BEYOND VACUUM INSULATION PANELS - HOW MAY IT BE ACHIEVED ?

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ABSTRACT

Buildings constitute a very large part of the total energy consumption in the world. In order to avoid heat losses according to stricter regulations, building envelope thicknesses are increasing continually when applying traditional thermal insulation materials. Vacuum insulation panels (VIPs) allow the combination of high thermal insulation and thin building envelopes, but unfortunately VIPs are suffering from ageing effects and lack of flexibility and robustness. This work investigates the possibilities of inventing and developing innovative and robust highly thermal insulating materials. That is, within this work the objective is to go beyond VIPs and other current state-of-the-art technologies. New concepts are introduced, e.g. vacuum insulation materials (VIMs), nano insulation materials (NIMs), gas insulation materials (GIMs) and dynamic insulation materials (DIMs). These materials may have closed pore structures (VIMs and GIMs) or either open or closed pore structures (NIMs). The DIMs aim at controlling the thermal conductivity. Fundamental theoretical studies aimed at developing an understanding of the basics of thermal conductance in solid state matter at an elementary and atomic level have been addressed. The ultimate goal is to develop tailor-made novel high performance thermal insulation materials and dynamic insulation materials, the latter one enabling to control and regulate the thermal conductivity in the materials themselves, i.e. from highly insulating to highly conducting. Furthermore, requirements of the future high performance thermal insulation materials and solutions have been proposed. Currently, the NIMs seem to represent the best high performance low conductivity thermal solution for the foreseeable future, while DIMs, if they can be made robust and practical, have great potential due to their thermal insulation regulating abilities.

1. INTRODUCTION

1.1. The Energy Savings Demand of the World

As buildings constitute a substantial part of the total energy consumption, savings within the building sector will be important, both for existing and new buildings. One of the key fields will be the thermal building insulation materials and solutions. Essentially, the focus has been and still will be to achieve the highest possible thermal insulation values, i.e. the lowest thermal conductivity for the materials and the lowest thermal transmittance, U-value, for the structures and buildings. This usually works well for cold climates, where the building envelopes should have as low U-value as possible. However, even cold climates may experience longer periods with overheating due to solar heat gains and excessive heat loads from miscellaneous indoor equipment and activities. Traditionally, the solution has also been to thermally insulate the building envelopes sufficiently well enough in warm climates due to seasonal variations and periods during the year with a heating demand. Office work spaces with extensive use of electrical equipment and large solar energy gains through large window glass facades are likely to experience overheating.

1.2. The Vacuum Insulation Panel (VIP) Solution

Today's traditional thermal insulation materials have thermal conductivities typically between 35 and 40 mW/(mK). Vacuum insulation panels (VIPs) represent state-of-the-art thermal insulation with 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 conductivity after 50 and 100 years will be somewhat or substantially higher than this value. This inevitably increase of 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. Brunner and Simmler (2008), Caps and Fricke (2000), Caps et al. (2008), Fricke et al. (2006), Schwab et al. (2005abc), Simmler and Brunner (2005a), Simmler et al. (2005b), Tenpierik and Cauberg (2007a), Tenpierik et al. (2007b, 2008) and Zwerger and Klein (2005), where a comprehensive review on VIPs has been made recently by Baetens et al. (2009b).

Nevertheless, despite 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 emission buildings. Thermal insulation thicknesses up to 50 cm or so in walls and roofs are not desired. Such thick building envelopes might require new construction techniques and skills. In addition, transport of thick building elements leads to increased costs. Height restrictions may apply for several bridges and 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 allow. Furthermore, in areas with a high living area market value per square meter, a reduced wall thickness may involve large area savings and 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 (Grynning et al. 2009). Therefore, 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.

1.3. Other State-of-the-Art Thermal Insulation Materials and Solutions

Other state-of-the-art thermal insulation solutions do exist. In principle, close to VIPs, is the technology of gas-filled panels (GFPs). 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. Thermal conductivities for prototype GFPs are quite high, e.g. 40 mW/(mK), although much lower theoretical values have been calculated. The future of GFPs may be questioned, as compared to them the VIPs seem to be a better choice both for today and tomorrow. Aerogels represent another state-of-the-art thermal insulation solution, and maybe the most promising with the highest potential of them all at the moment. 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). 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. Only the future will show how far and extensive the aerogels will be applied in buildings. Phase change materials (PCMs) are not really thermal insulation materials, but since they are interesting for thermal building applications, they are nevertheless mentioned, but not treated further within this context.

