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Effectiveness of VIPs and PCMs on the energy performance and thermal comfort in buildings

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Abstract— A strategy for improving the buildings energy efficiency is to diminish the energy demand for space heating and cooling. The European Directive has established a high standard of thermal insulation, involving stringent limits for building energy performance. However, such approach determines an increase of the cooling energy demand and noteworthy overheating of indoor spaces in the summer period.

This study investigates through dynamic thermal simulations the effectiveness of new thermal insulation materials, such as Vacuum Insulation Panels (VIPs) and Phase Change Materials (PCMs), on reducing heating and cooling energy demands, as well as guaranteeing the thermal comfort into a test room located in three different locations (Catania, Rome and Wien). The energy demand for space cooling and heating have been evaluated for the different facade configurations, as well as the attainable indoor thermal comfort.

The outcomes of the simulations in air-conditioned spaces highlight that the wall configurations that adopt VIPs allow reducing the heating energy needs but may increase the cooling energy needs. Remarkable differences are not detected for the heating and cooling energy demands when the PCMs are used. The daily fluctuation of the indoor operative temperature and the adaptive comfort model suggest that the PCM placed on the inner side of the walls shows a good thermal performance.

The outcomes of the study outline the strengths and weakness of the analyzed facade configurations, which may help designers in the search for suitable solutions.

Keywords—*Vacuum Insulation Panels (VIPs), Phase Change Materials (PCMs), dynamic simulations, indoor thermal comfort, energy needs*

I. INTRODUCTION

Many existing building envelopes rely on construction technologies which entail remarkable energy demands for heating and cooling [1]. In particular, buildings realized in the Sixties and Seventies suffer the influence of the outer forcing conditions during the hot season because their envelopes often have not adequate thermal inertia [2]. The goal of reducing the energy consumptions of the buildings has induced many developed countries to adopt standards to attain thermal performances of construction components lower than the prescribed minimum value. To this aim, researches in the building field have focused on improving the energy

performance of building components. In this sense, development and introduction of innovative materials play a key role in achieving the above-mentioned goal.

Some studies have proven that vacuum insulation panels (VIPs) are highly efficacious insulators for use in building construction [3, 4]. VIPs are recommended for building retrofitting because they can reduce the energy needs for heating by about 24% thanks to a reduction in the transmission losses through the walls by 23% [5, 6]. The adoption of VIPs has been widely investigated during the winter period but few studies are focused on the summer period [4]. In particular, there is a lack of studies for VIP application in massive or mixed brick-concrete structures in the Mediterranean climate [5].

PCMs have a noteworthy potential to reduce energy consumptions of buildings because they allow storing and release thermal energy as latent heat [7]. Kuznik F. and Virgone J. investigated the thermal behavior of PCMs positioned on the inner wall for different expositions during a typical summer day [8]. The results reveal that without PCM, the air temperature ranged between a minimum of 18.9°C and a maximum of 35.3°C. Afterwards the installation of PCM wallboards, air temperature ranged between 19.8°C and 32.7°C. It was found that the maximum indoor air temperature value is reduced by about 2.6 °C whereas the minimum air temperature is increased by about 0.8 °C.

Dynamic simulations performed on an office building realized by honeycomb PCM wallboards placed on the inner surface highlighted a reduction on the peak of the operative temperature of 1°C in the summer period [9].

This paper aims to investigate the effectiveness of advanced materials such as VIPs and PCMs, added on the external or internal sides of building facades, for a test room located in three different climate conditions by means a dynamic simulation analysis. The effectiveness of the use of VIPs and PCMs on the building energy performance and indoor thermal comfort is discussed.

II. METHODOLOGY

In this research, a calibrated and validated model of a real test room located in Milan [10] was used as a case study.

For the baseline configuration, the walls of the test room are made up with traditional double brick walls. The

alternative scenarios foresee the application of VIP and PCM on the outer side (Os) or the inner side (Is) of the walls of the test room.

