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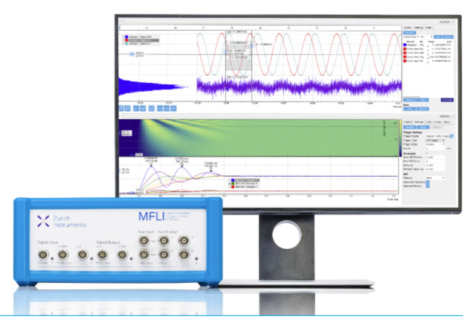

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Nano insulating materials and energy retrofit of buildings

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Abstract: The article offers an analysis of the use of nanotechnological insulation materials (NIMs) for energy upgrading of buildings, illustrating the possibility of their integration into the building envelope and the benefits achievable in terms of architectural quality, comfort and energy saving, within the new framework of European legislation aimed at achieving Zero energy buildings. Particular reference is given to Fibre Reinforced Aerogel Blankets for the building envelope, especially interesting for their wide possible applications even combined with phase change materials.

1. INTRODUCTION

The construction industry is one of the world priority action areas for a transition to a resource-efficient and low-carbon economy.

In fact, in 2012 buildings globally accounted for 32% of final energy consumption (in US and Europe more than 40%) and for one-third of direct and indirect CO_2 and particulate matter emissions [1].

Such high energy consumption in buildings is attributable mainly to low thermo-hygrometric performance of the building envelope (poor thermal insulation, low thermal inertia, the presence of thermal bridges, ineffective screening systems, air leaking, etc.), low efficiency of HVAC and lighting systems as well as a still low utilization of renewable energy sources. Most of the existing building stock in OECD countries was in fact built before 1970, in absence of specific energy performance requirements for building envelope or equipment [2].

With the aim of reducing energy consumption and greenhouse gas emissions, the commitment of all countries in improving the energy efficiency of buildings has therefore been greatly increasing over the past decade with the objectives of ensuring that all new buildings are characterized by high energy efficiency (very low energy buildings, VLEBs), significantly reducing the energy consumption of existing buildings (more than 50% of the current global building stock will still be operative in 2050 and in OECD countries this figure reaches or exceeds 75%) and using as much renewable energy as possible.

Converting the existing building stock from an energy waster to an energy producer, however, requires new technologies both for the building envelope and for equipment, including renewable energy sources, tailored to each specific construction period, building type and climatic zone.

As energy-efficiency standards for buildings become more and more stringent, using a traditional insulation material often means having to accept increasingly thick layers of insulation in walls, floors, and roofs. In renovation projects, provided it is possible to increase insulation thickness at all, significant aesthetic and functional compromises are often required to fit more insulation on the inside or outside of the building envelope.

It is therefore evident that traditional materials, products and technologies are not adequate to meet this challenge of upgrading the energy efficiency of buildings.

Instead, what is indeed necessary are advanced solutions able to combine the energy performance with the building architectural quality and the highest livability, ensuring the achievement of the optimal cost-effect ratio.

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In this picture, the use of nanotechnology can bring many benefits by improving the energy and environmental performance of buildings, with application potential in all technical elements, from structure, to opaque and transparent closures, internal partitions, up to systems and appliances [3].

Several applications are now available for the building sector in order to increase the mechanical, physical and chemical properties of materials, products and equipment, as well as their durability over time, with the aim of improving environmental comfort, safety, energy efficiency of buildings and at the same time reducing operating and maintenance costs and environmental impacts [4].

2. NANOTECHNOLOGY AND DEEP ENERGY RENOVATION OF BUILDING ENVELOPE

Buildings consume energy for heating, cooling and interiors ventilation, for domestic hot water production, for lighting appliances and for electrical equipment, for people transport and for food cooking, with a different incidence depending on the type of building, its year of construction and the climate zone in which it is located.

Space heating and cooling account for over 30% of all energy globally consumed in buildings, rising to as much as 50% in cold climate countries. In the residential sector, the share of energy consumption used for heating and cooling in cold climate countries is over 60% [5].

The goal of reducing energy consumption for space heating and cooling in existing buildings shall be pursued at three different levels [6]:

- at the technical and construction level, regarding the thermos-hygrometric characteristics of the building envelope;
- at the technological level, inherent to the efficiency of mechanical systems and appliances, the integration of renewable energy sources, the introduction of Building Energy Management Systems (BEMS);
- at the cultural and social level, concerning the behaviour of users.

