Development and Investigation of New Materials and Technologies for Utilization in Zero Emission Buildings

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ABSTRACT

The demand for zero emission buildings (ZEB) and energy-producing buildings is increasing along with the growing focus on material resources abundance and scarcity, energy efficiency, renewable and non-polluting energy sources and carriers, and environmental impact. In this respect, development and investigation of new materials and technologies will be crucial. This includes vacuum insulation panels (VIP), nano insulation materials (NIM), aerogel-incorporated concrete, translucent aerogel windows, low-emissivity coatings, anti-reflective coatings, solar-selective materials, snow- and ice-avoiding material surfaces, lightweight glass materials, smart windows and in particular electrochromic materials for solar radiation regulation, phase change materials, and building integrated photovoltaics (BIPV), with the possibility of combining these into multi-functional building envelopes.

Keywords: thermal insulation, aerogel, electrochromic, building integrated photovoltaics, zero emission building

1 INTRODUCTION

Zero emission buildings (ZEB) and energy-producing buildings will be increasing both in numbers and in importance along with the growing focus on material resources abundance and scarcity, energy efficiency, renewable and non-polluting energy sources and carriers, and environmental impact. Hence, it will be crucial to develop new materials and technologies in a large range of different scientific and technological fields, thus covering many functions and applications in buildings, including tailor-making of miscellaneous materials with specific and even dynamic, i.e. adaptive or controllable, properties.

This study will present the development and investigation of new materials and technologies in our laboratories for possible utilization in zero emission buildings. Among the materials and technologies which will be discussed herein are vacuum insulation panels (VIP), nano insulation materials (NIM) including hollow silica nanospheres (HSNS) with a quest to obtain as low thermal conductivity as possible, aerogel-incorporated concrete, translucent aerogel windows, low-emissivity coatings, anti-reflective coatings, solar-selective materials, snow- and ice-avoiding material surfaces, lightweight glass materials, smart windows and in particular electrochromic materials for solar radiation regulation, phase change materials, and building integrated photovoltaics (BIPV). Ultimately, these materials and technologies may be combined into multi-functional building envelopes. Emphasis will be given on experimental results, although some theoretical and conceptual studies have also been carried out.

2 VACUUM INSULATION PANELS

Vacuum insulation panels (VIP) have been investigated in several theoretical and experimental studies [1-7], where these include state-of-the-art VIPs, theoretical studies like e.g. lifetime predictions with calculations of the thermal conductivity increase in VIPs with different foil materials during elapsed time, climate exposure, accelerated climate ageing, retrofitting with VIPs, condensation risk studies and VIPs applied in various building envelopes.

3 NANO INSULATION MATERIALS

The idea giving the basis for nano insulation materials (NIM) is the possible exploitation of the Knudsen effect, where the gas thermal conductivity $\lambda_{gas+gas/solid}$, also including the gas and solid state pore wall interaction, is decreasing with decreasing pore diameter [8-10]. Thus, by 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, $\lambda_{gas+gas/solid}$ may become very low even with air-filled pores, i.e. where the pore diameter is smaller than the mean free path of the gas molecules. In addition, one must also take into account the thermal transport by solid state conduction and radiation.

A possible pathway is to make NIMs by synthesizing hollow silica nanospheres (HSNS) applying e.g. polystyrene (PS) as sacrificial templates, where the PS templates have been removed by a heating process [11-17]. The principle behind the HSNS synthesis is illustrated in Fig.1 alongside scanning electron microscope (SEM) images of corresponding actual fabricated materials. Close resemblance between theoretical concepts and experimental practice is observed.

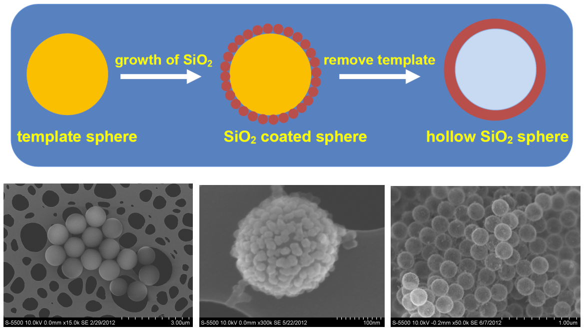

Figure 1. Principle drawing of the sacrificial template method for HSNS synthesis (top). SEM images (left to right) of PS templates, small silica particles coated around a spherical PS template, and HSNS after removal of PS [14].

