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Experimental investigation and numerical evaluation of adoption of multi- layered wall with vacuum insulation panel for typical Mediterranean climate

Fabrizio Ascione [a], Rosa Francesca De Masi [b,*], Rita Mariantonia Mastrullo [c], Silvia Ruggiero [d], Giuseppe Peter Vanoli [d,e]

[a] University of Naples Federico II, DII – Department of Industrial Engineering, Piazzale Tecchio, 80, 80125 Napoli, Italy
[b] University of Sannio, DING – Department of Engineering, Piazza Roma, 21, 82100 Benevento, Italy
[c] University of Naples Federico II, Department of Industrial Engineering, P.le Tecchio 80, 80125 Naples, Italy
[d] University of Sannio, DING – Department of Engineering, Piazza Roma, 21, 82100 Benevento, Italy
[e] University of Molise, Department of Medicine and Health Sciences -Vincenzo Tiberio, Via Francesco De Sanctis, 1, 86100 Campobasso, Italy

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ABSTRACT

This study is focused on the evaluation of the effectiveness of vacuum insulation panel (VIP) for typical Mediterranean climate. The interest for this material is due to indisputable advantages in term of insulation performance both for new and refurbished buildings; mainly in retrofit design, adoption of lower thickness assure same results with less invasive interventions. The problem is the behavior during the summer period, not investigated in the available scientific literature.

Numerical and experimental approaches are used in this paper to compare the performance of several wall packages integrating VIP with constructive technologies that result in different stationary and dynamic parameters. More in detail the results of a yearly measurement campaign in three real building of south Italy are presented; recorded data of the surface and the mean air temperatures as well as of the heat flux are commented. Data for one typical week of each season are evaluated to compare the wall made of concrete block and vacuum insulation material with a massive structure and also with a concrete wall with expanded polystyrene as insulation material. Furthermore, simulation results (by means of EnergyPlus) are presented to study, mainly during the summer, the effect of integration of vacuum insulation panel in multi-layered wall made of concrete blocks with different values of density and thermal conductivity; moreover these configurations are compared with a wall made of innovative insulated interlocking brick and with the wall types considered in the experimental phase. Using a typical office building as case study, energy consumptions and environmental and economic indexes are valuated.

Experimental and numerical results show the effectiveness of solution with VIPs also for Mediterranean climate.

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1. Insulation and thermal inertia: multi-layered wall in Mediterranean climate

Opaque walls are expected to provide thermo-hygrometric and acoustic comfort within an edifice, optimizing energy efficiency without compromising the aesthetic of the building. These aspects are generally fulfilled by means of different materials.

Considering the requirements in matter of building insulation and the importance of dynamic behavior, mainly in Mediterranean climate, the thermal conductivity (λ) and the volumetric heat capacity (ρc – product between density "ρ" and specific heat "c") can be considered the most important factors that affect the selection of materials for building walls. The volumetric heat capacity determines the thermal inertia of the opaque envelope defined by Ferrari [1] as the heat storage capacity of building structure and its attitude to delay the heat transmission. Thermal inertia affects the way in which a building reacts to changes in external and internal conditions reducing therefore the thermal load [2], mainly during the summer period; this allows to higher temperatures in the indoor environment, when the outdoor air temperature is much lower and consequently more stable indoor thermal conditions will be provided [3].

Besides, the thermal diffusivity should be evaluated. This parameter characterizes the kinetics of conduction heat transfer

* Corresponding author.
E-mail addresses: fabrizio.ascione@unina.it (F. Ascione), rfdemasi@unisannio.it (R.F. De Masi), ritamariaantonia.mastrullo@unina.it (R.M. Mastrullo), sruggiero@unisannio.it (S. Ruggiero), giuseppe.vanoli@unimol.it (G.P. Vanoli).

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Nomenclature

A_f	Floor area [m^2]
c	Specific heat [J/kg K]
CE	Exercise cost [€/year]
$CO_{2,eq}$	Equivalent carbon dioxide emission [$tCO_{2,eq}$]
Δt_f	Time-shift of decrement factor [h]
$DT_{VIP,i-o}$	Temperature difference between VIP on inside and outside ambient [°C]
DT_{in-VIP}	Temperature difference between inner layer and external face of VIP [°C]
DT_{in-out}	Temperature difference between inside and outside wall layers [°C]
EP	Primary energy demand [kWh/m^2]
$_{exp}f$	Experimental attenuation factor [-]
f	Decrement factor [-]
h_{si}	Internal conductance [W/(m^2 K)]
h_{se}	External conductance [W/(m^2 K)]
k	Areal heat capacity [kJ/m^2 K]
λ	Thermal conductivity [W/m K]
M_s	Superficial mass [kg/m^2]
PMV	Predicted mean vote [-]
PPD	Predicted Percentage of Dissatisfied [%]
ρ	Density [kg/m^3]
s	Thickness [m]
T_a	Mean air temperature [°C]
T_{int}	Value of inside mean air temperature [°C]
T_{min}	Minimum value for mean air temperature [°C]
T_{max}	Maximum value for mean air temperature [°C]
Ts_in	Inside surface temperature [°C]
Ts_in_VIP	Temperature of vacuum insulation panel on inner side [°C]
Ts_out	Outside surface temperature [°C]
Ts_out_VIP	Temperature of vacuum insulation panel on outer side [°C]
T_{out}	Value of outside mean air temperature [°C]
U	Stationary thermal transmittance [W/(m^2 K)]
U_{slab}	Thermal transmittance of the slab on the ground [W/(m^2 K)]
WFA	Percentage of window to floor area [%]
Y_{IE}	Periodic thermal transmittance [W/m^2 K]

phenomenon. It is directly proportional to thermal conductivity and inversely proportional to the volumetric heat capacity. A low value of thermal diffusivity indicates that the heat is mostly accumulated in the material, and thus attenuation and phase shift are high.