Thus, four alternative wall configurations (i^{th}): VIP(Is), VIP(Os), PCM(Is), PCM(Os) are investigated.

Dynamic simulations are executed by means the DesignBuilder software [11] using the Conduction Transfer Function (CTF) method. As regards the PCMs scenarios, the finite difference method was adopted [12, 13]. Twelve-time steps per hour are adopted for the dynamic energy balance equations. The space heating and cooling of the test room are provided by a natural gas boiler and a vapour compressor refrigerator. During the heating season the set-point temperature is of 20°C, whereas a set-point of 26°C is for the cooling season. The indoor thermal comfort is assessed through the adaptive model as defined by the ISO EN Standard 15251 [14].

The climate of three European cities, Catania (Lat. 37.47), Rome (Lat. 41.80) and Wien (Lat. 48.20) are taken into account to evaluate the influence of the site on the indoor thermal comfort and the energy demand.

A. Energy savings

The energy-saving ($ES_{H,C}$), deriving by the use of the thermal insulation material is calculated by equation 1:

$$(ES_{H,C})_{i,k} = (PE_{H,C})_{BS,k} - (PE_{H,C})_{i,k} \quad (1)$$

The index (i) and (k) are referred respectively to the insulation material and city. $(PE_H)_{i,k}$ and $(PE_C)_{i,k}$ are the heating and cooling energy demands for the different scenarios, $(PE_H)_{BS,k}$ and $(PE_C)_{BS,k}$ are the energy demand for the baseline scenario.

To compare the different scenarios, the energy savings $(ES_{H,C})_{i,k}$ are normalized respect to the max values of the baseline scenario $(PE_{H,C})_{BS,max}$ [15]:

$$(ES_H)_{i,k} = [(PE_H)_{BS,k} - (PE_H)_{i,k}] / (PE_H)_{BS,max} \quad (2)$$

$$(ES_C)_{i,k} = [(PE_C)_{BS,k} - (PE_C)_{i,k}] / (PE_C)_{BS,max} \quad (3)$$

$(PE_H)_{BS,max}$ and $(PE_C)_{BS,max}$ are the maximum energy demand for heating and cooling.

B. Indoor operative temperature

The operative temperature (T_{op}) was calculated by:

$$T_{op} = \gamma T_{mr} + (1 - \gamma) T_o \quad (4)$$

where:

T_{mr} = mean radiant temperature for the thermal zone

γ = the radiant fraction, whose typical value is 0.5

T_o = the outside dry bulb temperature

C. Adaptive thermal comfort

The adaptive thermal comfort criteria relies on the calculation of the running mean outdoor air temperature (T_{rm}) that is defined as the weighted running average of the prior seven daily mean outdoor air temperatures:

$$T_{rm}(d) = (1 - \alpha) \sum_{j=1} T_{o(d-j)} \alpha^{(j-1)} \quad (5)$$

where j is the number of prior days, d is the present-day and α is a constant equal to 0.8 as advised by Nicol and Humphreys [16]. T_{rm} indicates the adaptation of residents to

external conditions and the acceptability of internal conditions.

Three different categories of comfort are defined, from I to III. Category I relates to the highest level of expectation (90% satisfactoriness); Category II relates to a medium level of expectation (80% satisfactoriness), Category III relates to a moderate level of expectation (65% satisfactoriness). The higher and lower limits of temperature (T_{under} and T_{over}) for each category are formulated by means equations 6 and 7:

$$T_{under,cat,pqr} = 0.33 T_{rm} + 18.8 - p,q,r \quad (6)$$

$$T_{over,cat,pqr} = 0.33 T_{rm} + 18.8 + p,q,r \quad (7)$$

where the limit values for each comfort categories p, q and r are reported in Table I.

TABLE I. THRESHOLD VALUES AND DEFINITION OF CATEGORY I, II AND III.

