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Experimental and numerical investigation of thermal bridging effects of jointed Vacuum Insulation Panels

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ABSTRACT

Vacuum Insulation Panels (VIPs) are characterised by very low thermal conductivity, compared to traditional insulating materials. For this reason, they represent a promising solution to improve the thermal behaviour of buildings, especially in the case of energy retrofitting (where a higher performance and less thickness is desirable). VIPs are insulating components in which a core material is surrounded by an air tight envelope which allows a high degree of internal vacuum to be maintained. Such features, on the one hand, allow excellent thermal insulation properties to be achieved, but, on the other, require the manufacturing of prefabricated panels of fixed shape/size. This means that the use of these super insulating materials in the building envelope involves the problem of joining the panels to each other and of fixing them onto additional supporting elements.

As a result, purposely studied supporting structures or systems are required. However, these structures and systems cause thermal bridging effects. The overall energy performance of the resulting insulation package can therefore be affected to a great extent by these additional elements, and can become significantly lower than that of the VIP panel alone.

In order to verify the incidence of thermal bridges on the overall energy performance of an insulation system that makes use of VIP panels, an experimental campaign has been carried out using a heat flux metre apparatus and analysing different joint materials/typologies. First, a measurement method was proposed, tested and verified on the basis of data from the available literature. A series of measurements on different samples was then performed. The experimental results were then used to calibrate and verify a numerical model that allows the performance of various "VIP packages" to be predicted and the performance of the overall package to be optimised.

1. Introduction

Vacuum Insulation Panels (VIPs) represent a promising solution to reduce heat losses through a building envelope and to improve building energy efficiency. The thermal conductivity of these panels is in fact 5 to 10 times lower than that of traditional insulating materials. However, their widespread application is still hindered by their high costs, the uncertainty about their durability and the lack of experience on how to assemble the panels. Moreover, the actual performance of the system in real building applications, considering the effects of the joints between VIPs themselves and the fixing devices (laths and battens), has not yet been fully established (in this paper the term "assembly" will be used to identify the set of: VIP panels, fixing structure and joints).

In the last few years, a great number of researches have been conducted in relation to VIP technologies. Several studies have been related to the optimisation of the panel properties. Some of them have focused on the analyses and development of the core material [1,2] and of the envelope configuration [3–5]. Vacuum degradation due to gas and water vapour permeation, the risk of damage (VIP perforation) and the impact of environmental conditions have also been studied frequently [1,6,7]. Panels with different core materials and envelopes consisting of a multilayer barrier with metalized surfaces allow thermal conductivities of about $\lambda_{cop} = 0.003–0.005\,W/(m\,K)$ to be achieved in the centre of the panel (depending on the core material and void degree) [2].

Examples of VIP applications for the energy refurbishment of buildings and for new constructions have been reported in [8,9]. Some studies have focused on the real performances of VIPs [3], while others have concentrated on VIP assemblies [5,10,11] and thermal bridging effects [12].

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Nomenclature

λ_{cop}	centre of panel thermal conductivity (W/(m K))
λ_{eq}	equivalent thermal conductivity of a VIP assembly considering thermal bridging effects (W/(m K))
$\lambda_{eq\ practical}$	suggested values of the equivalent thermal conductivity of a VIP assembly considering thermal bridging effects (W/(m K))
$\lambda_{Air\ joint}$	thermal conductivity of a VIP assembly air joint (W/(m K))
$\lambda_{Still\ air\ VIP}$	thermal conductivity of air caught between a VIP assembly air joint (W/(m K))
$\lambda_{Still\ air\ joint}$	thermal conductivity of a VIP assembly air joint (W/(m K))
$\lambda\perp$	thermal conductivity of the equivalent layer (perpendicular heat flux) (W/(m K))
$\lambda_{//}$	thermal conductivity of the equivalent layer (parallel heat flux) (W/(m K))
ψ	linear thermal transmittance (W/(m K))
ψ_y	linear thermal transmittance along y axis (W/(m K))
ψ'_y	half of the linear thermal transmittance (W/(m K))
$\psi_{Air\ joint}$	linear thermal transmittance (air joint) (W/(m K))
ψ_{Joint}	linear thermal transmittance (structural joint) (W/(m K))
ψ_{EXP}	linear thermal transmittance—measured value (W/(m K))
ψ_{NUM}	linear thermal transmittance—calculated value (W/(m K))
$L^{2D(x,z)}$	2D coupling coefficient (W/(m K))
U	thermal transmittance (W/(m^2 K))
l	length (m)
A	surface area (m^2)
$\dot{Q}$	heat flux (W)
φ	specific heat flux (W/m^2)
ϑ_o	outdoor temperature (°C)
ϑ_i	indoor temperature (°C)
$\vartheta_{sur,o}$	surface temperature—outdoor side (°C)
$\vartheta_{sur,i}$	surface temperature—indoor side (°C)
R	thermal resistance ((m^2 K)/W)
P	semi-perimeter of the/a panel (m)
P/A	form factor (m^{-1})
s	panel or assembly thickness (m)
d	air joint width (m)