1.4. Other Materials and Solutions ?

Despite its several disadvantages, the vacuum insulation panel solution seems at the moment to be the most competitive solution and the one most likely to hit the market first. Though, the aerogels in various forms, without some of the disadvantages of the VIPs, might in the long run change this picture. *But might there exist some other materials and solutions which could exhibit as low thermal conductivity as the VIPs in their non-aged pristine condition, and without the several drawbacks of the VIPs? And if not, could they with some effort be envisioned, invented and finally manufactured? And what would be the requirements of these materials and solutions?*

2. REQUIREMENTS OF THE THERMAL INSULATION OF TOMORROW

The future thermal insulation materials and solutions need to have as low thermal conductivity as possible. In addition, the thermal conductivity should not increase too much over a 100 year or more lifetime span. Furthermore, these materials and solutions should also be able to maintain their low thermal conductivity even if they are perforated by external objects (e.g. nails), except the increase due to the local heat bridges. 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 loosing any of their thermal insulation performance. 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, including mechanical strength, fire protection issues, fume emissions during fire where preferably no toxic gases should be released, climate ageing durability, 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.

That is, 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 the non-aged VIP thermal insulation. Naturally, the thermal conductivity after a certain period of time or service life, is of vital importance. Here a conductivity less than 5 mW/(mK) after 100 years is proposed for the future thermal insulation materials and solutions to be developed.

Table 1. Proposed requirements of future high performance thermal insulation materials and solutions.

Property	Requirements
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
Dynamic thermal insulation	desirable as an ultimate goal
Costs vs. other thermal insulation materials	competitive

3. THERMAL INSULATION MATERIALS AND SOLUTIONS OF TOMORROW

The following subchapters will introduce and define the principles behind what could become the future high performance thermal insulation materials and solutions. An initial presentation of these materials and solutions may be found in Baetens (2009a) and Baetens et al. (2009b), where also various detailed thermal conductivity issues are discussed.

3.1. Vacuum Insulation Materials (VIM)

A vacuum insulation panel (VIP) consist of an open pore core material with vacuum enveloped by an airtight and water vapour tight foil. If the enveloping foil had been completely air and moisture impermeable for a sufficient long period of time (which is not the case), the VIP thermal insulation technology would have been far better than the current technology. However, even if you could somehow make the VIPs reasonable invulnerable towards any perforations during the building period and the service life, the VIPs still lack one very important property of flexibility. That is, the VIPs can not be cut and adapted at the building site without loosing their vacuum, the very reason for their low thermal conductivity. Therefore, one might ask – Even if we in the future could manufacture VIPs with no degradation over time, could we make a thermal insulation material or solution just as good as the VIPs, but without their disadvantages? One could then ask – Is it possible to make a thermal insulation material with a thermal conductivity as low as for VIPs in the pristine condition, but with no application of an enveloping foil?

That is, a basically homogeneous material with a closed small pore structure filled with vacuum with an overall thermal conductivity of less than 4 mW/(mK) in the pristine condition could be envisioned. Such a high performance thermal insulation material we define as a *vacuum insulation material* (VIM). This material could be cut and adapted at the building site with no loss of low thermal conductivity. In addition, perforating the VIM with a nail or similar would only result in a local heat bridge, i.e. no loss of low thermal conductivity. Figure 1 depicts the distinguished features between VIPs and the desired development of VIMs. In order to be able to manufacture a VIM a low thermal conductivity of the solid state grid structure has to be made. Furthermore, a closed small pore structure filled with vacuum has to be accomplished. That is, as the pore structure is closed, the vacuum pore structure must be created during the production process of the VIM. One way to accomplish this is to envision a solid state material blowing itself up from within during the formation and subsequent expansion of an inner pore structure. Another way, although totally different, might be to create a VIM grid structure or inner pore surfaces which will efficiently and completely absorb the pore gas molecules, e.g. by a chemical reaction process.