Index	Category	Limit	Definition
p	I	2.0	Highest level of satisfaction, recommended for spaces occupied by very weak and frail persons
q	II	3.0	Medium level of satisfaction used for new buildings and refurbishment
r	III	4.0	Moderate level of satisfaction, used for existing buildings

As the threshold of the comfort categories strictly depends on the external temperature, the interval of comfort for each category varies following the daily temperature variation.

The values of the indoor operative temperature identify the category of comfort attainable or lower of the ranges of temperature above explained.

Thus, it is possible to calculate the percentage of time during which a Category of comfort is accomplished (e.g. Category I) for a short time basis or for seasonal perspective.

Such analysis are used in this study for comparing the different solutions of thermal insulation investigated under free-running conditions.

III. OFFICE TEST ROOM

The office test room is oriented toward the cardinal points, has a gross surface of 5.00 x 5.00 m and an internal height of 3.00 m. There are no obstructions or shields over the test room (see Fig. 1).



Fig. 1. 3D Model view of the test room.

The façade facing south has a window of 3.00 x 1.35 m, that is the 30.0% of the facade. The main geometric features of this test room are reported in Table II.

TABLE II. GEOMETRIC FUTURE OF THE TEST ROOM.

Heated gross volume	V	75	m ³
Total external surface	S	110	m ²
Shape factor	S/V	1.46	m ⁻¹
Opaque transparent ratio	S _w /S _o	0.04	-
Net floor area	S _u	19.40	m ²

The internal loads generated by occupants, computers and lighting systems give a total of 396.0 W, which corresponds to power density of 20.4 W/m². The air change rate is fixed to 0.5 vol/h. The test room has a heating system represented by a natural gas boiler with an efficiency ($\eta=0.85$), and a chiller for cooling purposes with a coefficient of performance (COP=2.50) to keep the indoor air temperature equal to 20°C in winter and 26°C in summer.

A. Building envelope

In the baseline scenario, the building envelope has opaque vertical closures made by double brick with a thickness (s) of 30 cm, the finished layer is plaster. The wall has an internal air gap with thermal resistance (R) of 0.18 m²K/W. The outer plaster has solar absorbance ($\alpha=0.60$) and thermal emissivity ($\epsilon=0.90$). The wall surface mass (SM) is of 160 kg/m² and the internal thermal capacity (C) is of 65.58 kJ/m²K.

A traditional slab of concrete and brick with a thickness of 20 cm characterizes the flat roof and the floor.

The window has an aluminium frame without a thermal break ($U_{\text{frame}} = 5.9 \text{ W/m}^2\text{K}$) and a conventional double-glazing (separated by an air gap of 12 mm) ($U_{\text{glass}} = 2.78 \text{ W/m}^2\text{K}$) and a solar gain factor $g=0.70$. The values of thermal transmittance (U) and the surface mass (SM) of the building components are reported in Table III.

TABLE III. U-VALUES AND SM OF THE BUILDING COMPONENTS.

Building components	U (W/m ² K)	SM (kg/m ²)
Wall	1.02	160
Roof	1.84	332
Ground floor	1.24	1060
Window	3.25	-

B. Climate features

The dynamic simulations on the test room are conducted for the five proposed wall scenarios in the three investigated cities. The weather files available on Energy Plus were adopted.

All climate localities are classified as temperate climates (Cf) according to International Köppen classification. Wien is characterized by humid summers (Cfb) whereas Rome and Catania (Csa) have relatively dry summers.

IV. INVESTIGATED SCENARIO

VIPs or PCMs are added either on the external or the internal sides of the walls of the office test room. The various scenarios and wall configurations, which emerge with VIPs and PCMs placed on the inner surface (Is) or on the outer surface (Os) are synthetized in Table IV.

