The High Performance Thermal Building Insulation Materials and Solutions of Tomorrow

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ABSTRACT

The traditional thermal building insulation materials and solutions of today have the drawback that they require rather thick building envelopes in order to meet the increasingly demanding thermal insulation requirements. Increasing the building envelope thickness up to between 400 and 500 mm, e.g., by use of mineral wool and similar insulation materials, forces new challenges both with respect to building physics and practice. In addition, such thick envelope structures are less cost-effective at locations where the area is restricted, i.e. by restrictions in physical dimensions or by high living area costs per square meter. Thus, with increasing thermal insulation, there is a strive to not increase the thickness of the building envelope substantially. Currently, vacuum insulation panels (VIPs) are being developed and manufactured commercially. These panels are rather expensive at the moment, but they may already offer competitive insulation solutions where the area is restricted. State-of-the-art VIPs have thermal conductivities ranging from between 3 mW/(mK) to 4 mW/(mK) in pristine condition, which is about ten times lower than the typical thermal conductivity of 36 mW/(mK) for traditional insulation materials like mineral wool and the like. However, with time water vapor and air are diffusing through the VIP foil envelope and into the open pore core structure of VIPs, thereby increasing the thermal conductivity up to typically 8 mW/(mK) after 25 years aging. Puncturing the VIP envelope causes an increase in the thermal conductivity to about 20 mW/(mK). Hence, the VIPs cannot be cut or adjusted at the building site and care has to be taken in order not to perforate the VIP foil during building construction and service life. Thus, there should also be an aim to invent or develop new robust high performance thermal building insulation materials and solutions with as low thermal conductivity as the VIPs, but without the disadvantages.

This work explores the possibilities of inventing and developing new innovative and robust high performance thermal insulating materials. The aim is to go beyond VIPs and other current state-of-the-art technologies and envision the thermal insulation materials and solutions of tomorrow. New concepts like vacuum insulation materials (VIMs), nano insulation materials (NIMs), gas insulation materials (GIMs), dynamic insulation materials (DIMs) and NanoCon are introduced. The VIMs and GIMs have closed pore structures, whereas the NIMs have either open or closed pore structures. The objective of the DIMs are to dynamically control the thermal insulation material properties, e.g. solid state core conductivity, emissivity, and pore gas content. NanoCon is essentially a NIM with construction properties matching or surpassing those of concrete. In addition, fundamental theoretical studies aimed at developing an understanding of the basics of thermal conductance in solid state matter at an elementary and atomic level will also be carried out. The ultimate goal of these studies will be to develop tailor-made novel high performance thermal insulating materials and dynamic insulating materials, the latter one enabling to control and regulate the thermal conductivity in the materials themselves, i.e,. from highly insulating to highly conducting.

INTRODUCTION

Buildings constitute a substantial part of the world's total energy consumption, thus savings within the building sector will be essential, both for existing and new buildings. The thermal

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building insulation materials and solutions constitute one of the key fields. Recent studies (McKinsey 2009) point out that energy efficiency measures are the most cost-effective ones, whereas measures like solar photovoltaics and wind energy are far less cost-effective than insulation retrofit for buildings.

The traditional thermal insulation materials like mineral wool, expanded polystyrene (EPS) and extruded polystyrene (XPS) have thermal conductivities between 33 mW/(mK) to 40 mW/(mK). Polyurethane (PUR) with conductivities typically ranging from 20 mW/(mK) to 30 mW/(mK) is also applied as a thermal insulation material, but 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 is 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.

Nevertheless, in order to reach sufficient low thermal transmittances (U-values) for buildings in cold and/or changing climates where the outdoor temperature may drop well below 0°C, other thermal insulation materials or solutions are needed to avoid too thick buildings envelopes, e.g. walls with thicknesses between 40 cm and 50 cm as to obtain passive house or zero energy building requirements.

Today's state-of-the-art thermal insulation solutions cover vacuum insulation panels (VIPs), gas-filled panels (GFPs), and aerogels. In addition, although not strictly a thermal insulation solution, phase change materials (PCMs) may also be mentioned as they contribute to the total thermal building envelope performance by heat storage and release during solid state to liquid phase transformations. However, the PCMs are not treated further in this context.

