtracted from the values in Table 3 if one wants the available means for VIP purchase due to only the living area savings.

Table 3. Available means for VIP purchase as function of living area market value and wall thickness reduction. An interior floor to ceiling height of 2.5 m is assumed. Mineral wool costs of 15, 18, 20, 24 and 26 EUR/m^2 are used for mineral wool thicknesses of 25, 30, 35, 40 and 45 cm, respectively, for a corresponding wall thickness reduction of 10, 15, 20, 25 and 30 cm by application of VIPs.

Available Means for VIP Purchase due to Living Area and Traditional Thermal Insulation Savings (EUR/m^2 wall area)					
Market Value Living Area (EUR/m^2 living area)	**Reduction of Wall Thickness (cm)**				
	10	15	20	25	30
1 000	50	80	100	120	140
2 000	90	140	180	220	260
3 000	130	200	260	320	380
4 000	170	250	330	410	490
5 000	210	310	410	510	610

Table 4 and Table 5 with the two corresponding graphical plots in Fig.12 treat a case where the wall thickness is reduced from a timber frame work with 35 cm mineral wool (20 EUR/m^2) to a 15 cm timber frame work with 6 cm VIPs (200 EUR/m^2), i.e. a wall thickness reduction of 20 cm with approximately the same thermal transmittance (U-value). The wall thickness reduction could have been even lower with respect to the thermal resistance of the VIPs, but a minimum wall thickness of 15 cm is chosen due to construction reasons including load-bearing properties. With a VIP thickness of 6 cm could the remaining 9 cm in the timber frame work if desirable be filled with e.g. mineral wool to increase the thermal resistance even further. VIPs placed in the middle of the wall construction with cavities on both sides will increase the robustness versus perforations. In the calculations an interior floor to ceiling height of 2.5 m is assumed, in addition to an example building of 10 m x 10 m, giving an interior floor area (living area) of 100 m^2 and an interior wall area of 100 m^2 after the wall thickness reduction. Table 4 and Table 5, in addition to Fig.12, present the profit by applying VIPs, as EUR/(m^2 living area) and EUR/(total m^2 living area), respectively. This profit represents money you have as surplus when the building have been built with VIPs, i.e. sheer profit due to VIPs. As may be seen from the tables and graphical plots, relatively large profits may be gained, especially when the market value of the living area is high.

Table 4. Profit in EUR/(m^2 living area) by application of VIPs as function of living area market value where the wall thickness reduction is 20 cm for an example building of 10 m x 10 m. An interior floor to ceiling height of 2.5 m is assumed. See Fig.12.

Living Area (m^2) 10 x 10	Market Value Living Area (EUR/m^2 living area)	Increased Living Area Gain by Application of VIPs and Reduced Wall Thickness (m) of 0.2 (EUR/m^2 living area)	VIP Costs 6 cm Thickness (EUR/m^2 VIP)	Traditional Thermal Insulation Costs 35 cm Thickness (EUR/m^2 insulation)	Profit Due to VIP Application (EUR/m^2 living area)
	1 000	80	200	20	-100
	2 000	160	200	20	-20
	3 000	240	200	20	60
	4 000	310	200	20	130
	5 000	390	200	20	210

Table 5. Profit in EUR/(100 m^2 living area) by application of VIPs as function of living area market value where the wall thickness reduction is 20 cm for an example building of 10 m x 10 m. An interior floor to ceiling height of 2.5 m is assumed. See Fig.12.