The used Vacuum Insulation Panel (VIP) is made up of open porous core of fumed silica shrouded by metallized polymer laminate [6, 17, 18]. Fumed silica is composed by silicon carbide (SiC), fibres are added into the pores for increasing its structural stability [16]. The thermal conductivity for the VIP panel is $\lambda=0.007 \text{ W/m}\cdot\text{K}$, density $\rho=160 \text{ kg/m}^3$ and specific heat $c_p=800 \text{ J/kg}\cdot\text{K}$.

The PCMs developed by CSTB (Centre Scientifique and Technique du Batiment) were used in this study. They are made by an aluminium honeycomb matrix that contains 60% of micro-encapsulated paraffin with a diameter of approximately 6 mm (Micronal T23 produced by BAFS) [19, 20]. Two thin aluminium covers contain the PCM panel whose depth is 2.0 cm. The thermophysical properties of the PCM are $\rho=545 \text{ kg/m}^3$; $\lambda=2.7 \text{ W/m}\cdot\text{K}$; the melting temperature is supposed being 30°C.

V. RESULTS

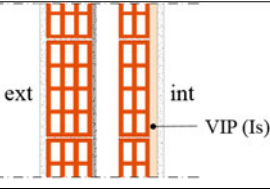
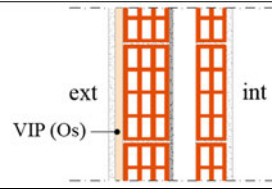
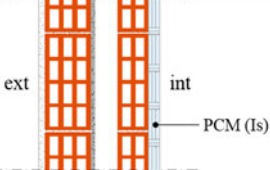
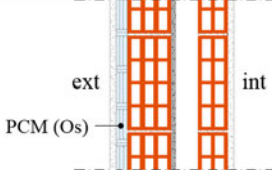
A. Energy performance

The heating demands are calculated considering that the heating system is switched on from December 1 to March the 31 in Catania, from November 1 to April 15 in Rome and from October 1 to April 30 in Wien. For calculating the cooling demands the period (June 1st - September 30th) is adopted for all the investigated localities.

Heating and cooling energy demands, as well as the energy savings, calculated for the baseline configuration (BS) and the other wall configurations, are displayed in Fig. 2a and 2b.

The obtained outcomes highlight that both the VIPs scenarios remarkably reduce the energy demand for space heating (PE_H) in all the investigated cities. The highest energy saving is obtained in Wien, about 38.0%, whereas in Catania an energy saving of 10.0% is attained. In particular, the scenario VIP (Is) allows achieving an ES_H higher than the scenario VIP (Os) of about 4-9%.

TABLE IV. THERMAL TRANSMITTANCE (U), SURFACE MASS (SM), AND HEAT CAPACITY (C) VALUES OF WALL SCENARIOS: VIPs AND PCMs ON THE INNER (IS) AND OUTER SURFACE (OS).

VIP (Is)		VIP (Os)	
	$U = 0.26 \text{ W/m}^2\text{K}$ $SM = 163 \text{ kg/m}^2$ $C = 59.05 \text{ kJ/m}^2\text{K}$ $s_{VIP} = 2 \text{ cm}$		$U = 0.26 \text{ W/m}^2\text{K}$ $SM = 163 \text{ kg/m}^2$ $C = 65.98 \text{ kJ/m}^2\text{K}$ $s_{VIP} = 2 \text{ cm}$
PCM (Is)		PCM (Os)	
	$U = 1.00 \text{ W/m}^2\text{K}$ $SM = 171 \text{ kg/m}^2$ $C = 69.98 \text{ kJ/m}^2\text{K}$ $s_{PCM} = 2 \text{ cm}$		$U = 1.00 \text{ W/m}^2\text{K}$ $SM = 171 \text{ kg/m}^2$ $C = 65.98 \text{ kJ/m}^2\text{K}$ $s_{PCM} = 2 \text{ cm}$

Conversely, both VIPs scenarios entail an increase of the cooling energy needs in all the three cities, The cooling energy needs are the highest in Wien (+13%) and the lowest in Catania (+8%).

