Evaluation of innovative thermal insulation systems for a sustainable envelope

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Highlights

Dynamic building envelope is primarily responsible for the improvement of energy saving. Strategies for improving the performance of the housing. Experimentation of innovative solutions that involve vacuum type systems such as VIG. Thermal insulation solutions that use renewable materials from the reuse and recycling of waste materials from agricultural production. The waste material of the Opunthia Ficus Indica (prickly pear) pruning from widespread and luxuriant plantations in Sicily has been transformed into a system of insulation panels and granules (Patent n. 1402131). Thermal bridges control.

Abstract

The paper presents the results of the research on thermal insulation systems for the building casing. We present the results of computer simulations that have enabled us to verify and optimize the transmission of heat through several innovative insulation systems, such as vacuum solutions for transparent façades, or the possibilities offered by the recycling of waste material of Opunthia Ficus Indica (prickly pear) pruning, which, properly treated, allowed to obtain an insulating material (Patent n. 1402131), in the form of panels or bulk grains (thermal coefficient values 0.07-0.057 W/mK).

Keywords

Thermal insulation, Waste materials, Insulation panel, Vacuum systems VIG

1. BUILDING ENVELOPE: A DYNAMIC SYSTEM FOR ENERGY SAVING

Living beings regulate their body’s well-being through the skin that defines the personal space. Even the buildings behave in the same way through the casing. The building envelope is indeed the most responsible of heat loss, and therefore the resulting energy savings obtainable.

The new energy-saving targets are moving towards architectural design systems and innovative technologies to optimize energy consumption in the building sector, one of the most expensive fields from energy point of view. The main stage, and perhaps also the most difficult to achieve, does not so much from scratch design of low consumption buildings (even zero energy in the case of the recent regulations required) but especially the implementation of innovative technologies to adapt the existing buildings by improving their
energy performance. In this sense moves an important architectural sector, which studies the thermal and acoustic insulation systems. Especially post-war Italy was affected by a strong expansion, especially in the residential sector. The construction of housing, providing timing and methods exclusively suited to meeting the growing demand, ignoring the architectural quality of the buildings themselves, leading to results without any care to environmental protection and reducing energy consumption. According to these criteria, it has been realized most of the buildings built until today, responsible for high-energy consumption and the harmful emissions into the atmosphere, both in the production phase and in the end use. It is therefore a clear need to adapt to the new demands of current regulations for the construction of new buildings and to act on existing buildings, taking into account the further effort imposed by the need to adapt the space available and the previous construction techniques to strategies energy improvement. One of the main problems is represented building casing, complex dynamic system and in charge of the key relationships between internal and external areas. Eliminate obsolescence to increase the energy performance means to minimize the energy losses from the casing made possible by optimizing the insulation ability of its opaque and transparent components, in order to reduce the need for heating and cooling of the inner rooms and to increase the occupant comfort. In particular, from the seventies to today different researches about it, with huge progress we have been made on the possibility of improving the thermal insulation in buildings through innovative materials and techniques for housing insulation itself. The use of insulating materials, from the thermal and hygrothermal aspect, allows the reduction of the heat transfer in each of the technical elements increasing their thermal inertia and reducing the thermal bridges. Current lines of research in this area mainly concern three issues:
• The application of innovative materials with high thermal insulation values and reduced thickness;
• Environmental Protection by the use of recycled or renewable materials;
• The thermal bridges control.
In every situations, the ultimate common goal, not easy to solve, is to work on reducing CO$_2$ emissions.

2. VACUUM INNOVATIVE INSULATED SYSTEMS

In this direction, we have been made significant progress in the field of innovative technology VIP (Vacuum Insulation Panel) that achieves very low
values of thermal conductivity with reduced thickness.
This latter aspect is even more appreciable in the energy retrofit of constructions, where the request for an adjustment to higher levels of energy efficiency requires an addition of insulating material layers with reduced thickness. Particularly, the VIP (Figure 1) [1] consist of an open cell structure, made with different kinds of materials, for the realization of an evacuated chamber and an envelope to maintain the very low internal pressure ($10^{-5} - 10^{-3}$ mBar) [2].

![Figure 1. VIP Panel with silica core and aluminium outer laminate.](image)

The same methodology has been applied to transparent envelope systems that, starting from the glassware technology, has led to the design and manufacture of vacuum glasses through the possibility of replacing the gas contained in the gap with the vacuum, that eliminates the heat transfer between the glass plates for gaseous conduction and convection, making it more effective than any gas. (Figure 2).

Some manufacturers have already implemented this system, which, however, shows some limitations on visibility through and cost currently too high for spreading (Figure 3).

The thermal benefit does not depend on the thickness of the cavity that determines it, allowing it to leave a few tenths of millimetres of space between one slab and the other.

| GLASS TYPE       | Simple glass (6mm) | Double glazing with air (6-16-6 mm) | Double glazing with argo (6-16-6mm) | Double glazing krypton (6-16-6 mm) | VIG (0.00133 Pa) (3-0.2-3) |
|------------------|--------------------|-------------------------------------|-------------------------------------|-------------------------------------|--------------------------|
| U (W/m²K)       | 5.7                | 2.8                                 | 2.5                                 | 2.2                                 | 1.1                      |

![Figure 2. Comparison of the transmittances obtainable with different types of glass.](image)
The system can be made up of different solutions that include two or three glass plates (hardened, tempered, laminated with or without low-e glass treatment) sealed to the edges with glass, metal or other organic-inorganic polymer based materials.