State-of-the-art VIPs have thermal conductivities ranging between 3 mW/(mK) and 4 mW/(mK) in the pristine non-aged condition, hence about ten times lower than the typical thermal conductivity of 36 mW/(mK) for traditional insulation materials. However, with time water vapor and air are diffusing through the VIP foil envelope and into the open pore core structure of VIPs, thereby increasing the thermal conductivity up to typically 8 mW/(mK) after 25 years aging. Furthermore, perforating the VIP envelope causes an increase in the thermal conductivity to about 20 mW/(mK). Hence, the VIPs cannot be cut or adjusted at the building site and care has to be taken in order not to perforate the VIP foil during building assembly and throughout its service life. The commercially available VIPs are rather expensive, but calculations show that VIPs may already offer competitive thermal insulation solutions where the area is restricted (Grynning et al. 2009; Tenpierik 2009).

The GFPs, applying a gas less thermal conductive than air, e.g. argon (Ar), krypton (Kr), and xenon (Xe), exhibit the same major disadvantages as the VIPs. Besides, although much lower theoretical values have been calculated, the lowest reported thermal conductivities are around 40 mW/(mK) in the pristine condition, thus at the high end compared to traditional thermal insulation. Hence, the future of GFPs in buildings may be questioned, as compared to them the VIPs seem to be a better choice both for today and tomorrow.

The 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. The aerogel costs are still quite high, though. 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 2008a, 2008b). Furthermore, it is noted that aerogels can be produced as either opaque, translucent, or transparent materials, thus enabling a wide range of possible building applications. The coming years will show how far and extensive the aerogels will be applied in the building sector.

Thus, there should be an aim to invent or develop new robust high performance thermal building insulation materials and solutions with as low thermal conductivity as the VIPs, but without all the major disadvantages. This work, therefore, explores the possibilities of inventing and developing these new innovative and robust high performance thermal insulating materials, where the aim is to go beyond VIPs and other current state-of-the-art technologies and envision the thermal insulation materials and solutions of tomorrow.

THERMAL INSULATION REQUIREMENTS OF TOMORROW

The thermal insulation materials and solutions of tomorrow need to have as low thermal conductivity as possible. Besides, 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 like 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 crucial requirement for the future thermal insulation materials is that they can be cut and adapted at the building site without losing 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 aging durability, resistance towards freezing/thawing cycles and water in general, dynamic properties (i.e., the ability to

Table 1. Proposed Requirements of the High Performance Thermal Insulation Materials and Solutions of Tomorrow

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 aging durability	Resistant
Biological growth (e.g. fungi)	Resistant
Freezing/thawing cycles	Resistant
Water	Resistant
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

regulate the thermal insulation level) and costs which should be competitive versus other thermal insulation materials.

Hence, the future thermal insulation materials and solutions have to satisfy several crucial requirements. Table 1 summarizes the various properties with their proposed requirements. 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. In this context a conductivity less than 5 mW/(mK) after 100 years is proposed for the future thermal insulation materials and solutions to be developed.

THE FUTURE THERMAL INSULATION MATERIALS AND SOLUTIONS

In the following various possible future thermal insulation materials and solutions are presented at a conceptual basis. An initial presentation of these advanced insulation materials (AIMs) may be found in Baetens (2009), Jelle et al. (2009), and Baetens et al. (2010).

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 the pristine condition. The development from VIPs to VIMs is depicted in Figure 1.

Due to its closed pore structure the VIM can 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.

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. The development from VIPs to GIMs is depicted in Figure 2.

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..

NANO INSULATION MATERIALS (NIM)

A *nano insulation material* (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.

The development from VIPs to NIMs is depicted in Figure 3. 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.

