The High Performance Thermal Building Insulation Materials of Beyond Tomorrow - From Concept to Experimental Investigations

Bjørn Petter Jelle[a], Tao Gao[b], Linn Ingunn Christie Sandberg[c], Bente Gilbu Tilset[d], Mathieu Grandcolas[d] and Arild Gustavsen[b]

[a]SINTEF Building and Infrastructure, Department of Materials and Structures, NO-7465 Trondheim, Norway, and, Norwegian University of Science and Technology (NTNU), Department of Civil and Transport Engineering, NO-7491 Trondheim, Norway, bjorn.petter.jelle@sintef.no.
[b]Norwegian University of Science and Technology (NTNU), Department of Architectural Design, History and Technology, NO-7491 Trondheim, Norway.
[c]Norwegian University of Science and Technology (NTNU), Department of Civil and Transport Engineering, NO-7491 Trondheim, Norway.
[d]SINTEF Materials and Chemistry, Materials and Nanotechnology Sector, NO-0314 Oslo, Norway.

ABSTRACT

Traditional thermal insulation materials require thicker building envelopes in order to satisfy the requirements of the emerging zero energy and zero emission buildings. This study summarizes our work from concepts to experimental investigations for making the high performance thermal building insulation materials of beyond tomorrow like e.g. nano insulation materials (NIM).

Keywords: thermal insulation, building, concept, experiment, nano insulation material

1 INTRODUCTION

Energy-efficiency and zero emissions in the building sector represent a major mean on the path towards a more sustainable world, where thermal insulation for both new and existing buildings has an important role [1, 2]. Very thick building envelopes are not desirable due to several reasons, e.g. considering space issues with respect to economy, floor area, transport volumes, architectural restrictions and other limitations, material usage and existing building techniques. Vacuum insulation panels (VIP) represent a state-of-the-art thermal insulation solution, however due to the risk of loss of vacuum caused by perforation or moisture and air diffusion during many years, the VIP is not a robust solution [2-5].

Hence, there is a demand for developing high performance thermal insulation, also denoted as advanced insulation materials (AIM) and superinsulation materials (SIM). The objective of this work is to summarize the path from concepts to experimental investigations for tailor-making the high performance thermal building insulation materials of beyond tomorrow like e.g. nano insulation materials (NIM). A special focus is given on our current attempts to manufacture NIM based on hollow silica nanospheres (HSNS).

2 THE CONCEPT OF NIM

In a nano insulation material (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 defined as 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 [2].

A NIM achieves its low thermal conductivity, without applying a vacuum in the pores, by utilizing the so-called Knudsen effect. The gas thermal conductivity λ_{gas} taking into account the Knudsen effect may be written in a simplified way as [2-4]:

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

where

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

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

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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, and where the solid state and gas interaction is taken care of by the β coefficient. Hence, the resulting gas thermal conductivity λ_{gas}, also including the gas and pore wall interaction, versus pore diameter and pore gas pressure, may be calculated in this simplified model and depicted as in Fig.1. Further details on NIM and the Knudsen effect, also including thermal radiation aspects, are given in the work by Jelle et al. [2].

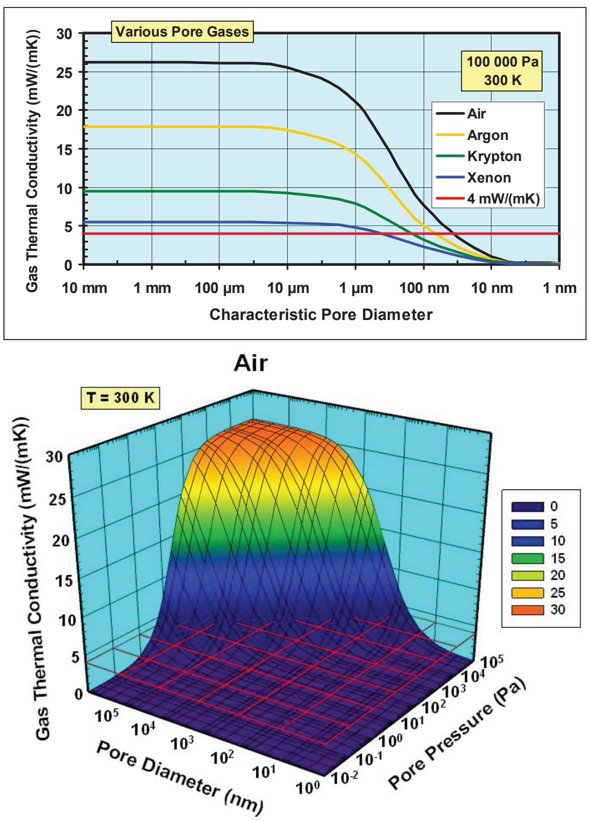

Figure 1: Gas thermal conductivity with (top) 2D-plot depicting the effect of pore diameter for air, argon, krypton and xenon and (bottom) 3D-plot depicting the effect of pore diameter and gas pressure in pores for air [2].