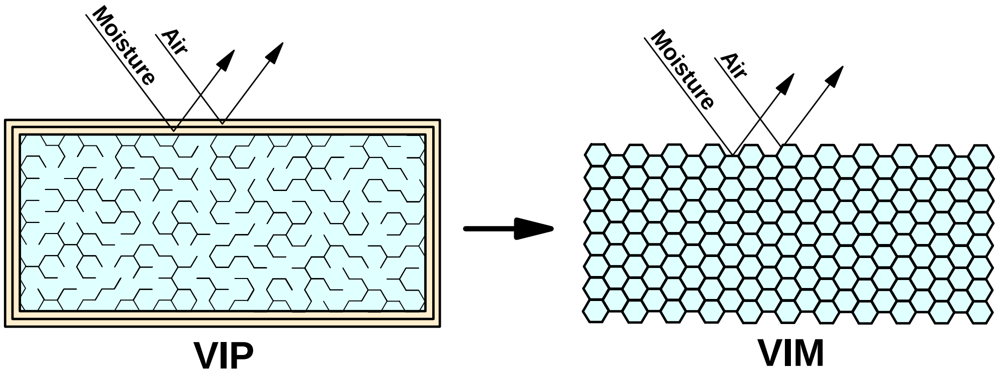

Figure 1. The development from vacuum insulation panels (VIPs) to vacuum insulation materials (VIMs).

The inner surface of the pores, could have as low emissivity as possible in order to decrease the thermal radiation transport. However, this might be in direct contradiction to attaining as low solid state thermal conductivity as possible. The VIM grid structure has to be strong enough to withstand the vacuum inside its pores. Finally, the air and water vapour diffusion or transport through the grid structure and into the vacuum pores have to be sufficient small enough so that the VIMs will maintain their low thermal conductivity below a certain value (e.g. 5 mW/(mK)) for at least 100 years. Maintaining the vacuum inside the pores during a long service life may be the most 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.

3.2. Gas Insulation Materials (GIM)

A *gas insulation material* (GIM) is basically the same as a VIM, except that the vacuum inside the closed pore structure is substituted with a low-conductance gas. That is, a GIM is basically a homogeneous material with a closed small pore structure filled with a low-conductance gas with an overall thermal conductivity of less than 4 mW/(mK) in the pristine condition. As for the VIMs, the GIMs may also be cut and adapted at the building site with no loss of low thermal conductivity. Likewise, perforating the GIM with a nail or similar would only result in a local heat bridge, i.e. no loss of low thermal conductivity. 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. However, 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.

3.3. Nano Insulation Materials (NIM)

Both the vacuum insulation material (VIM) and gas insulation material (GIM) solution share two of the same disadvantages. That is, firstly, the VIM and GIM grid structure need to prevent air and moisture penetration into their pore structure during their service life for at least 100 years. Secondly, perforating VIMs and GIMs with nails and alike causes local thermal bridges. Nail penetration and similar is considered to be of less importance for VIMs and GIMs, as this will normally only be minor local heat bridges. Ideally, if a 100 % airtight and water vapour tight VIM or GIM structure could be made, the former disadvantage would not represent any problem. However, we don't live in an ideal world, so some air and water diffusion into the VIM and GIM pore structure are probably bound to occur with time. The question then remains if the VIMs and GIMs are able to maintain their low thermal conductivity below a certain value (e.g. 5 mW/(mK)) for at least 100 years. Next, one may then ask if it is possible to envision and manufacture a high performance thermal insulation material or solution like the VIMs and GIMs, but without their disadvantages?

An answer to that question is the *nano insulation material* (NIM). If we still envision a VIM where we decrease the pore size within the 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 grid structure) even with air filled pores. This is due to the Knudsen effect where the mean free path of the gas molecules is larger than the pore diameter. In addition, many small pores lead to an increased number of thermal radiation transfers, thus also reducing the total thermal conductivity. The expressions for the gas thermal conductivity taking into account the Knudsen effect are given elsewhere (Scwab et al. 2005b, Simmler et al. 2005b, Baetens et al. 2009), and are applied for the calculations of 2d and 3d graphical plots for air, Ar, Kr and Xe in Figs.2, where also the low thermal conductivity value of 4 mW/(mK) has been depicted.