Note that the grid structure in NIMs do not, unlike VIMs and GIMs, need to prevent air and moisture penetration into

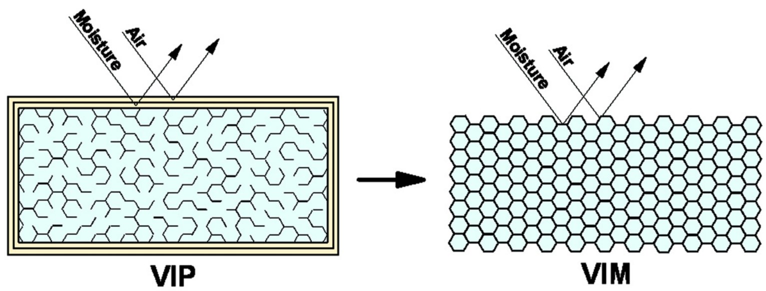

Figure 1 *The development from vacuum insulation panels (VIPs) to vacuum insulation materials (VIMs).*

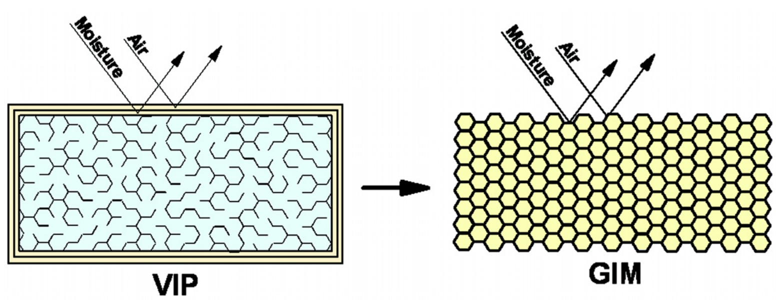

Figure 2 *The development from vacuum insulation panels (VIPs) to gas insulation materials (GIMs).*

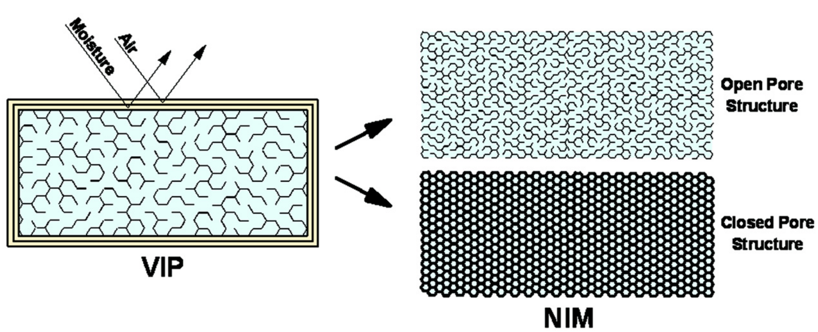

Figure 3 *The development from vacuum insulation panels (VIPs) to nano insulation materials (NIMs).*

their pore structure during their service life for at least 100 years.

But how do the NIMs achieve their low thermal conductivity without applying a vacuum in the pores? The answer to that is the so-called Knudsen effect (or nano pore effect), explained in the following.

THE KNUDSEN EFFECT—NANO PORES IN NIMS

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 due to 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 ballistically hit the pore wall and not another gas molecule. The gas thermal conductivity λ_{gas} taking into account the Knudsen effect may

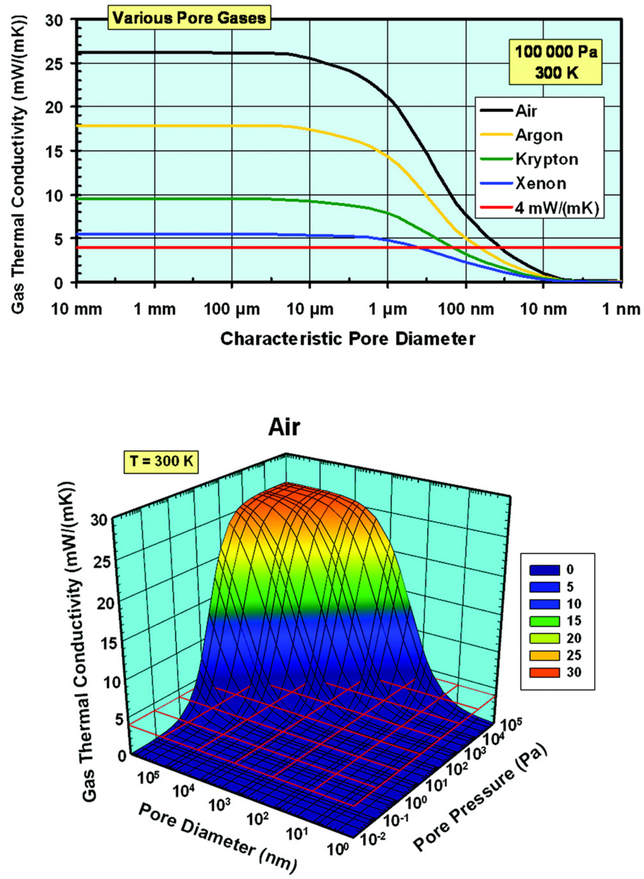

Figure 4 *The effect of pore diameter for air, argon, krypton, and xenon (two-dimensional model above) and both pore diameter and gas pressure in pores for air (three-dimensional model below) on the gas thermal conductivity. From Equations 1 and 2.*