Regarding in particular the building envelope, a number of critical elements will be required to achieve deep reductions in space heating and cooling energy needs and fossil fuels consumption of existing buildings [6]:

- high levels of insulation in walls, roofs and floors to reduce heat losses in cold climates, optimized using life-cycle cost assessment;
- high levels of thermal inertia and highly reflective surfaces in roofs and walls to reduce summer overheating in hot climates;
- high-performance windows with low thermal transmittance and climate-appropriate solar heat gain coefficient (SHGC);
- properly sealed structures to ensure low air infiltration rates with controlled ventilation for fresh air;
- minimization of thermal bridges (components that easily conduct heat/cold), such as highly thermal conductive fasteners and structural elements;
- renewable energy systems more efficient and better integrated in the building envelope.

Nanoscience and nanotechnology may yield important improvements in the energy efficiency of the building envelope and in the integration of renewable energy, allowing advanced materials with fixed or dynamic high performance response able to balance performance requirements with aesthetic requirements and architectural constraints. These in particular consist in [6]:

- advanced insulating materials (Fibre Reinforced Aerogel Blankets, Vacuum Insulated Panels) with extremely reduced thickness, able to allow architectural integration, minimal encumbrance, thermal bridges reduction and piping application;
- Transparent Insulating Materials (Aerogel TIMs) to combine daylighting with energy efficiency;
- Phase Change Materials (PCMs) to raise thermal inertia of the envelope or internal partitions and provide thermal heat storage for solar passive heating without increasing mass;
- reflective coatings to increase thermal insulation or reduce overload solar radiation (cool roofs);
- self cleaning and anti reflective glazing to maximize luminous transparency;
- advanced thermal insulation glazing (monolithic aerogel IGUs) and heating glazing to reduce thermal loss from windows in cold climates and improve thermal comfort;
- dynamic glazing (smart windows) to allow dynamic control of solar radiation and HVAC integration;

- PV glazing to reduce incoming solar radiation and at the same time produce electricity.

The application of nanotechnology products can in in fact bring sensible benefits in energy upgrading of buildings both in hot and cold climates, if employed in an appropriate manner in relation to the type of users, the complexity of the building and the local environmental (heating or cooling dominated), economic (developed or undeveloped) and cultural context.

TABLE I – Main application of nanotechnological products in energy retrofit interventions

Climate	Nano materials and technologies for energy retrofit of building envelope
Hot	Very low-SHGC glazing or dynamic glazing Solar control films for windows Cool roofs and reflective coatings PV Shading systems Phase Change Materials (thermal inertia) Self cleaning glazing and surfaces
Cold	Advanced insulation glazing Dynamic glazing Anti reflective glazing Suspended film glazing Light redirection and optical systems Heating glazing BIPV/BAPV shell Self cleaning glazing and surfaces Advanced insulating materials for interior or exterior insulation and equipment insulation Phase Change Materials (for passive solar gain or in case of internal insulation) Reflective thermal coatings for interior walls

3. NANO INSULATING MATERIALS

Nanotechnology can be used to create new advanced high performance insulating materials able to provide exceptional heat flow resistance performance, thanks to their nanoporous structure achieved via sol-gel processing (silica aerogel), can be employed in vacuum applications (VIP) or additionally provide transparency to solar radiation (TIM).

Due to their low thermal conductivity (λ<0.02 W/mK), is it possible to obtain high thermal resistance values of the building envelope with extremely thin insulating layers (less than a third compared to conventional insulating materials). These products are thus particularly suitable for the correction of thermal bridges and for energy retrofit of existing buildings, especially of historic buildings subjected to architectural constraints, and in all cases in which it is necessary to increase energy efficiency and comfort with minimum space loss.

In fact, existing buildings envelopes are characterized by high thermal transmittance values, which for walls is typically between 1 and 3.5 W/m^2 K in relation to the time of construction. Thus, in order to reach the minimum thermal insulation values required by law in case of retrofit (in Italy between 0.28 and 0.48 W/m^{2}K according to the function of the technical element) through the use of traditional insulation with λ of 0.030 - 0.045 W/mK, it is necessary to provide between 6 and 10 cm of additional thickness.

This thickness may often be incompatible with the building aesthetics and design, or, if placed inside, cause an excessive reduction of space or be incompatible with the finishing (brick molds, jambs, architraves, thresholds, etc.).