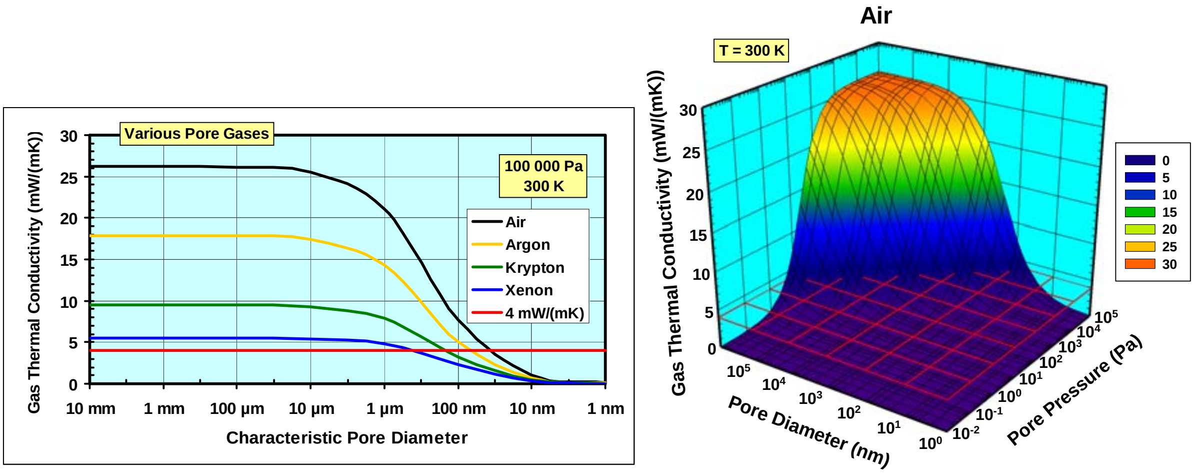

Figure 2. Gas thermal conductivity dependence on pore diameter and gas pressure in pores.

Hard sphere collision diameters have been applied in the calculations, i.e. 3.66, 3.58, 4.08 and 4.78 Å for air, Ar, Kr and Xe, respectively (Handbook of Chemistry and Physics 2003-2004), i.e. covalent gas molecule diameters have not been employed. In the 2d plot in Fig.2 a pore gas pressure of 100 000 Pa has been chosen. The 2d and 3d plots in Fig.2 demonstrate a rapid decrease in the gas thermal conductivity for pore diameters between 1 μm – 10 nm and gas pressures between 10 Pa – 0.1 Pa for all the four gases.

Thereby, the NIMs obtain a very low thermal conductivity with either an open or a closed pore structure. That is, firstly, the NIM grid structure does not need to prevent air and water vapour to diffuse into the pores. Secondly, 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. Naturally, a nail or similar through the whole NIM might lead to air leakages through the NIM and thereby increased heat loss from a building, as with all other thermal insulation materials, both traditional ones and new high performance materials.

Figure 3 depicts the distinguished features between VIPs and the desired development of NIMs. Note that in principle, aerogels could be made so they could be considered as NIMs. Naturally, NIMs with an open pore structure will be containing air, where such a structure has to be resistant towards miscellaneous ageing degradation mechanisms as air gases including various pollutions will freely be admitted into the pores of the NIMs. The NIM closed pore structure may be containing any gases, e.g. air, Ar, Kr and Xe. A *true* NIM will still maintain a total and local thermal conductivity below 4 mW/(mK) when perforated, including the gas thermal conductivity in a single pore which has been perforated.

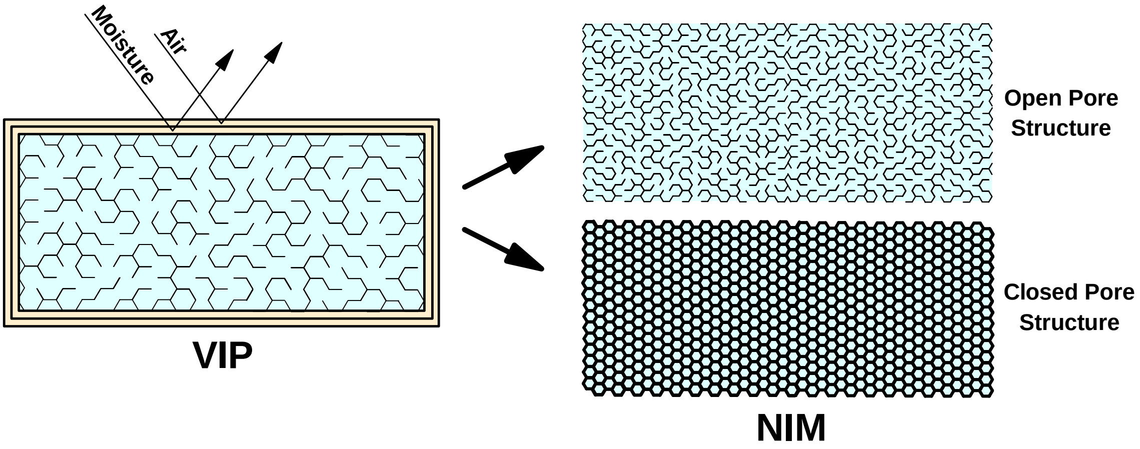

Figure 3. The development from vacuum insulation panels (VIPs) to nano insulation materials (NIMs).