Living Area (m^2) 10 x 10	Market Value Living Area (EUR/m^2 living area)	Increased Living Area Gain by Application of VIPs and Reduced Wall Thickness (m) of 0.2 (EUR/100 m^2 living area)	VIP Costs 6 cm Thickness (EUR/m^2 VIP)	Traditional Thermal Insulation Costs 35 cm Thickness (EUR/m^2 insulation)	Profit Due to VIP Application (EUR/100 m^2 living area)
	1 000	8 000	200	20	-10 000
	2 000	16 000	200	20	-2 000
	3 000	24 000	200	20	6 000
	4 000	31 000	200	20	13 000
	5 000	39 000	200	20	21 000

It should be noted that the calculations are simplified and do not consider all conditions. As an example it may be mentioned that thinner timber frame walls lead to less material costs related to the timber frame work. That is, even higher cost savings in favour of VIPs, which are not included in these calculations. Furthermore, costs and interest expenses per month related to additonal loan raising by the VIP purchase, compared to additional rental income due to increased living area, are nor included in the calculations. All the values in Tables 3-5 are rather roughly approximated estimated values. The purchase costs of VIPs are important for the potential profit and how large it may become, and may dominate the other costs not accounted for in the above. The VIP costs of 200 EUR/m^2 for a total VIP thickness of 6 cm, which are used in the calculations, are to be regarded as an example. The VIP costs are expected to decrease relatively much in the coming years.

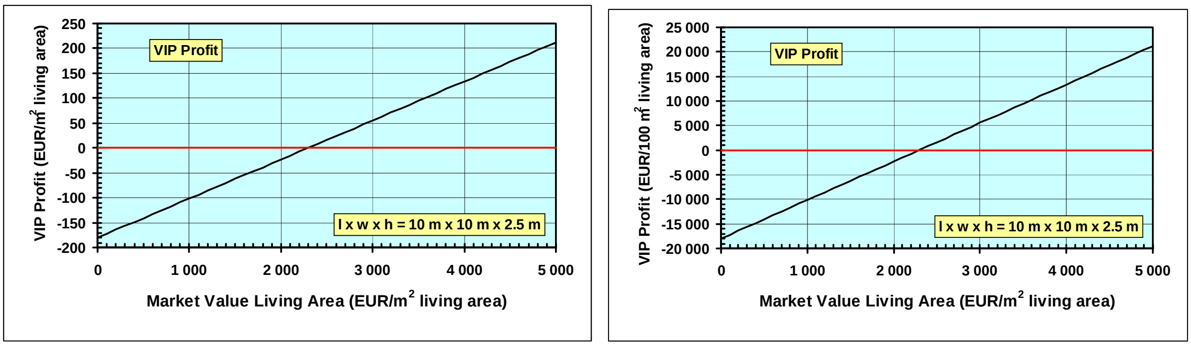

Figure 12. Profit in (left) EUR/(m^2 living area) and (right) EUR/(100 m^2 living area) by application of VIPs as function of living area market value where the wall thickness reduction is 20 cm for an example building of 10 m x 10 m. An interior floor to ceiling height of 2.5 m is assumed. See Table 4 and Table 5.

7.8 Condensation risk by applying VIPs in the building envelope

A very low water permeability close to zero, e.g. for VIPs, may represent a condensation risk depending on the actual construction and the indoor and outdoor climate conditions, for both new buildings and thermal retrofitting of existing buildings. These issues have been addressed by Sveipe et al. (2011) through experimental and numerical investigations of temperature and humidity conditions in building envelopes during thermal retrofitting of timber frame walls with VIPs.

7.9 The cardinal weaknesses of VIPs

Vacuum insulation panels (VIP) have the lowest pristine thermal conductivity of all thermal insulation materials, with typical values around 4 mW/(mK) in the non-aged condition. Some VIPs have even been reported to have achieved thermal conductivities as low as down to about 2 mW/(mK). However, as mentioned earlier the VIP thermal solution has several drawbacks, which may be summarized into the following four cardinal weaknesses of VIPs:

- The fragility.
- The perforation vulnerability.
- The increasing thermal conductivity during time.
- The lack of building site adaption cutting.

These four VIP cardinal weaknesses all originate from the challenge of maintaining a vacuum inside a core material with a protective foil around the core, where a total loss of vacuum leads to an increase in thermal conductivity from typically around 4 mW/(mK) up to about 20 mW/(mK).