TABLE 2 - Thermal trasmittance limit values for envelope elements of new buildings in Italy (DM 26 of June 2015)

Climatic Zone	Perimeter walls U (W/m^2K)	Roofs U (W/m^2K)	Floors U (W/m^2K)
A and B	0.45	0.34	0.48
C	0.40	0.34	0.42
D	0.36	0.28	0.36
E	0.30	0.26	0.31
F	0.28	0.24	0.30

Thus, for example, in order to reduce the thermal transmittance of the wall of an existing building (U_{in}), equal to 1.10 W/m^2K (empty cavity wall with holed bricks), to meet the requirements of the Italian DM 26 of June 2015 for the climate zone D, corresponding to Rome (U_{fin} = 0.36 W/m^2K), by using a good traditional thermal insulator with a thermal conductivity λ of 0.035 W/mK, the minimum thickness to be applied would be at least 6.5 cm.

In particular, thermal resistance of the existing wall R_{in} is obtained from:

$$R_{in} = \frac{1}{U_{in}} = \frac{1}{1.10} = 0.90 \ \frac{\mathrm{m}^2 \cdot \mathrm{K}}{\mathrm{W}} \tag{1}$$

Thermal resistance of the wall after the intervention R_{fin} is obtained from:

$$R_{fin} = \frac{1}{U_{fin}} = \frac{1}{0.36} = 2.77 \ \frac{\mathrm{m}^2 \cdot \mathrm{K}}{\mathrm{W}} \tag{2}$$

The additional layer of insulating material shall therefor provide a resistance increment ΔR of:

$$\Delta R = R_{fin} - R_{in} = 1.87 \ \frac{\mathrm{m}^2 \cdot \mathrm{K}}{\mathrm{W}} \tag{3}$$

As the thermal resistance of a layer of homogeneous material with thickness d is obtained from:

$$R = \frac{d}{\lambda} \ \frac{\mathrm{m}^2 \cdot \mathrm{K}}{\mathrm{W}} \tag{4}$$

Assuming the choice of an insulating panel with thermal conductivity value λ=0,035 W/mK, the thickness needed to provide the thermal insulation required is calculated as:

$$d = \Delta R \cdot \lambda = 1.87 \cdot 0.035 = 0.065 \ \mathrm{m} = 6.5 \ \mathrm{cm} \tag{5}$$

It is therefore evident that the minimum thickness required can often be incompatible both with the building aesthetics and with the housing needs of the users (reduction of net area or minimum height).

The use of nanotechnological insulating materials with thermal conductivity λ<0.02 W/mK can allow to reduce additional thickness down to 1 to 3 cm at maximum.

Nanomaterials can also find application in other product categories for increasing energy efficiency of the building envelope.

Hence, for example near infrared reflecting coatings such as nanopaints can also be used for roof and wall applications in order to reduce the summer overheating and Urban Heat Island Effect (Cool roofs). Furthermore, nanomaterials addition can significantly alter the thermophysical properties of heat storage materials, especially in phase change materials (PCMs) for latent thermal energy storage (LTES) applications. There, the incorporation of specified proportions of nanomaterials can increase thermal conductivity, accelerate freezing and melting rates, improve thermal stability, and ensure thermal reliability over time.

4. FIBRE REINFORCED AEROGEL BLANKETS FOR BUILDING ENVELOPE

Within nanotechnology insulating products, particularly interesting for their wide possible applications to energy retrofit of buildings are those made of aerogel (air+gel), a solid nanoporous material with ultra-low density obtained through the dehydration of a colloidal gel by replacing the liquid component with a gaseous one.

Among different aerogels, those based on silica (dubbed silica aerogels) are the most widely used for thermal insulation due to their properties and their relatively simple and reliable preparation method.

Also known as frozen smoke, solid smoke or blue smoke due to its transparency, silica aerogel is an amorphous material that appears as a solid foam with a tactile feeling akin to foam rubber. Consisting of more than 90% air, aerogels are the solid substance with the lowest weight per volume unit known today (as low as 3 kg/m^3).

Silica aerogels present extraordinary low thermal conductivity values, typically 0.015 W/mK up to 0.004 W/mK in modest vacuum (vacuum insulating panels with nanoporous core, VIPs).

Such performance is achieved thanks to the higher rarefaction of air inside the insulation materials, due to their high porosity and nanoporous solid structures with interconnected pore sizes typically ranging from 5 to 100 nm and an average pore diameter between 20 and 40 nm [7,8].