Hence, as a conclusion, the NIMs obviously represent what could become the high performance thermal insulation materials for the future.

3.4. Dynamic Insulation Materials (DIM)

Usually we think about thermal insulation materials as something static, i.e. the insulation materials have a constant value which does not change. The normal choice is then to choose as low thermal conductivity as physically possible and within prevailing economical and building (e.g. area and height) restrictions. However, one might envision a building envelope which can change its thermal properties according to energy and user comfort demands. This might be solved by a *dynamic insulation material* (DIM) where the thermal conductivity can be controlled within a desirable range.

DIMs 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 solar energy and dynamic control of solar energy through glazing systems, respectively. PCMs are basically adaptive materials, whereas ECMs are materials which can be controlled by applying an external electrical voltage, aiming at regulating as much of the solar radiation throughput in smart windows as possible.

How can DIMs achieve their thermal conductivity regulating abilities? In fact, this might be accomplished in several ways, i.e. by controlling the (a) inner pore gas content or concentration including the mean free path of the gas molecules and the gas-surface interaction, (b) the emissivity of the inner surfaces of the pores, and finally (c) the solid state thermal conductivity of the lattice. Dynamically changing the inner pore gas content or concentration might be envisioned in several ways, e.g. by chemical reactions or inner pore surface adsorption processes, e.g. controlled by an applied electrical field. The emissivity of the inner surfaces of the pores might be controlled by changing the plasma wavelength and thus the free electron density. Materials with a high free electron density will be highly reflecting materials with a low emissivity, whereas a low free electron density corresponds to a low reflectivity and thus a high emissivity. The solid state thermal conductivity may be changed by dynamically controlling the phonon thermal conductivity or the free electron thermal conductivity, see further details in the following chapter concerning this. The process of changing the conductivity back and forth within a desirable range may require a certain amount of energy. Naturally, this energy consumption should be kept as low as possible in DIMs. The thermal insulation regulating abilities of DIMs give these materials a great potential. However, first it has to be demonstrated that such robust and practical DIMs can be manufactured.

3.5. What Is Really Thermal Conductivity ?

In order to be able to invent and design the thermal insulation materials and solutions of tomorrow, one should initiate fundamental theoretical studies aimed at developing an understanding of the basics of thermal conductance in solid state matter at an elementary and atomic level. The ultimate goal of these studies will be to develop tailor-made novel high performance thermal insulation materials and dynamic insulation materials, the latter one enabling to control and regulate the thermal conductivity in the materials themselves, i.e. from highly insulating to highly conducting. As a first thought, one might think that everything is well understood about thermal conductivity with a sound underlying theory. Restricting ourselves to solid state thermal conductivity, the heat flow process seems to be rather straightforward. That is, one atom bouncing into the next one and so on in a solid state lattice structure, thus transferring heat from atom to atom. The term bouncing might be more appropriate concerning heat conduction in gases than solid state matter though, as the thermal energy is transferred through the chemical bonds in the solid state structure.

Then we might ask ourselves, could we change these chemical bonds between the various atoms and thereby change the thermal conductivity? What kind of materials could be appropriate? What is characterizing a thermally highly conducting versus a highly insulating material? Could we utilize this information to tailor-make materials with the desired low thermal conductivity? What physical model could describe and explain thermal conductivity? Investigating these fields closely, could it be possible to dynamically change the thermal conductivity from very low to very high, i.e. making a dynamic insulation material (DIM)?