The fragility of VIPs represents a serious concern and a major drawback. VIPs may be handled and stored with great care, but nevertheless will many panels suddenly and unexpectedly lose all their vacuum for no evident reason. In our laboratory during our various experiments with VIPs, we have also experienced this vacuum loss for no evident reason for different types and manufacturers of VIPs. Hence, there is a risk and likely probability that several VIPs may be installed in a building envelope with the vacuum intact, and then after a relatively short time period lose their vacuum.

The perforation vulnerability or lack of perforation robustness of VIPs represents another major disadvantage. This vulnerability may imply miscellaneous restrictions to the applications of VIPs, e.g. other building envelope techniques or various restrictions to perforate the building envelopes. That is, you may not put up your pictures everywhere on the all the walls in the same way as you have done before. Nevertheless, despite various building techniques and restrictions, VIPs are prone to get perforated in different ways during a building's lifetime. Besides, a certain amount of VIPs are also likely to be perforated during transport and handling.

The increasing thermal conductivity during time represents yet another cardinal weakness of VIPs. Depending on the VIP type, VIP envelope foil type and VIP size, water, oxygen, nitrogen and other air molecules will with time diffuse through the VIP envelope and into the VIP core, thereby decreasing the vacuum inside the VIPs and hence increasing the thermal conductivity (see e.g. Fig.3). That is, the thermal resistance of a building envelope based on VIPs will decrease with time, which then have to be taken into account when determining the necessary VIP thickness.

The lack of building site adaption cutting of VIPs is also a cardinal drawback. All VIPs have to be manufactured in a VIP production facility with the required dimensions, usually limited to a number of standard sizes due to cost limitations, and no adaption or cutting of the panels can be carried out at the building site as any cutting will lead to loss of vacuum. Hence, any adjustments at the building site have to be performed with other thermal insulation materials with a higher thermal conductivity than the VIPs.

Note that the heat bridge effect caused by the metallized envelope foil of VIPs, and the relatively high costs of VIPs, are not considered as cardinal weaknesses of VIPs. The heat bridge effect decreases with increasing VIP size, and is much smaller for metallized films (MF types) than for metall films (AF), see e.g. Fig.2. Besides, the heat bridge effect will by far be outweighed by the large thermal resistance in VIPs. As commented earlier the the application of VIPs may actually result in an economic profit in areas with a high living area market value per square meter, where a reduced wall thickness may involve large area savings and thus a higher value of the real estate (ch. 7.7).

7.10 EPS encapsulated VIPs

Thermal insulation solutions with VIPs wrapped in expanded polystyrene (EPS) have been proposed and are also in actual use. These EPS-VIPs have an extra protection due to the EPS covering, and enables some adjustments at the building site as parts of the EPS perimeter may be cut away. Applying EPS encapsulated VIPs in two layers, ensuring there is always at least one VIP layer in the EPS joints, reduces the (EPS) heat bridges.

However, these EPS covered VIPs have also some drawbacks. Firstly, the loss of vacuum in VIPs totally covered in EPS is not so easy to detect and increases thus the probability of installing VIPs with no vacuum. Contrary, in VIPs with no EPS (or other) covering it is normally very easy to detect if the vacuum has been lost, both by visual inspection of the very tight foil around the VIP core as long as a vacuum is maintained, also giving the panel a rather rigid structure, and by touching or hearing by snapping one's fingers at the VIP foil, where the response will be quite different for a panel with and without vacuum. Secondly, the EPS replaces part of the VIP area, and as the EPS thermal conductivity is considerably larger than the VIP conductivity, there is a question what configuration would have given the lowest U-values, i.e. EPS-VIPs or only VIPs, which then has to be calculated or measured.