The air inside the cavity is extracted through a hole on one of the outer plates, subsequently sealed. The vacuum generated (10 Pa) tends to bring together the slabs but the separation is maintained by an array of micro spacers generally made of ceramic materials or metals such as stainless steel.

These spacers have a diameter between 0.25 and 0.50 mm with a height varying between 0.10 and 0.20 mm and placed at a distance of 20 - 25 mm [3].

This is currently a limitation for the vision through, also they require the integration of different aspects such as the choice of sealing material so that it is tight but does not reach melting temperatures too high, to avoid damaging the low emissive treatment of the inside of the glass plate. To get a good seal it must have loss rates less than or equal to 10-12 mbar l/s [4].

3. RECYCLING FOR INSULATION

For several years, there have been, on the housing market, insulation systems that combine satisfactory thermal transmittance values with the ability to help the environment protect and to contain costs. In this sense, we have been developed insulation systems formed by highly renewable materials, such as wood and its derivatives, or which use waste from other industrial processes. The novelty of the proposed solution is represented by the type of used material which until now has had no application in the construction sector and
has instead a great potential for both the ease of retrieval which constitutes a source of renewable raw material, both for the great availability on the Sicilian country, both for the good thermo-acoustic performance that are reached.

Particularly a new panel was produced by using the cladodes of Opuntia Ficus-Indica [5], a widespread plant in Sicily (Figure 4), according to the principles of sustainable and eco-friendly development.

Particularly, cladodes of this plant were properly dried, shredded, sorted and mixed with a glue to make a rigid panel.

The prototypes realized (figure 5) have shown thermal performance that can be considered satisfying and competitive with those of other commercially available panels [6] [7].

In fact, values of thermal conductivity equal to 0.071 W/mK and 0.057 W/mK were experimentally measured for the rigid panel and bulk materials, respectively.

From this study, the new eco-friendly panel realized from cladodes of Opuntia ficus-indica could be used in several building application as insulating layer.

We report in detail some information on research development.

3.1 MATERIALS AND MANUFACTURING

The prickly pear or Opuntia ficus-indica is a plant, member of the Cactaceae family [9], originated from the American continent and reached the Mediterranean countries during the 16th century.

Opuntia ficus-indica is commonly used also in traditional medicine both for its hypoglycaemic actions and for its healing activity as cicatrizant [10].

Like other countries of the Mediterranean area, in Italy the cultivation of the materiale sigillante in modo tale che sia ermetico ma non raggiunga temperature di fusione troppo alte per evitare di danneggiare il trattamento basso emissivo della parte interna della lastra di vetro. Per ottenere una buona tenuta è necessario avere tassi di perdita minori o pari di 10-12 mbar l/s [4].

3. IL RICICLO PER L’ISOLAMENTO

Già da alcuni anni sono apparsi, sul mercato edilizio, sistemi di isolamento che contengono sostitutenti valori di trasmissività termica con la possibilità di contribuire alla salvaguardia dell’ambiente ed al contenimento dei costi.

In questo senso sono stati sviluppati sistemi di isolamento costituiti con materiali altamente rinnovabili, come il legno ed i suoi derivati, o che utilizzano gli scarti provenienti da altre lavorazioni industriali.

La novità della soluzione proposta è rappresentata dalla tipologia del materiale usato che fino ad oggi non ha avuto applicazione nel settore edilizio ed ha invece grandi potenzialità sia per la facilità di reperimento che costituisce una fonte di materia prima rinnovabile, sia per la grande disponibilità sul territorio siciliano, sia per le buone prestazioni termo-acustiche che si sono raggiunte.

In particolare, questo nuovo soluzione utilizza, secondo i principi dello sviluppo sostenibile, i cladodi di Opuntia ficus-indica (Pale di Fico d’India) [5], una pianta molto diffusa in Sicilia (Figure 4), che è stata adeguatamente essiccati, triturati, e mescolati con un collante, per realizzare un pannello rigido.

I prototipi realizzati (Figura 5) hanno dimostrato prestazioni termiche che possono essere considerate soddisfacenti e competitive rispetto a quelle degli altri pannelli disponibili in commercio [6] [7].

Infatti, i valori di conducibilità termica pari a 0,071 W/mK e 0,057 W/mK [8] sono stati misurati rispettivamente per...
plant is fairly widespread, particularly in the regions of the southern country (i.e. Sicily, Calabria, Puglia and Sardinia). According to the latest grant, the cultivation area of Sicily is today equal to 2,500 hectares, i.e. the 90% of the cultivation area of Italian Opuntia ficus-indica.

In spring or late summer of every year pruning is done both to prevent contact between cladodes and to eliminate those sick or damaged. Therefore, it produces a large amount of waste material. One of the advantages proposed is precisely to reuse the scrap material to achieve an environmentally friendly insulating material.