The worst-case occurs when VIPs are applied on the inner surface “VIP(Is)” with an increase of cooling demands of about 4% in all the investigated localities.

These outcomes confirm that envelope, highly insulated, hinders the cooling of the building during the night, determining the overheating in hot summer days.

The PCMs scenarios cause negligible variations on the heating and cooling energy needs. PCM (Is) scenario shows a negligible reduction of cooling demand and a slight increase in heating energy demand.

The prior results are caused by the set-point of the indoor temperature, being 20°C for the heating period and 26°C for the cooling period. These temperatures are below the melting temperature of the PCMs which remain in solid-phase almost for the whole day.

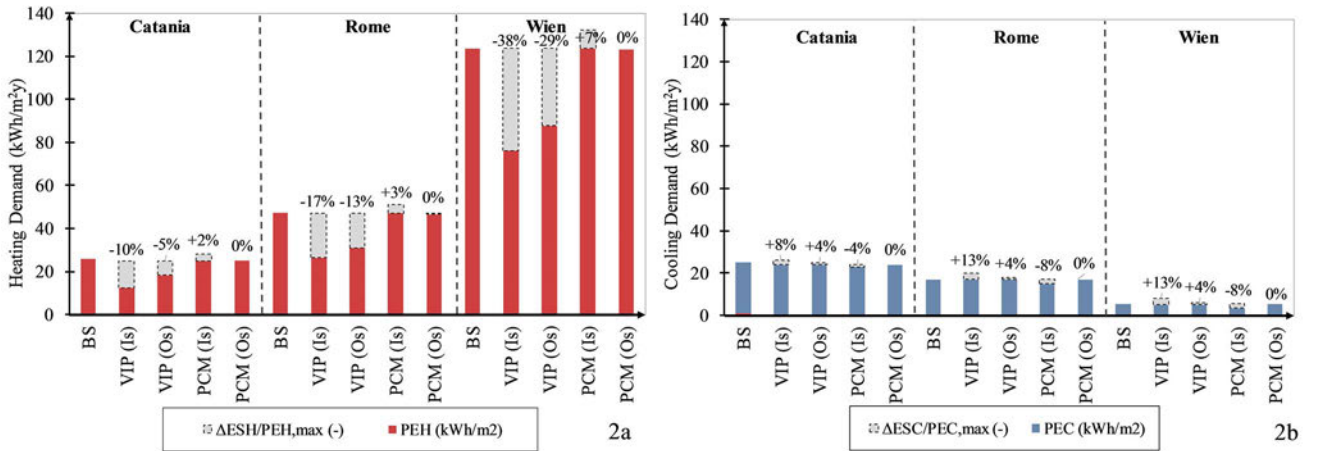


Fig. 2. Energy needs and energy savings: a) Heating; b) Cooling.

B. Assessment of indoor thermal comfort

The adaptive comfort model is adopted for assessing the indoor thermal for the different investigated scenario. To this aim the hourly variations of the operative temperature (T_{op}), under free-running condition, are calculated from 22 to 25 July for three investigated localities.

Figure 3 depicts the hourly variation of T_{op} . In the same figure the range of the comfort temperatures for the categories I, II and III are indicated.

The hourly path-line of T_{op} is quite similar for the three localities, while substantial are the differences among the

different scenarios. For the BS scenario, the operative temperature (T_{op}) ranges from a minimum of 25.0°C to a maximum of 31.1°C in Catania, from 23.6°C to 30.3°C in Rome and from 20.0°C to 27.9°C in Wien.

For the VIP(Is) scenario, the peak values of T_{op} are slightly higher than the baseline scenario whereas the minimum value of T_{op} is the lowest of all the analysed cases. As an example, in Wien the highest value of T_{op} increases of about 1.5°C in comparison to the baseline scenario. These outcomes can be explained considering that VIPs behave as a barrier to the heat flux transferred from inside to outside, so causing remarkable overheating even in a cold climate.