3 EXPERIMENTAL PATHWAYS

3.1 From Concepts to Experiments

Based on our conceptual studies [2-4, 6-8], different experimental pathways have been attempted in the quest of making thermal superinsulation materials, where at the moment most of these are based on fabricating hollow silica nanospheres (HSNS) by the sacrificial template method [9-15]. However, it should be noted that manufacturing a bulk material with nanopores directly, may be regarded as a more ideal and efficient way of producing a superinsulation material, i.e. and not first making hollow nanospheres which then need to be pieced together and assembled into a bulk material. Nevertheless, currently the HSNS represent an experimental feasible method of actually obtaining a thermal superinsulation material.

3.2 Membrane Foaming Method

The principle of membrane foaming is to make foams with nanoscale bubbles, followed by condensation and hydrolysis within the bubble walls to obtain a silica nanofoam. In the process, gas is pressed through a membrane to obtain bubbles with controlled size. Hydrolysis and condensation of precursors at the bubble-liquid interface should result in formation of gas capsules. The gas pressure must be very accurately adjusted, i.e. if the pressure is too low, no bubbles will be formed and if it is too high, a continuous gas stream will be the result. The size of the bubbles may be decreased by decreasing the pore size of the membrane and adjusting its surface properties to obtain a high contact angle with the solvent, i.e. the solvent should be repelled from its surface. Furthermore, the solvent density should be rather high and its surface tension low. In principle, it should be possible to design a reaction system that fulfills these requirements, so that production of nanosized bubbles is viable. However, no surfactant was found that could stabilize nanofoams long enough, thus work along this line has so far been abandoned [9].

3.3 Gas Release Method

Applying the gas release method would require simultaneous formation of nanosized gas bubbles throughout the reaction system, followed by hydrolysis and condensation to form a solid at the bubble perimeter. Bubble formation could be achieved by either evaporation or decomposition of a component in the system. However, the gas release process entails several challenges. To obtain nanosized bubbles with a sufficiently narrow distribution, the temperature must be the same throughout the liquid phase, which would be difficult to achieve at ordinary reaction conditions. Furthermore, the reaction to form the solid shell must proceed very rapidly if the shell is to be formed before the bubbles grow too large, which would require very reactive chemicals where their application would require strict control of humidity both in the working environment and in the solvents used. Due to these practical difficulties, work in this direction has at the moment been terminated [9].

3.4 Template Method

Utilizing the template method, a nanoscale structure in the form of a nanoemulsion or polymer gel is prepared, followed by hydrolysis and condensation to form a solid.

This procedure is applied for preparing e.g. catalysts and membrane materials. Our current approach is to prepare hollow silica nanospheres, followed by condensation and sintering to form macroscale particles or objects. For thermal insulation applications, small pore sizes combined with small wall thicknesses are desired and required [9].

4 HOLLOW SILICA NANOSPHERES

Detailed experimental information and procedures concerning the various fabrications of hollow silica nanospheres (HSNS) are found in our earlier studies [9-15]. Basically, the HSNS manufacturing applies the template method as described earlier, with either polyacrylic acid (PAA) or polystyrene (PS) as sacrificial templates, where PAA and PS have been removed by a washing and a heating process, respectively (the template materials diffuse and evaporate through the silica shell). The principle of the sacrificial template method for HSNS fabrication is illustrated in Fig.2.

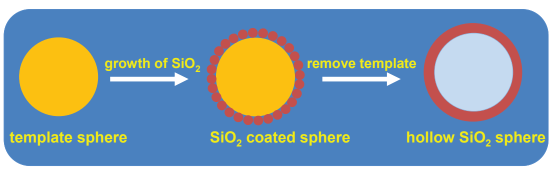

Figure 2: Illustration of the sacrificial template method for HSNS fabrication.

Nano insulation materials (NIM) have been attempted made in the laboratory as various hollow silica nanospheres (HSNS). In Fig.3 there is shown a principle drawing of a NIM alongside a transmission electron microscope (TEM) image of actual manufactured HSNS, depicting the close resemblance from theoretical concepts to experimental fabrication attempts.