Fig. 1 shows these thermo-physical properties for several building materials and products using the standard UNI 10351 [4] for choosing the reference values and UNI EN ISO 10456 [5] regarding the insulation materials.

It can be noted that materials with high volumetric heat capacity values, like standard concrete ($\rho c \approx 2000 \div 2400$ kJ/(m^3 K)) or natural rocks ($\rho c \approx 2100 \div 3174$ kJ/(m^3 K)), have also high thermal conductivity values ($\lambda \approx 0.85 \div 2.08$ W/(m K) – concrete – and $\lambda \approx 1.70 \div 4.10$ W/(m K)- rocks). The variations of concrete density and concrete thermal conductivity for multi-layered walls have been considered by Kontokeon et al. [6]. Moreover Chikhi et al. [7] have experimentally demonstrated the advantage, mainly for heating period, of replace the ordinary concrete with a polystyrene one.

Otherwise, wooden and insulation materials have thermal conductivity less than 0.06 W/(m K) and volumetric heat capacity that varies over a wide range (from 17 to 1620 kJ/(m^3 K)).

Several investigations have been done to introduce or verify the performances of new products Ibrahim et al. [8] have presented a new thermal insulating based on silica aerogels for which the optimal thickness is in the range of 1.7–4.4 cm depending on the climate.

The thermal characterization of a composite clay–wool has been done by Mounir et al. [9]. The composite clay–5% wool presents the best thermal characteristics in term of thermal conductivity (0.19 W/(mK)) and thermal diffusivity (3.01×10^{-7} m^2/s). In addition, they have shown that by increasing the wool volume fraction, the depth of heat flow diffusion decreases, while the delay of the maximum temperatures increases.

Recycled textile materials were studied by Hadded et al. [10]. Results show that the thermal conductivity and diffusivity of are 0.033 W/(m K) and 5.8 10^{-3} m^2/h for samples of waste linter; these are 0.039 W/(m K) and about 3.8 10^{-3} m^2/h for samples of table cloth.

PCMs also seem a suitable solution to improve thermal mass of materials or existing wall [11,12] and some testing activities have demonstrated that the PCM addition can determine also a reduction in the thermal conductivity of gypsum and Portland cement matrix [13].

Among materials with high potentialities in building sector, the vacuum insulation panels are an emerging solution, because they are thinner, lighter and more energy efficient than conventional insulation materials. A panel is made up of evacuated foil-encapsulated porous material. Due to vacuum, VIPs have thermal conductivity 5–10 times lower than conventional insulating materials, and thus around $0.004 \div 0.008$ W/(m K) [14]. The achievable insulating performance depends on the materials of which the main components of a VIP panel are made: the inner core, the barrier envelope and getters/desiccants. Fumed silica (SiOx) is a well-known core material. A pressed board made out of fumed silica, has a low conductivity (close to 0.003 W/mK at 50 mbar) and it has a conductivity of 0.020 W/mK at ambient pressure in dry conditions [15]. However, some papers analyze new core materials in order to decrease thermal conductivity, to develop lower cost or longer service life, or also, green panels [16,17]. Some authors have also studied the optimization of enveloping method and the material adopted for vapor barrier with the aim to reduce the permeation of gas and water vapor from environmental into the core and for decreasing the edge conduction of VIPs [18,19]. Due to high thermal resistance of vacuum panel, the thermal bridge, between jointed panels, has to be taken into account in order to determine real envelope performance. Indeed, Lorenzati et al. [20] have underlined that values provided by manufactures for considering thermal bridges, generally can lead errors. However, the use of cover layers made of insulating material helps to reduce the thermal bridging effect.

The main bottlenecks to the full development of VIPs are the high cost and the early aging, if compared to conventional materials. However, considering an average price of 80 £/m^2, Alam et al. [21] have demonstrated that in some installation, VIP payback period can be comparable or even lower than the expanded polystyrene payback periods, if also the economic value of space saving is taken into account. Due to their thin dimensions, VIPs are a good solution in the refurbishing of old buildings, since the space is often limited and interventions are constrained. Cho et al. [22] have carried out a Life Cycle Cost Analysis of three VIPs and one structural insulated panel for a time-period of 40 years. Regarding the lifetime, it depends by increment of thermal conductivity during the operation period. It can be considered the end of VIP useful lifetime as the time period in which at the middle of the panel the thermal conductivity reaches a certain value (usually 0.008 W/(m K)) [23]. There are some studies, above all in subarctic climates, that show no performance changes over a period of

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