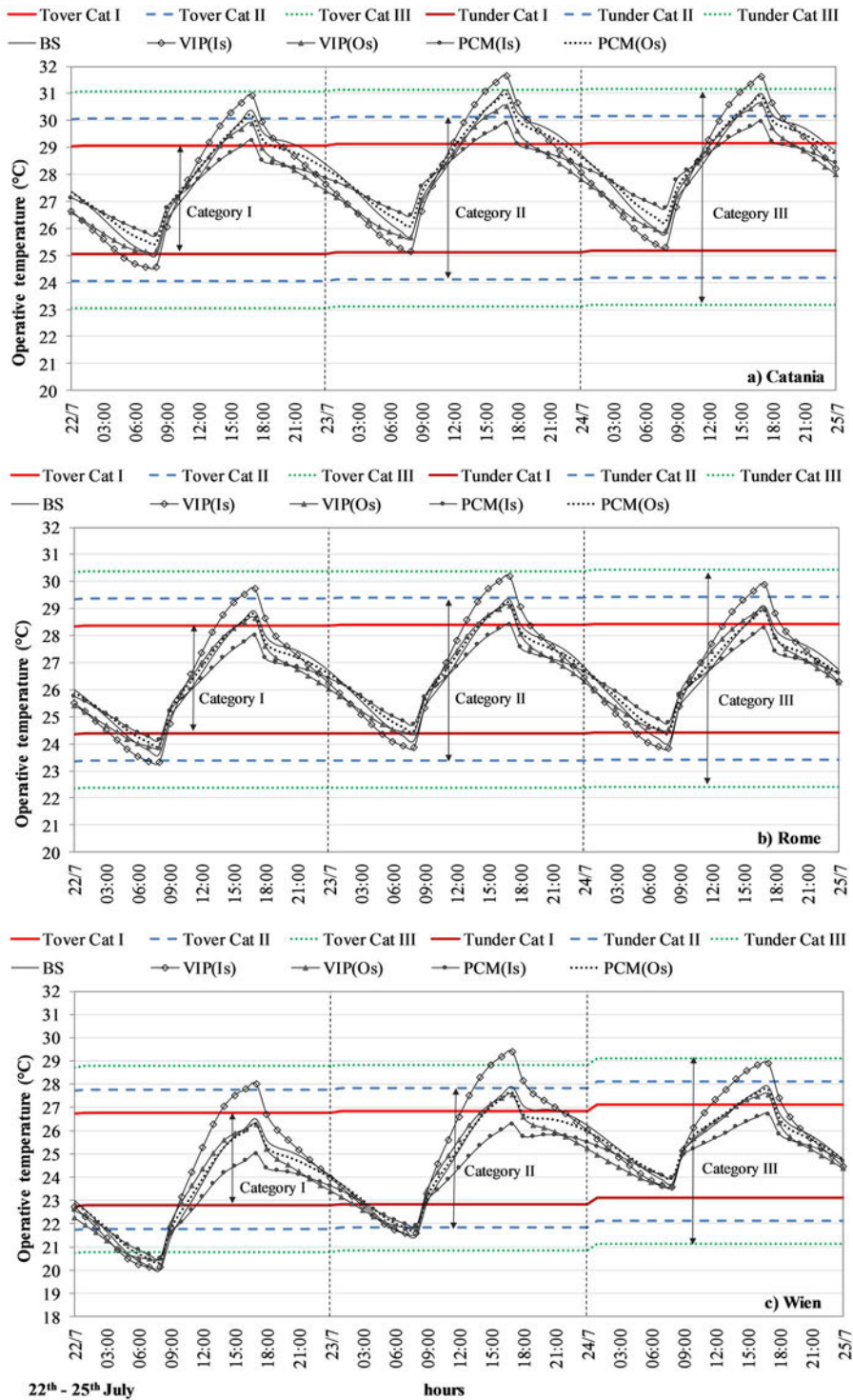


Fig. 3. Trend of operative temperature of the five scenario and thresholds values (T_{under} , T_{over}) for category I, II and III: a) Catania; b) Rome; c) Wien.