be written in a simplified way as (Handbook of Chemistry and Physics 2003–2004; Schwab et al. 2005; Baetens et al. 2010):

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

where

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

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 (dimensionless number between 1.5–2.0)
Kn = Knudsen number (dimensionless)
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)

The Knudsen effect is visualized in two-dimensional and three-dimensional graphical plots in Figure 4, also depicting the low thermal conductivity value of 4 mW/(mK). Note that these plots are logarithmic with respect to the pore diameter and the pore pressure.

The hard sphere collision diameters have been applied for d in the calculations, i.e., 3.66, 3.58, 4.08, and 4.78 Å for air, Ar, Kr, and Xe, respectively (given at 298.15 K, Handbook of Chemistry and Physics 2003–2004). That is, the covalent diameters of the gas molecules have not been employed in these calculations. Furthermore, $\beta = 1.75$ and T = 300 K have been chosen in the calculations. In addition, $\lambda_{gas,0}$ values of 26.2, 17.9, 9.5, and 5.5 mW/(mK) have been applied for air, Ar, Kr, and Xe (at 300 K), respectively. In the left (two-dimensional) plot in Figure 4 a pore gas pressure of 100 000 Pa ($\approx$ 1 atm = 101 325 Pa) has been chosen

Furthermore, for these chosen values in Figure 4, a rapid decrease between pore diameters 1 μm–10 nm and pore pressures 10 Pa–0.1 Pa is demonstrated in the gas thermal conductivity.

THERMAL RADIATION IN NIMS

Applying the Stefan-Boltzmann equation to find the total radiation heat flux through a material with *n* air gaps in series with infinite parallel surfaces of equal emissivity, which may be approximated as *n* pores along a given horizontal line in the material, the radiation thermal conductivity λ_{rad} in the NIM pores may be approximately calculated by:

$$\lambda_{rad} = \frac{\sigma\delta}{\left[\frac{2}{\varepsilon} - 1\right]} \frac{(T_i^4 - T_e^4)}{(T_i - T_e)} \tag{3}$$

where

λ_{rad} = radiation thermal conductivity in the pores (W/(mK))

σ = $\pi^2 k_B{}^4/(60\hbar^3 c^2)$ = Stefan-Boltzmann's constant $\approx 5.67\cdot10^{-8}$ W/(m^{2}K^4)

k_B = Boltzmann's constant $\approx 1.38\cdot10^{-23}$ J/K

$\hbar$ = $h/(2\pi) \approx 1.05\cdot10^{-34}$ Js = reduced Planck's constant (h = Planck's constant)

c = velocity of light $\approx 3.00\cdot10^{8}$ m/s

δ = pore diameter (m)

ε = emissivity of inner pore walls (assumed all identical) (dimensionless)

T_i = interior (indoor) temperature (K)

T_e = exterior (outdoor) temperature (K)

The radiation thermal conductivity λ_{rad} decreases linearly with decreasing pore diameter δ as expressed by Equation 3, and with the emissivity ε of the inner pore walls as an important parameter. That is, the smaller the pores, and the lower the emissivity, the lower the radiation thermal conductivity.

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. A pore diameter of 10 μm is several orders of magnitude larger than the small pore diameter (e.g., 40 nm for air-filled pores) required to obtain a very low λ_{gas} according to the Knudsen effect (without applying a vacuum) as depicted by Figure 4.

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.

TOTAL THERMAL CONDUCTIVITY IN NIMS

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.

DYNAMIC INSULATION MATERIALS

A *dynamic insulation material* (DIM) is a material where the thermal conductivity can be controlled within a desirable range. 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)
- 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.