7.11 VIMs and GIMs versus NIMs

A vacuum insulation material (VIM) or a gas insulation material (GIM) needs to maintain a vacuum or a gas inside a closed pore structure, respectively. These materials could be cut and adapted at the building site with no loss of low thermal conductivity. In addition, perforating the VIM or GIM with a nail or similar would only result in a local heat bridge, i.e. no loss of low thermal conductivity. The VIM grid structure has to be strong enough to withstand the vacuum inside its pores, and the air and water vapour diffusion through the grid structure and into the vacuum pores have to be so small enough that the VIMs will maintain their low thermal conductivity below a certain value for at least 100 years. Keeping the vacuum inside the pores during a long service life may be the most difficult or challenging task for the VIMs. That is, the most challenging task after the VIMs have been manufactured, as to make VIMs is a highly challenging task in itself. Nevertheless, when an appropriate VIM production process has been established, such a production might hopefully be found to be both efficient and competitive. With respect to GIMs, it might be easier to create a closed pore structure filled with a low-conductance gas than vacuum. Furthermore, the GIM grid structure does not have to be as strong as the VIM grid structure, as a vacuum pore structure will be prone to collapse before a gas-filled pore structure. In addition, it may be easier to maintain the original low thermal conductivity within a gas-filled pore structure than in a vacuum pore structure. Comparing the VIMs and GIMs, the VIMs ultimately have the largest potential of these two as the lowest thermal conductivity is achieved in a vacuum compared to a gas-filled pore structure.

As both the VIMs and GIMs share the same disadvantage that their grid structures need to prevent air and moisture penetration into their pore structures during their service life for at least 100 years, one may ask if it is possible to envision and manufacture a high performance thermal insulation material like the VIMs and GIMs, but without their disadvantages? The answer of this is as noted earlier the nano insulation material (NIM). The NIMs may obtain a very low thermal conductivity with either an open or a closed pore structure, and the NIM grid structure does not need to prevent air and water vapour from diffusing into the pores as the NIMs may attain a very low thermal conductivity with air inside the pores, see e.g. the Knudsen effect depicted by Eqs.2-3 and Figs.8-9. Furthermore, perforating the NIMs do not create any local thermal bridges induced by air and water vapour leakage into the pore structure locally around the intrusion, except the thermal bridges caused by the perforating agents (e.g. nails) themselves. Hence, compared to VIMs and GIMs, the NIMs are regarded to have the largest potential. NIMs with an open pore structure will be containing air, and thus the structure has to be resistant towards various ageing degradation mechanisms as air gases including different pollutions will freely be admitted into the NIM pores. It is essential that water condensation in such tiny nano pores has to be prevented, or else the thermal conductivity will increase substantially and might ruin the whole concept of the NIMs.

7.12 The regulating potential of DIMs

To be able to understand thermal conductance so well that one may tailor-make materials where one can dynamically regulate the thermal conductivity of a material from a very low to a very high conductivity has a tremendous potential. These dynamic insulation materials (DIM) may constitute a part of an intelligent building envelope which includes the emerging solutions phase change materials (PCMs) and electrochromic materials (ECMs), i.e. for day/night storage/release of accumulated or other surplus solar energy and dynamic control of solar energy through glazing systems, respectively. Limiting ourselves to solid state thermal conduction, changes in the thermal conductivity involve changes in the chemical bonds between atoms. To change the thermal conductivity in DIMs back and forth within a desirable range may require some energy, which naturally should be as low as possible. Analogies might also be drawn towards the field of electrical superconductivity, i.e. the ability to transport electrical current without resistance and hence without loss of energy. There is still much to be discovered and understood within the realms of atoms, quantum mechanics and the matter that surrounds us. Future applications of DIMs may find large areas of use outside the building sector, e.g. envision how a thermal superconductor could be utilized. Clearly, both theoretical and practical, the DIMs represent a tremendous potential for applications in buildings and several other areas.