As known, overall thermal conductivity of porous materials depends in fact on convection within the pores, conduction within the pores, conduction in the solid matrix, and radiation. In particular:

- convective heat transfer decreases with the decrease of air motion inside the pores;
- conduction decreases with the decrease of pressure around it and inside the pores;
- radiation decreases significantly with a decrease in temperature and with a decrease in pore size;
- conduction in the solid part of the porous matrix is defined by the type and amount of material used.

In nanoporous materials, high porosity reduces heat conduction through the solid part, while the small size of the pores reduces the radiation and the conduction in the gas. Reducing the pore size to nanoscale level increases in fact the collisions between the gas molecules and the pore walls leading to suppressed gas conduction by exploiting the Knudsen effect, which typically comes into play when the scale length of a system is comparable to the mean free path of gas particles involved (70 nm for air molecules) [6].

In nanoporous materials, instead of freely moving through the pores of the medium keeping most of their energy intact, air molecules collide with the pore walls more often than with each other dispersing most energy within the porous structure. Moreover, aerogel structure network is heavily crosslinked and full of dead-ends, helping in trapping air molecules inside. This way it is possible to block effectively heat transfer by convection.

The open structure of the pores makes aerogel permeable to water vapour, whereas its composition based on hydrophobic silica makes it waterproof and fireproof. Moreover, aerogel peculiar nanoporous structure ensures thermal performance conservation regardless of operating temperature, whereas traditional insulating materials usually become more conductive as air temperature rises and air molecules excite and move more freely within the porous network.

These characteristics make silica aerogel the best material for thermal insulation in the world, capable of operating in a temperature range between -200 and +650 °C.

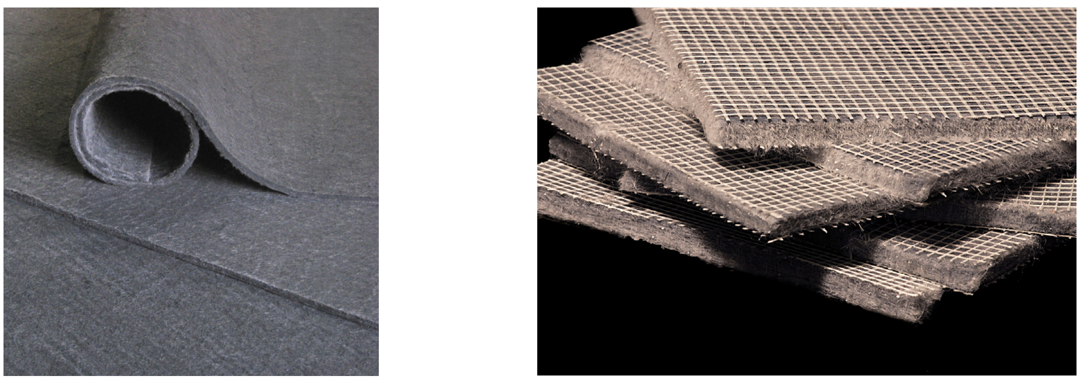
Despite being extremely friable, its dendritic microstructure, with a specific surface area up to 800 m^2/g, gives aerogel compression resistance able to bear a load of up to 4000 times its own weight [7].

To improve its mechanical characteristics in order to ease its use in insulating opaque enclosures, Aerogel is usually integrated in a PET fibrous support structure, obtaining Fibre Reinforced Aerogel Blankets (FRAB) such as Aspen Aerogels Spaceloft.

Final FRAB composition is 40-55% silica, 20-45% PET/glass fibre and 0-15% additives. Specific fire resistant FRABs forego PET in favour of only glass fibre to achieve a Euroclass A2 fire rating (Spaceloft A2). FRABs can be applied in their original mat form (Spaceloft) or coupled with support materials such as fiberglass meshes, polypropylene reinforced layers (AMA Composites Aeropan) or gypsum wall boards (AMA Composites Aerogips) for different applications.

