Innovative High Performance Thermal Building Insulation Materials - Todays State-of-the-Art and Beyond Tomorrow

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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 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 e.g. solar photovoltaics and wind energy are far less cost-effective than insulation retrofit for buildings.

Today's State-of-the-Art Thermal Insulation

The state-of-the-art thermal insulation materials and solutions of today includes:

- **Vacuum Insulation Panels (VIP)**
  "An evacuated foil-encapsulated open porous material as a high performance thermal insulating material"
  - Core (silica, open porous, vacuum)
  - Foil (envelope)
  - 4 mW/(mK) fresh
  - 8 mW/(mK) 25 years
  - 20 mW/(mK) perforated
- **Gas-Filled Panels (GFP)**
  - 40 mW/(mK)
- **Aerogels**
  - 13 mW/(mK)
- **Phase Change Materials (PCM)**
  - Solid State ↔ Liquid
  - Heat Storage and Release
- **Beyond State-of-the-Art High Performance Thermal Insulation Materials**

Traditional thermal insulation (e.g. mineral wool) has a conductivity of typical 36 mW/(mK) and concrete conductivities range between 150 - 2500 mW/(mK).

Major Disadvantages of VIPs

VIPs have several advantages, but also several drawbacks:

- Thermal bridges at panel edges
- Currently expensive, but calculations show that VIPs may be cost-effective even today
- Ageing effects – Air and moisture penetration
- Vulnerable towards penetration, e.g nails
- Can not be cut or adapted at building site
- Possible improvements?

Requirements of Tomorrow's Insulation

Proposed requirements for the thermal insulation of tomorrow are given in Table 1.

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

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
Environmental impact (including energy and material use in production, emission of polluting agents and recycling issues)	low negative impact

Advanced Insulation Materials

Advanced insulation materials (AIM) and concepts of beyond tomorrow are introduced:

- Vacuum Insulation Materials (VIM)
- Gas Insulation Materials (GIM)
- Nano Insulation Materials (NIM)
- Dynamic Insulation Materials (DIM)

Vacuum Insulation Materials (VIM)

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.1).

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.

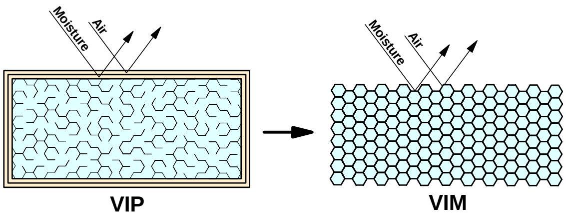

Fig.1. The development from VIPs to VIMs.

Gas Insulation Materials (GIM)

GIM is basically a homogeneous material with a closed small pore structure filled with a low-conductance gas, e.g. argon, krypton or xenon, with an overall thermal conductivity of less than 4 mW/(mK) in pristine condition.

Nano Insulation Materials (NIM)

By decreasing the pore size within NIM below a certain level, i.e. 40 nm or below for air, one may 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 pristine condition (Fig.2).

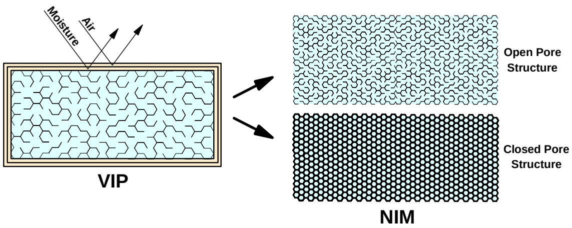

Fig.2. The development from VIPs to NIMs.

Note that 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.

The Knudsen Effect – Nano Pores in NIMs

The rapid decrease in thermal conductivity as the pore size decreases below a certain level, even with air-filled pores, 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} may be written in a simplified way as (Scwab et al. 2005, Baetens et al. 2010):

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

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)
- $Kn = \sigma_{mean}/\delta = k_B T/(2^{1/2}\pi d^2 p\delta)$ = the Knudsen number
- k_B = Boltzmann's constant $\approx 1.38 \cdot 10^{-23}$ 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 Figs.3-4.

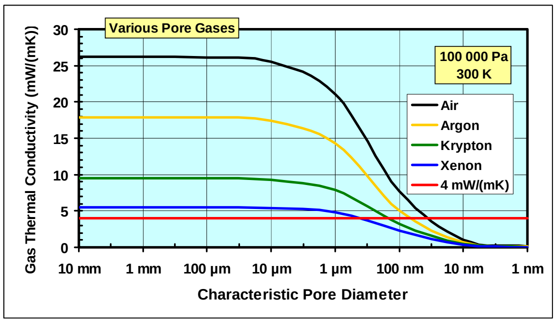

Fig.3. The effect of pore diameter on the gas thermal conductivity for air, argon, krypton and xenon. From Eq.1.

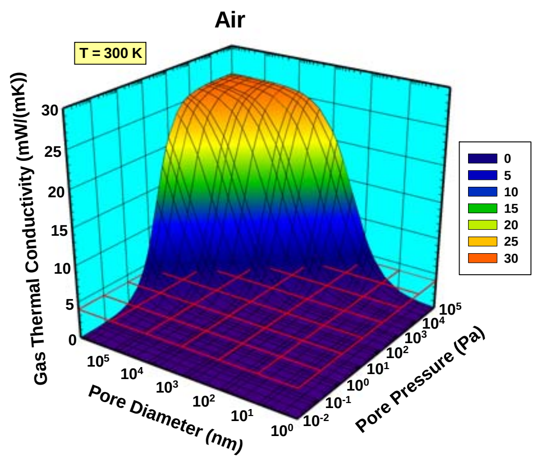

Fig.4. The effect of pore diameter and gas pressure in pores on the gas thermal conductivity visualized for air. From Eq.1.

Dynamic Insulation Materials (DIM)

DIM is a material where the thermal conductivity can be controlled within a desirable range.

- **Thermal conductivity control may be achieved by:**
  - 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
- **What is solid state thermal conductivity? Two models:**
  - Phonon thermal conductivity - atom lattice vibrations
  - Free electron thermal conductivity
- **What kind of physical model could describe and explain thermal conductivity?**
- **Could it be possible to dynamically change the thermal conductivity from very low to very high, i.e. making a DIM?**

Inspiration from other fields of science, e.g.?:

- Electrochromic Materials
- Quantum Mechanics
- Electrical Superconductivity
- Others? *Think thoughts not yet thought of!*

Potential of State-of-the-Art and Beyond

A short summary of the potential of becoming the high performance thermal insulation materials and solutions of tomorrow is given in Table 2.

Table 2. The potential of 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
Today's 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 – Advanced Insulation Materials (AIM)					
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

Conclusions

New concepts of advanced insulation materials (AIM) have been introduced, i.e. vacuum insulation materials (VIM), gas insulation materials (GIM), nano insulation materials (NIM) and dynamic insulation materials (DIM).

Nano insulation materials (NIM) 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 (DIM) have great potential due to their controllable thermal insulating abilities.

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