There exist two models for describing thermal conductivity, i.e. the phonon model (atom lattice vibrations) and the free electron model. The origin of both these models might be seen as an analogue to the thermal conduction of molecules in gases with mean free path calculations, i.e. a gas of phonons and a gas of free electrons. It has to be emphasized that these thermal conduction models are just that, i.e. *models*. Be reminded that the atom model is also just that, i.e. a model. Analytical expressions for the thermal conductivity are derived from both the phonon model and the free electron model. However, the utilization of these models on real materials for quantitative practical applications might be considered as rather limited. For example, the free electron thermal conduction model applies strictly to metals, not other materials, and is further complicated by the electron distribution being dependent on both the thermal gradient and the electrical field. Just the fact that there exists two models explaining only parts of the observed thermal conductance properties, tells us that thermal conductivity is not really understood on an atomistic level for solid state matter. A single model explaining all observed properties will always be the ultimate goal.

To what extent quantum mechanics, which is also mere a model, might be applied into the field of thermodynamics remains to be seen. One might also bear in mind the sudden and unexpected experimental discoveries and breakthroughs within the field of electrical superconductivity, where several models or theories (e.g. the BCS theory) have been proposed without being able to fully explain the observed phenomenon. Analogously and ultimately, one might also envision the whole span from thermal insulator to thermal supraconductor. We may for now end this section with the following words of wisdom: *The more we know the more we know we don’t know.* And that’s the whole fun of it, scientific research included!

3.6. Materials and Solutions Not Yet Thought Of ?

The ultimate thermal solution will always be subject to change as time is progressing. That is, the 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*.

4. SUMMARY OF THE STATE-OF-THE-ART AND BEYOND

In Table 2 there is given a short summary of the potential of the state-of-the-art and beyond with respect to becoming the high performance thermal insulation materials and solutions of tomorrow. Traditional thermal insulations like mineral wool and expanded or extruded polystyrene (EPS or XPS) are included as a reference for comparison. In addition to being a summary, Table 2 might be used to initiate a chain of thoughts of how to proceed beyond todays state-of-the-art thermal solutions. It should also be noted 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. At the moment, the NIM solution seems to represent the best high performance low conductivity thermal solution for the foreseeable future. In order to be able to regulate the thermal conductivity, the DIM solution may accomplish such a feat. However, how long time it would take before DIMs with satisfactory properties could be made, is rather questionable and difficult to predict.

Table 2. The potential of todays and beyond state-of-the-art solutions for becoming the high performance thermal insulation materials and solutions of tomorrow.

Thermal Insulation Materials and Solutions	Low Pristine Thermal Conductivity	Low Long-Term Thermal Conductivity	Perforation Robustness	Possible Building Site Adaption Cutting	A Thermal Insulation Material and Solution of Tomorrow ?
Traditional					
Mineral Wool and Polystyrene	no	no	yes	yes	no
Todays State-of-the-Art					
Vacuum Insulation Panels (VIP)	yes	maybe	no	no	today and near future
Gas-Filled Panels (GFP)	maybe	maybe	no	no	probably not, near future
Aerogels	maybe	maybe	yes	yes	maybe
Phase Change Materials (PCM)	-	-	-	-	heat storage and release
Beyond State-of-the-Art					
Vacuum Insulation Materials (VIM)	yes	maybe	yes	yes	yes
Gas Insulation Materials (GIM)	yes	maybe	yes	yes	maybe
Nano Insulation Materials (NIM)	yes	yes	yes, excellent	yes, excellent	yes, excellent
Dynamic Insulation Materials (DIM)	maybe	maybe	not known	not known	yes, excellent
Others ?	-	-	-	-	maybe

5. CONCLUSIONS

New concepts beyond the state-of-the-art thermal materials and solutions have been introduced, e.g. vacuum insulation materials (VIMs), nano insulation materials (NIMs), gas insulation materials (GIMs) and dynamic insulation materials (DIMs). These materials may have closed pore structures (VIMs and GIMs) or either open or closed pore structures (NIMs). The DIMs aim at controlling the material insulation properties, e.g. solid state conductivity, emissivity and pore gas content. Fundamental theoretical studies aimed at developing an understanding of the basics of thermal conductance in solid state matter at an elementary and atomic level have also been addressed. The ultimate goal of these studies is to develop tailor-made novel high performance thermal insulation materials and dynamic insulation materials, the latter one enabling to control and regulate the thermal conductivity in the materials themselves, i.e. from highly insulating to highly conducting. Requirements of the future high performance thermal insulation materials and solutions have been proposed. At the moment, the NIM solution seems to represent the best high performance low conductivity thermal solution for the foreseeable future. If robust and practical DIMs can be made, they have great potential due to their controllable thermal insulating abilities.

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