For the VIP(Os) scenario the trend of T_{op} is almost the same as of the baseline scenario. The minimum values of T_{op} grow-up in comparison to the baseline scenario for the three investigated cities.

The most effective configuration is that with the PCMs layer placed on the inner side. Indeed, for this scenario the peak values of T_{op} are the lowest compared to the other scenarios. The maximum of the operative temperature decreases of 1.2°C. Since the minimum of T_{op} increases, the

fluctuation amplitude of the indoor temperature diminishes by about 1.0°C.

The PCM(Os) configuration does not provide a noteworthy variation on the maximum and minimum value of T_{op} compared to the baseline scenario.

Table V synthesizes the percentages of the analyzed period (July, 22-25) in which the investigated scenarios allow attaining comfort conditions in the categories I, II and III respectively.

TABLE V. PERCENTAGE OF TIME DURING 22nd -25th JULY IN WHICH THE INVESTIGATED SCENARIOS ARE IN COMFORT CATEGORIES I, II AND III.

Cities	Catania					Rome					Wien				
	BS	VIP (Is)	VIP (Os)	PCM (Is)	PCM (Os)	BS	VIP (Is)	VIP (Os)	PCM (Is)	PCM (Os)	BS	VIP (Is)	VIP (Os)	PCM (Is)	PCM (Os)
Category I	60%	60%	75%	84%	66%	64%	55%	70%	76%	67%	62%	55%	72%	75%	69%
Category II	28%	21%	16%	16%	23%	24%	25%	20%	19%	22%	20%	23%	22%	17%	19%
Category III	11%	13%	9%	-	11%	9%	15%	8%	5%	8%	15%	16%	3%	6%	9%
Out Category III	1%	6%	-	-	-	3%	5%	2%	-	3%	3%	6%	3%	2%	3%

For the PCM(Is) scenario, the category I of adaptive comfort, is achieved for most of the time in Catania (84%), Rome (76%) and Wien (72%) respectively.

For PCM(Os) scenario, the hourly trend of the operative temperature overcomes the thresholds values of Category I for a percentage higher than 30%. Appreciable outcomes are also attained in the VIP(Os) scenario whose operative temperature lies in Category I for a percentage never below 70% in the three localities. On the contrary, the VIP(Is) scenario offers the worst indoor thermal comfort conditions. The hourly values of operative temperature do not fit the requisites of the category I for a percentage of time above 40.0%. Besides, the trend of indoor temperature overcomes Category III for a time percentage of 6%.

VI. CONCLUSION

This paper investigated the effectiveness of Vacuum Insulation Panels (VIPs) and Phase Change Materials (PCMs), in reducing heating and cooling energy demands, as well as ensuring thermal comfort of occupants for the different facade configurations in Catania, Rome and Wien.

This study shows that there is an optimum location for PCM and VIP on building envelope surfaces depending upon the resistance values between the PCM or VIP layer and the exterior boundary conditions.

In air conditioning environments, VIPs are very useful to reduce the heating energy demand in cold climates by about 38% (Wien) and much less in warm climates where, instead, lead to an increase of cooling energy demand by +13% (Catania). PCMs do not provide appreciable advantages for heating and cooling energy demands considering the setpoint temperatures maintained by HVAC systems.

In free-running conditions, the adaptive comfort model suggests that the PCM(Is) scenario has the highest percentage of time in which the operative temperature is in Category I.

For all foregoing considerations and outcomes, PCMs panels could be a good energy retrofit solution because they should reduce appreciably the phenomenon of summer overheating in free-running conditions if they are placed on the inner surface of the walls.

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