The thermal conductivity for various powder samples of HSNS has typically been measured in the range 20 to 90 mW/(mK), though some uncertainties in the Hot Disk apparatus method have to be clarified [14]. Specific powder packing of HSNS in bulk condition is also important to address. Thermal conductivity is currently being attempted lowered by parameter variation and optimization of the hollow silica sphere inner diameter and shell thickness.

4 AEROGEL-INCORPORATED CONCRETE

Aerogel granulates have been incorporated in concrete in an attempt to lower the thermal conductivity of concrete [18-22]. Aerogel-incorporated concrete (AIC) samples with compressive strengths of up to about 19 MPa were achieved with a corresponding thermal conductivity of about 0.4 W/(mK). For more thermally insulating concrete, 70 vol% aerogel was needed and AIC samples with thermal conductivity as low as about 0.1 W/(mK) were cast. In general, AIC samples with strengths of up to 5 MPa could be achieved when thermal conductivities of between 0.1 and 0.2 W/(mK) were desired. In Fig.2 there is given a SEM image of an AIC sample showing the interface between an aerogel granulate and the concrete matrix.

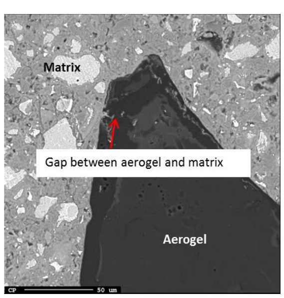

Figure 2. SEM image of AIC sample with aerogel granulate and concrete matrix interface. Scale bar = 50 μm [20].

5 TRANSLUCENT AEROGEL WINDOWS

Miscellaneous investigations have been conducted on translucent windows and glazing systems with aerogel granulates between the glass panes [23-28]. These include studies related to aspects such as e.g. impact of granulate particle size on solar radiation transmittance, impact of air convection on thermal performance, their application potential from an energy saving perspective, ageing issues by moisture and solar radiation, and various other perspectives of aerogel glazings in energy-efficient windows. A photo of float glass window panes with air, large-sized aerogel granulates (3-5 mm) and small-sized aerogel granulates (< 0.5 mm) in the cavities is given in Fig.3, where corresponding total and diffuse transmittance spectra may be found in the study by Gao et al. [23].

Figure 3. Photo of float glass window panes with (left) air, (middle) large-sized aerogel granulates and (right) small-sized aerogel granulates in the cavities [23].

6 LIGHTWEIGHT GLASS MATERIAL

A new lightweight aerogel glass material has been synthesized by sintering monolithic silica aerogel precursors at elevated temperatures [29]. A high visible transparency ($T_{vis} \approx 91$ - 96 % at 500 nm), a low thermal conductivity ($\lambda \approx 0.17$ - 0.18 W/(mK)), a low mass density ($\rho \approx 1.60$ - 1.79 kg/dm^3) and an enhanced (compared to our earlier experiments) mechanical strength (typical elastic modulus $E_r \approx 2.0$ - 6.4 GPa and hardness $H = 0.23$ - 0.53 GPa) were achieved. Corresponding values for float glass are $T_{vis} \approx 92$ % at 500 nm, $\lambda \approx 0.92$ W/(mK), $\rho \approx 2.5$ kg/dm^3, $E_r \approx 50.77$ GPa and $H = 1.64$ GPa.

7 VARIOUS COATING MATERIALS

Miscellaneous coating materials have been fabricated, e.g. antireflective HSNS [30] and solar selective core-shell-typed Ag@SiO_2 nanoparticle [31] materials. A typical application area may be in window panes. Transmission electron microscope (TEM) images of as-prepared HSNS and Ag@SiO_2 nanoparticles are shown in Fig.4.

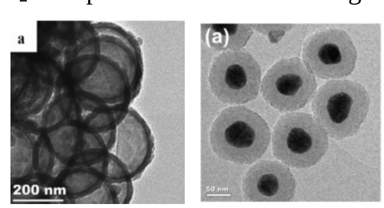

Figure 4. TEM images of as-prepared (left) HSNS [30] and (right) Ag@SiO_2 nanoparticles [31].