7.13 The construction potential of NanoCon

The idea of making a construction material which also possesses the properties of a high performance thermal insulating material has a huge potential. NanoCon represents an ultimate solution in this respect. Even if the very ambitious goal of as low thermal conductivity as 4 mW/(mK) for NanoCon is not reached within a foreseeable near future, every order of magnitude the thermal conductivity may be lowered from the high value of concrete down towards the values of the traditional and the state-of-the-art thermal insulation building materials, while still exhibiting most of or substantial parts of the crucial construction properties of concrete, will be very important. Combinations of nano insulation materials and carbon nanotubes may be utilized in order to reach the goals of a NanoCon high performance thermal insulation and construction material. Naturally, the fire resistance of NanoCon will also be important to address.

NanoCon may be envisioned both with and without the use of steel rebars. Today the corrosion of rebars in concrete constructions represents a very large worldwide problem. If concrete constructions, and ultimately NanoCon, may be used without steel reinforcement, this will have an enormous impact on the construction industry and the built environment. Hence, every effort and investment put into the research and development of NanoCon and similar materials may pay off tremendously and be worth every single penny.

7.14 Assessing weaknesses and strengths

When assessing which thermal building insulation material or solution to choose for a specific application or building, all the important properties should be evaluated with regard to their weaknesses and strengths. As of today, no single thermal insulation material or solution exists which is superior or best in all respects, i.e. the evaluation of all the pros and cons for the different properties and applications is crucial when determining which thermal insulation material or solution to choose.

7.15 Does the future belong to NIMs, DIMs and NanoCon?

The large challenges associated with inventing and developing thermal insulation materials like nano insulation materials (NIMs), dynamic insulation materials (DIMs) and NanoCon or similar concepts should neither be concealed nor understated. Research efforts will be needed, both along known theoretical principles within physics, chemistry and material science, but maybe also along more unknown paths within these areas. Theoretical investigations have to be followed with concurrent experimental examinations and explorations. The efforts put into these research paths will for certain pay off sooner or later, thus leading to the development of new thermal building insulation materials and solutions.

Hence, we may conclude that NIMs, DIMs and NanoCon may take the step or leap from the conceptual stage to being part of the high performance thermal insulation materials of beyond tomorrow. And nevertheless, whatever will be the specific thermal solutions in the near or distant future, the ideas around NIMs, DIMs and NanoCon will undeniable contribute to the development of the future thermal building insulation materials and solutions.

7.16 Future research paths

The day after and beyond tomorrow will see other thermal insulation materials and solutions than exist today. As an endnote, one may conclude that future research may beneficially be conducted along three paths, i.e. (i) improving the existing traditional thermal insulation, (ii) improving the existing state-of-the-art thermal insulation, and (iii) exploring the possibilities of discovering and developing novel high performance thermal insulation materials and solutions with properties surpassing all of today’s existing materials and solutions.

8. Conclusions

Properties, requirements and possibilities for traditional, state-of-the-art and future thermal building insulation materials and solutions, with their advantages and disadvantages, have been investigated. Essential properties and issues raised are among others thermal conductivity, perforation vulnerability, building site adaptability and cuttability, mechanical strength, fire protection, fume emission during fire, robustness, climate ageing durability, resistance towards freezing/thawing cycles, water resistance, costs and environmental impact.

It is concluded that currently there exist no single thermal building insulation material or solution which satisfies all the requirements with respect to the most crucial properties. Hence, it is important to (a) choose the most suitable one from today’s existing traditional and state-of-the-art thermal insulation materials and solutions, (b) conduct research and continuously improve today’s existing traditional and state-of-the-art thermal insulation materials and solutions, (c) initiate research which explores the possibilities of discovering and developing novel high performance thermal insulation materials and solutions with properties surpassing all of today’s existing materials and solutions. Promising candidates for tomorrow and the future are nano insulation materials (NIM), dynamic materials (DIM) and the load-bearing insulation material NanoCon, or some material or solution hitherto not yet thought of.

Acknowledgements

This work has been supported by the Research Council of Norway and several partners through the SINTEF and NTNU research projects ”*Robust Envelope Construction Details for Buildings of the 21st Century*” (ROBUST), the ”*Concrete Innovation Centre*” (COIN) and ”*The Research Centre on Zero Emission Buildings*” (ZEB).

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