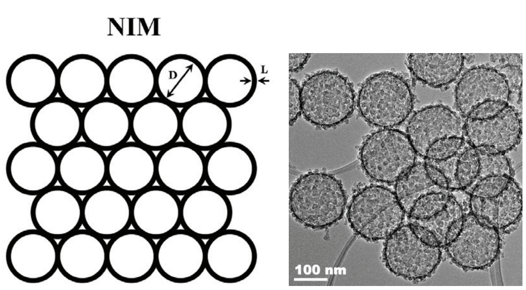

Figure 3: Principle drawing of a NIM (left) alongside a TEM image of actual manufactured HSNS (right).

A SEM image of manufactured spherical PS templates is shown in Fig.4 (left). The PS templates were hence coated with small silica particles, where an example is depicted in Fig.4 (right). Another example of HSNS with PS templates underneath is depicted in Fig.5 (left). By removal of the templates, HSNS are formed, where an example is depicted in Fig.5 (right).

Thermal conductivity has been measured for various powder samples of HSNS, where the conductivity values are typically in the range 20 to 90 mW/(mK), though some uncertainties in the Hot Disk apparatus measurement method have to be further clarified [13, 14]. In this respect, the specific powder packing of the HSNS in the bulk condition is also an issue to be addressed. The thermal conductivity is currently being attempted lowered by a parameter variation and optimization of the hollow silica sphere inner diameter and wall thickness. Furthermore, aspects like e.g. thermal radiation, mesoporosity, powder packing at bulk scale and nanosphere packing at nano scale should be addressed.

Life cycle analysis (LCA) of NIM as HSNS has been carried out in the study by Gao et al. [11], and follow-up investigations are currently being conducted. Initial experiments attempting to improve the thermal resistance of concrete by incorporation of aerogel have also been performed [16], where naturally any new development of NIM will be interesting for further work. More information on monodisperse PS nanospheres [17] and hollow silica nanospheres [18-21] may be found in the literature.

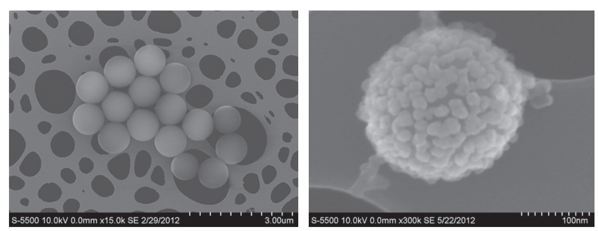

Figure 4: SEM images of spherical PS templates (left) and small silica particles coated around a spherical PS template (right).

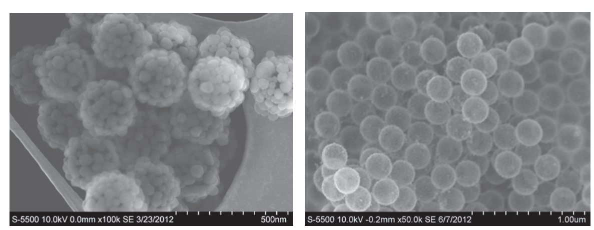

Figure 5: SEM image of small silica particles coated around spherical PS templates (left) and SEM image of HSNS after removal of PS (right) (not the same spheres).

5 FURTHER WORK

Currently, our SIM and NIM research is mainly focused on various attempts to tailor-make HSNS by manufacturing and applying different sacrificial templates, synthesis procedures, parameter variations, and inner diameters and shell thicknesses of the nanospheres. A crucial issue will be how to assemble the HSNS into a practical bulk material. It should be noted that the future NIM may not necessarily be based on HSNS, nevertheless the investigations on the

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HSNS represent a possible stepping-stone towards the ultimate goal of achieving thermal superinsulation materials. Although we at the moment are not pursuing fabricating NIM according to the membrane foaming and gas release methods, these methods should definitely not be forgotten as they may still represent a possible way of achieving SIM and NIM. Finally, it should be emphasized that also methods and materials not included within this summary, even hitherto unknown methods and materials, may hold the solution for the future SIM and NIM.

6 CONCLUSIONS

Theoretical concepts and experimental investigations for making high performance thermal building insulation materials have been summarized. A special focus has been given on nano insulation materials (NIM). Hollow silica nanospheres (HSNS) have been manufactured, which hence represent a possible stepping-stone for the development of the NIM of beyond tomorrow.

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