CONCRETE RETROFITTING OR SANDWICH CONFIGURATIONS WITH NIMS

As the thermal conductivity of insulation materials decreases, new solutions should also be found for the load-bearing elements of the building envelope. And, as only relatively thin layers of NIM are required in order to attain a satisfactory thermal insulation resistance, the NIMs may be applied as concrete retrofitting or in various sandwich configurations where there will be restrictions in the overall building envelope thickness.

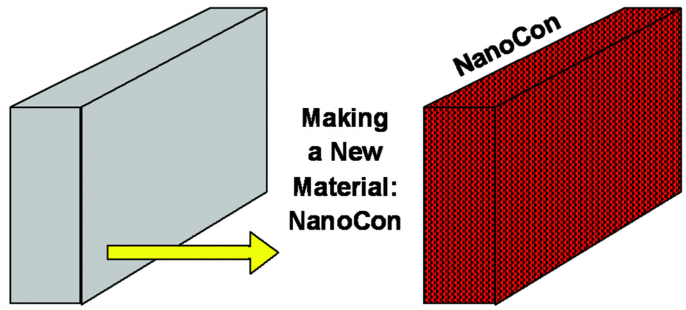

Figure 5 *NanoCon is essentially a NIM with construction properties matching or surpassing those of concrete.*

In principle, by employing NIMs with a thermal conductivity of 3.6 mW/(mK) instead of mineral wool or expanded or extruded polystyrene with 36 mW/(mK), the thermal insulation thickness reduces with a factor 10, e.g. a 4 cm thick NIM retrofitting instead of a 40 cm traditional thermal insulation retrofitting. That is, a vast reduction of the the thermal insulation layer and thereby the total building envelope thickness.

NIM AND CONCRETE MIXTURE

The NIMs may also be mixed 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.

TO ENVISION BEYOND CONCRETE

Concrete has a high thermal conductivity, i.e., 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.

In addition, 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). Concrete is also prone to cracking induced by corrosion of the reinforcement steel.

On the positive side concrete has a high fire resistance, i.e., concrete does not normally burn, but note that under certain circumstances spalling may occur and lead to early loss of stability due to exposed reinforcement and reduced cross-section. Furthermore, concrete is easily accessible and workable, is low cost, and enables local production.

To envision a building and infrastructure industry without an extensive usage of concrete, is that at all possible? Not at the moment and perhaps not for the near future, but maybe in a long-term perspective.

EMPHASIS ON FUNCTIONAL REQUIREMENTS

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.

NANOCON—INTRODUCING A NEW MATERIAL

With respect to the above discussion we hereby introduce a new material on a conceptual basis:

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 (Figure 5).

Note that 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. Dependent on the mechanical or construction properties of the NanoCon material, it may be envisioned both with or without reinforcement or rebars.

It may take a long time to invent and develop a material like NanoCon, but that does not mean it is impossible. Ideas might also be gained from other research fields, e.g., note the extremely large tensile strength of carbon nanotubes. Finally, maybe we even have to think thoughts not yet thought of.

THE POTENTIAL OF THE STATE-OF-THE-ART AND BEYOND

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 is given in Table 2.

CONCLUSION

New concepts of advanced insulation materials (AIMs) have been introduced, i.e., vacuum insulation materials (VIMs), gas insulation materials (GIMs), nano insulation materials (NIMs), dynamic insulation materials (DIMs), and NanoCon.

Nano insulation materials (NIMs) seem to represent the best high performance low conductivity thermal solution for the foreseeable future. Possible applications of NIMs cover all building types including timber frame and concrete buildings.

Dynamic insulation materials (DIMs) have great potential due to their controllable thermal insulating abilities.

Finally, NanoCon as essentially a NIM with construction properties matching or surpassing those of concrete has been introduced and defined.

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REFERENCES

Aspen Aerogels. 2008a. Spaceloft® 3251, 6251, 9251, Flexible insulation for industrial, commercial and residential applications. www.aerogel.com.

Aspen Aerogels. 2008b. Spaceloft™ 6250, Extreme protection for extreme environments. www.aerogel.com.