TABLE 3 – Main aerogel insulating product specifications

Aerogel Product	Aspen Aerogels Spaceloft®
Thermal conductivity (W/mK)	0.015
Maximum use temperature °C	200
Water vapour permeability μ	5
Compressive strength (10% deformation) kPa	80
Density (kg/m^3)	150
Specific heat (J/kg)	1000
Fire reaction (Euroclass)	C, s1, d0
Visible light transmission (thickness)	0.203 (5 mm) 0.055 (10 mm)
Solar transmittance	0.196 (5 mm) 0.052 (10 mm)
Site adaptability	Cut to size, flexible
Appearance	Translucent white/grey
Use	Underfloor insulation, thermal bridges correction in buildings



(a) (b)

FIGURE 1. Main aerogel insulating products on the market: (a) Aspen Aerogels Spaceloft, (b) AMA Composites Aeropan Basic

Compared to conventional insulation materials of vegetal (cork, wood fibre, hemp fibre, coconut fibre, etc.), animal (sheep wool), mineral (fiberglass, rock wool, expanded vermiculite, pumice etc.) or synthetic origin (polyurethane, polystyrene, polyethylene foams etc.), in addition to offering greater thermal insulation values (λ = 0.015 W/mK), FRABs have important advantages, including in particular [9]:

- constant thermal performance regardless of operating temperature;
- high hydrophobicity values while maintaining high water vapour permeability;
- low flammability (Euro Class C to A2: fire-resistant materials);
- mold, UV and elements resistance;
- no performance drop over time due to perforation or material decay;
- ease of installation, thanks to their lightness, and ease of adaptation;
- ease of handling and storage;
- high environmental sustainability and no toxicity.

An interesting application of FRABs is also in combination with Phase Change Materials in energy retrofits of existing walls by using interior insulation systems [6].

By combining a PCM board with aerogel insulation, it is in fact possible to obtain an insulated double wall with minimum thickness (2-3 cm), capable of reducing energy loss and at the same time of supporting heating systems, minimizing air temperature fluctuations and reducing overheating during summer. A solution with comparable performance using traditional materials would determine an increase in wall thickness of up to 30 cm.

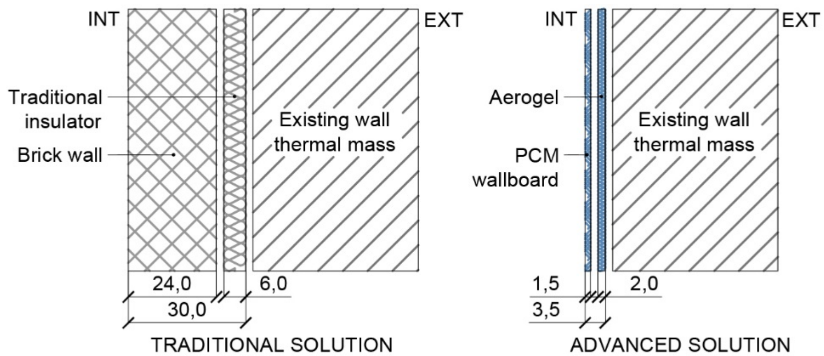


FIGURE. 2. Combined use of PCM and Aerogel [6]

5. CONCLUSIONS

In this paper, an evaluation of the application of nano insulating products in the building envelope is discussed and compared to traditional insulation materials. The analysis shows that their use in buildings is an effective solution to improve the hygro-thermal performance of the envelope, allowing to reconcile the objectives of energy consumption reduction with the need to preserve their integrity, authenticity and architecture quality.

The combined use of FRABs and phase change materials on opaque components (perimeter walls, ground floors, roofs) allows to improve both thermal insulation, in order to reduce energy loss during winter, and thermal inertia, in order to minimize air temperature fluctuations and to reduce overheating during summer.

In view of these advantages, FRABs cost per square meter is however still high, about 8-10 times higher than traditional insulation.

The cost is a primary barrier to greater application. There is also a lack of knowledge about innovative applications, and detailed design guidelines are limited. Greater effort is needed to highlight applications that are viable in market terms, such as locations in buildings with space limitations that will usually require a combination of high thermal performance insulation with lower material cost.

The main development scopes are on the one hand the simplification of the most cumbersome and expensive processes in its manufacturing - in order to make industrial preparation much cheaper and thus make aerogels more competitive – and on the other hand the substitution of the fibre reinforced blanket with other substrates (such as a melamine one) to avoid dust dispersion in both manufacturing and application phases.

An interesting future development regards the production of environmentally friendly insulating materials by combining bio-based materials with nanotechnology using a low-tech high-tech approach. In this frame, particularly interesting is the method recently patented by a team of researchers from the National University of Singapore (NUS) faculty of engineering, which is able to convert in a "simple, cheap and quick way" waste paper in cellulose aerogel, using 70% less energy than traditional sol-gel processes. The final result is a biodegradable material which is non-toxic, ultralight, flexible, extremely resistant and waterproof.

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