The issue of thermal bridges in technologies that make use of VIPs is very important. Thermal bridging effects can be generated from three different sources:

"a" the VIP envelope alone (two panels laid in perfect, ideal contact with each other) [13];
"b" the air gap between two adjacent envelopes (two mounted VIP panels lying one beside the other) [12];
"c" the presence of structural joints, made of various materials (wood, polystyrene, aerogel, . . .), used to couple two adjoining VIP panels (this configuration can be considered as a thermal bridge at the scale of the building envelope component) [12,14].

Thermal bridges due to the VIP envelope – case "a" – have been analytically and numerically investigated in [15], considering the four parameters that mainly influence their linear thermal transmittance, that is: laminate thickness, laminate thermal conductivity, core material thermal conductivity and panel thickness. Other researchers have proposed various solutions to reduce the thermal bridging effects for cases "b" and "c" [16–18].

Case "c" is the typology which has the most influence on the overall thermal properties of a VIP assembly, especially as far as the vertical building envelope components are concerned. For such configurations, the installation of VIP panels necessarily requires a mounting and support system. This can be achieved (analysing the solutions available in literature) with laths and battens of different materials (such as MDF and XPS) [9], with metal and plastic rail systems [9,19], or with plaster and adhesives [9]. A new fastening method has been analysed in [20]. With this solution, VIPs have to be prefabricated with two holes (insulated or not) where dowels are later inserted to anchor the panels to the building structure. Instead, for horizontal building surfaces, VIP panels are usually laid down without any additional structural support. In this case, only air joints are of interest (case "b") [3]. In general, for mechanical protection, VIP panels need to be surrounded by two (additional) protective layers, which can also act as finishing surfaces. Such layers can play a role in enhancing or lowering thermal bridges, as highlighted in [13,21,22]. The effect of thermal bridging on VIP panels in real building applications has been one of the main topics of recent research activities. Sprengard and Holm [23] have investigated the effects on the overall assembly performances of: additional cover layers, VIP panel sizes and air gaps between panels (with different widths and filler materials), by means of numerical simulations. However, these studies have not covered all the possible joint configurations (e.g. thinner air gaps and structural joints between panels) and, besides, have been based on purely numerical methods.

In this frame, a research has been conducted with the aim of obtaining more detailed knowledge on the overall thermal behaviour of VIP assemblies (through the concept of "equivalent thermal conductivity", λ_{eq}) and of assessing the linear thermal transmittance, ψ, of thermal bridges. In order to achieve such goals, a method for measuring the ψ parameter has been conceived, tested and verified through a comparison with literature data. After the validation, the measurement procedure was applied to experimentally analyse the dependence of the thermal bridge effects on:

- the geometry of the air joint between two adjacent panels (e.g. size of the air gap), case "b";
- the type of structural joints (e.g. adoption of different materials), case "c";
- the panel size/shape (for both air and structural joints).

Finally, the experimental results were used to verify a numerical model. This model, once it had been verified, was used to carry out sensitivity analyses in which the geometry of the joints and their configurations were varied.

2. Analysis methods

In the first phase of the research, an experimental method was proposed and tested to quantify the linear thermal transmittance of the thermal bridge between the VIP panels. This procedure was then applied to analyse the equivalent thermal conductivity of typical VIP assemblies, considering the influence of joints (either structural or air joints). Various materials, whose thermal properties influence the effects of thermal bridges, as well as several geometrical configurations, were tested. This sensitivity analysis included variations of the VIP size and shape, the thermal conductivity of the joint materials and the coupling methods (air joints or structural joints).

In a second stage of the activity, the experimental results were used to verify a numerical model that was then applied to perform sensitivity analysis by changing the joint configurations.