Baetens, R. 2009. Properties, requirements and possibilities for highly thermal insulating materials and solutions in buildings - State-of-the-art and beyond. *M.Sc. Thesis*. Catholic University of Leuven - Department of Architecture, Urban Design and Regional Planning (Leuven, Belgium), SINTEF Building and Infrastructure - Department of Materials and Structures (Trondheim, Norway) - Norwegian University of Science and Technology - Department of

Table 2. The Potential of Today’s 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	Load-Bearing Capabilities	A Thermal Insulation Material and Solution of Tomorrow?
Traditional Solutions						
Mineral Wool and Polystyrene	No	No	Yes	Yes	No	No
Today’s State-of-the-Art Solutions						
Vacuum Insulation Panels (VIP)	Yes	Maybe	No	No	No	Today and near future
Gas-Filled Panels (GFP)	Maybe	Maybe	No	No	No	Probably not
Aerogels	Maybe	Maybe	Yes	Yes	No	Maybe
Phase Change Materials (PCM)	–	–	–	–	No	Heat storage and release
Beyond State-of-the-Art—Advanced Insulation Materials (AIM)						
Vacuum Insulation Materials (VIM)	Yes	Maybe	Yes	Yes	No/Maybe	Yes
Gas Insulation Materials (GIM)	Yes	Maybe	Yes	Yes	No/Maybe	Maybe
Nano Insulation Materials (NIM)	Yes	Yes	Yes, excellent	Yes, excellent	No/Maybe	Yes, excellent
Dynamic Insulation Materials (DIM)	Maybe	Maybe	Not Known	Not Known	No/Maybe	Yes, excellent
NanoCon	Yes	Yes	Yes	Yes	Yes	Yes, excellent
Others?	–	–	–	–	–	Maybe

Civil and Transport Engineering (Trondheim, Norway).

Baetens, R., B.P. Jelle, J.V. Thue, M.J. Tenpierik, S. Grynning, S. Uvsløkk, and A. Gustavsen. 2010. Vacuum insulation panels for building applications: A review and beyond. *Energy and Buildings* 42:147-172.

Grynning, S., R. Baetens, B.P. Jelle, A. Gustavsen, S. Uvsløkk, and V. Meløysund. 2009. Vakuumisolasjonspaneler for bruk i bygninger – Egenskaper, krav og muligheter (Vacuum insulation panels for application in buildings – Properties, requirements and possibilities), (in Norwegian), SINTEF Byggforsk Prosjektrapport, nr. 31.

Handbook of Chemistry and Physics. 2003-2004. 84th edition, pp. 6-47 and 6-195, CRC Press.

Jelle, B.P., A. Gustavsen, and R. Baetens. 2009. Beyond vacuum insulation panels - How may it be achieved?. *Proceedings of the 9th International Vacuum Insulation Symposium (IVIS 2009)*, London, England, 17-18 September, 2009.

Joulain, K., J.-P. Mulet, F. Marquier, R. Carminati, and J.-J. Greffet. 2005. Surface electromagnetic waves thermally excited: Radiative heat transfer, coherence properties and Casimir forces revisited in the near field. *Surface Science Reports* 57:59-112.

McArdle, P., and P. Lindstrom. 2009. Emissions of greenhouse gases in the United States 2008. U.S. Energy Information Administration, DOE/EIA-0573(2008), December 2009.

McKinsey. 2009. Pathways to a low-carbon economy. Version 2 of the global greenhouse gas abatement cost curve. McKinsey & Company.

Mulet, J.-P., K. Joulain, R. Carminati, and J.-J. Greffet. 2002. Enhanced radiative heat transfer at nanometric distances. *Microscale Thermophysical Engineering* 6:209-222.

Schwab, H., U. Heinemann, A. Beck, H.-P. Ebert, and J. Fricke. 2005. Dependence of thermal conductivity on water content in vacuum insulation panels with fumed silica kernels. *Journal of Thermal Envelope & Building Science* 28:319-326.

Tenpierik, M.J. 2009. Vacuum insulation panels applied in building constructions (VIP ABC). *Ph.D. Thesis*, Delft University of Technology (Delft, The Netherlands).

World Business Council for Sustainable Development. 2002. The cement sustainability initiative – Our agenda for action. July 2002.

Zhang, Z.M. 2007. *Nano/microscale heat transfer*. McGraw-Hill.