The registered patent describes the different operations that were carried out to transform the waste pruning of the insulating material in the form of granules and rigid panel [11].

This eco-friendly panel (Figure 5) could represent a useful product in most applications of building field (i.e. roofs, floors, interior and exterior walls), to improve the thermal insulation of the structures.

It has been manufactured with a production technology similar to those commonly used for panels commercially available and thus could be industrially produced at competitive costs.

The thermal conductivity of the samples was measured according to ISO standards by using a heat flow meter mod (Figure 6).

**3.2 THERMAL PERFORMANCE**

The Opuntia ficus-indica panel has shown an average value of thermal conductivity equal 0.071 W/mK.

This result has been compared with the conductivity data of rigid panel actually used in several fields as thermal insulators. As shown in Figure 8, the thermal conductivity of the new eco-friendly panel, is comparable to that of the fibre mineralized wood panel, whose performances result significantly improved...
thanks both to use optimized industrial techniques and most suitable binders. On the other hand, our Opunthia Ficus Indica panel shows lower insulation properties than the other commercially panels considered. In spite of that, our panel can be considered less expensive in terms of energy consumption (during the production phase) compared to these commercial panels. For instance, the porous wood fibre panel shows lower conductivity (0.038 W/mK) but his technology production is more expensive (energy consumption = 17.00 MJ/kg).

To evaluate the influence of the glue on the insulation properties, it was also measured the thermal conductivity of a reference panel, realized with only Opuntia ficus-indica granules without glue as binder, with thickness equal to 21 mm.

As expected, the presence of glue lead to decrease the insulating properties: the reference panel (without resin) has shown an average thermal conductivity equal to 0.057 W/mK [12].

Regarding the bulk materials commonly used as insulators, the thermal conductivity of the Opuntia Ficus Indica granules are comparable to that of vermiculite, less than those of expanded clay, pumice, granulated foam glass and cellulose granules [13] [14]. (Figure 7).

Moreover, the reference panel is less insulating but also less expensive because it is constituted by a waste material, renewable, and widespread in several country of the Mediterranean area.

Definitely, we have demonstrated how starting from an eco-friendly and widespread material as cladode of Opuntia ficus-indica, it was possible to produce a panel which could represent a product useful (Figure 8) to improve the thermal insulation of the building envelope.
4. THERMAL BRIDGES CONTROL

A fundamental criterion that guides contemporary design requires the elimination of all thermal bridges in order to ensure an optimal level of energy performance and making minimum heat loss.

Figure 7. Comparison of thermal conductivity of bulk granules with commercial ones.

Figure 8. Comparison of thermal conductivity of panels with commercial ones.
As stipulated by the regulations (UNI EN ISO 10211: 2008) you can determine the thermal bridges according to the finite element calculation. In particular, in order to analyse the thermal performance of the building envelope and its components, you can use the software finite element THERM 7.1, which allows you to study and analyse the performance of two-dimensional heat fluxes within components building.

The program operates in line with the assessment procedure developed by the NFRC (National Fenestration Rating Council) and in accordance with ISO 15099. The heat flow through the building envelope is never one-dimensional type, in fact the presence of elements such as windows, pillars, foundations and all border line elements, determining the deviation of the flow lines, highlighting the thermal bridges.

The UNI EN 10211 defines the thermal bridge as "part of the building envelope where the thermal resistance elsewhere uniform, significantly changes due to: total or partial interpenetration of materials with different thermal conductivity into the building envelope, the thickness variation of the construction or differences between the area of the dispersing surface on the inner side and that of the outer side, as happens for example at the joints between wall and floor and wall and ceiling.

In correspondence of these areas, there are an increase of heat flux, associated with a distortion of the flux lines and to a modification of the temperature distributions.

The simulations were carried out by fixing an outside boundary condition of 0° C and an indoor of 21° C.

In figure 9 you can observed, from the heat flow, the indoor insulation provides an important obstacle to the spread of the cold stream, causing internally perceived temperature to the touch is on 15 °C along the frame and between 19 and 21° C along the wall, effectively reducing the presence of thermal bridges.

The priority objective in the design phase, that is to reach in each node examined an optimal level of energy performance, can be achieved through different and successive simulations that can gradually improve the thermal insulation characteristics of the components, eliminating or reducing to the maximum the heat dispersion - thermal bridges - and thus guaranteeing a considerable reduction in costs for the heating systems. In a study case, the insertion between the insulation panels proposed, of a panel of only 15 mm gypsum fibre has interrupted, for example, the cold heat flow, ensuring a high internal temperature, and thereby obtaining an optimal level of internal comfort.
The adoption of such solutions, from a thermal point of view and thermo-hygrometric, allows to reduce the heat flows of the individual technical elements increasing the thermal inertia.

5. CONCLUSIONS

The presented paper should provide some insights a way to intervene to improve the building’s envelope insulation conditions.

What we have shown is not an exhaustive value but thanks to a set of studies that we have developed in different conditions we would like to demonstrate how innovation in recent years, in various fields, can allow an effective action to obtain the energy sustainability in building.

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