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8 LOW-EMISSIVITY MATERIAL

A low-emissivity (low-e) [32] material coating based on silver nanoparticles with an emissivity as low as 0.015 has been synthesized [33]. SEM images of an as-synthesized Ag nanoparticle film and after heat treatment at 200°C are shown in Fig.5, whereas more SEM images and reflectance spectra at several heat treatment temperatures are given in the study by Gao and Jelle [33].

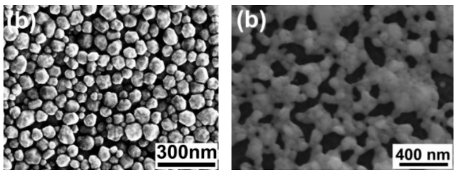

Figure 5. SEM images of as-synthesized Ag nanoparticle film (left) and after heat treatment at 200°C (right) [33].

9 SMART WINDOWS AND ELECTROCHROMIC MATERIALS

Smart windows are able to dynamically change the transmittance of solar radiation into buildings, which may be achieved by either adaptive or controllable technologies applying different materials. Electrochromic windows control the transmittance throughput by an applied voltage, and represent one of the very promising smart window technologies [34-37].

Transmittance spectra regulation of an electrochromic window utilizing the electrochromic materials polyaniline (PANI), prussian blue (PB) and tungsten oxide (WO_3) is depicted in Fig.6, where this specific electrochromic window had a total solar transmittance regulation as high as ΔT_{sol} = 57 % and a visible solar transmittance regulation as high as ΔT_{vis} = 61 %.

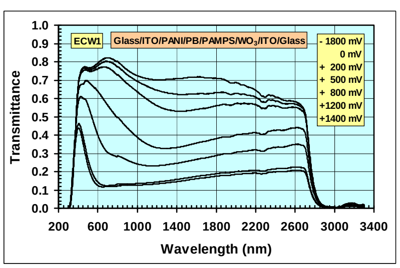

Figure 6. Transmittance spectra regulation of an electrochromic window [37].

10 PHASE CHANGE MATERIALS

The adaptive technology of phase change materials (PCM) [38,39] being able to absorb and release heat when needed may become part of the thermal building envelope, thus also part of multi-functional building envelopes.

Laboratory measurements of indoor air and surface temperatures of a test wall with and without PCM panels versus elapsed time, demonstrated the ability of the PCM panels to decrease the indoor temperature variations with about 2 °C [39].

11 BUILDING INTEGRATED PHOTOVOLTAICS

Building integrated photovoltaics (BIPV) represent an elegant way of turning the exterior weather protection building skin into an electrical power source harvesting the solar radiation energy [40-45].

Today BIPV systems are designed as various foil, tile, module and solar cell glazing products which need to be pieced together in different, and often cumbersome, ways, with respect to both the main panels (e.g. tiles) and their electrical cable connectors. For future BIPV products, one may envision robust and less labour-intensive plug-and-play systems. That is, plug-and-play BIPV (PaP BIPV) systems where individual panels (e.g. tiles) are clicked/snapped together in a single and simple operation ensuring both satisfactory electrical connections and weather tightness, and likewise when removing individual panels [45]. Large-scale laboratory investigations of wind-driven rain exposure of a BIPV system is shown in Fig.7.

Figure 7. Large-scale laboratory investigations of wind-driven rain exposure of a BIPV system [42].

12 MULTI-FUNCTIONAL BUILDING ENVELOPES

Combinations of the technologies described in the above, and others, may become part of the multi-functional building envelopes of tomorrow, incorporating miscellaneous materials and components with tailor-made properties, thus resulting in building envelopes being able to take care of several functions and satisfy various requirements. Some materials may even exhibit the ability to perform more than one single function, e.g. materials with both electrochromic and photovoltaic properties.

13 CONCLUSIONS

Several new materials and technologies for possible and promising utilization in zero emission buildings have been developed and investigated in our laboratories alongside some theoretical and conceptual studies. The application and combination of these ones may also result in the making of multi-functional building envelopes.

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