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Trombe walls for lightweight buildings in temperate and hot climates. Exploring the use of phase-change materials for performances improvement.

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Abstract

This paper is summarizing the results of a research carried out for assessing thermal performances of Trombe walls integrated in lightweight constructions. Phase-change materials, substituting heavy thermal storage mass, have been used in order to improve the energy performance of the system.
For evaluating the device sensibility to external environmental conditions, five Australian cities (representative of five different climatic zones) have been considered. Furthermore, variations of PCM position in the external envelope and of melting point temperatures have been taken in account in order to define the most suitable technology for each climatic area.

Keywords: Trombe wall; lightweight buildings; phase-change materials; thermal storage; indirect solar gains

1. Introduction

Architectural technology is more and more trying to solve problems connected with the replacement of old and energy expensive buildings with lightweight ones, thus producing a double environmental advantage: on one hand a significant cut of total energy consumptions and, on the other hand, the reduction of building embodied energy. However reduction of heat storage mass will significantly affect solar energy systems performances, especially where direct solar gains storage is required. Smart and

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innovative devices, using indirect solar gains, are required in order to get solar technologies more implementable in lightweight constructions.

Phase Change Materials (PCMs) have ever shown great potentialities if integrated with solar systems. Preliminary studies have been carried out in order to assess Trombe-Michel wall performances related to the integration of PCMs [1], through the definition of simulation algorithms. The results show important benefits, even though further dynamic analysis need to be carried on. As a matter of fact the real benefit of PCMs integration is not only dealing with the reduction of thermal storage mass weight, but mainly linked with the different behaviour of this smart material under dynamic solar radiation exposure.

Further researches [2] explored the potential benefits of integration of PCMs in external heavy envelopes with integrated solar walls, through the execution of in-site tests on mock-up cubicles. The results showed how, also in heavy constructions, benefits connected with implementation of PCMs could be significant and up to 17% of energy saving could be expected. Also recent in-site tests [3] are showing the benefits of PCMs integration in modified Trombe walls, useful for existing building energy retrofitting. All these experimentations show the importance of an accurate choice of material typology and position for different climates. Therefore the general aim of the here summarized research is to provide a comparative assessment of thermal comfort variability deriving from several PCMs integrated into the internal partition of a Trombe wall exposed to cold, mild and hot climates.

Nomenclature

k	thermal conductivity	(W/m K)
ρ	density	(kg/m^3)
C_p	specific heat capacity	(J/kg K)
α	thermal diffusivity	(m^2/s)
U	thermal transmittance of building component	(W/m^2 K)
ϕ	thermal flux	(W/m^2)
T	temperature	(°C)
T_C	PCM's main crystallization temperature	(°C)
σ	standard deviation of the population of temperature values	(°C)
s	layer's thickness	(m)
Δx	node spacing for thermal simulations	(m)
Δt	time step of thermal simulations	(s)

subscripts and superscripts

A, B	partition's inside (facing the air cavity) and outside (facing the test room) surface
1 ... 5	partition's layers (number increasing from inside to outside)
i, i+1	simulation and adjacent node
j, j+1	simulated and consecutive time step

2. Methods

A simple test room has been modelled and simulated with EnergyPlus^{TM}, a dynamic energy simulation software, in order to evaluate its behaviour under different climatic conditions. Five cities have been chosen as significant in order to take into account several Australian climatic areas in which the use of Trombe Wall could be beneficial during winter. For each city, the typical design winter week has been considered. The chosen cities are:

- Hobart (TAS, typical week 15/5-21/5) and Melbourne (VIC, typical week 6/7-12/7) representing the cold and mild climatic areas (respectively climate zones 7 and 6 of BCA [4]);
- Sydney (NSW, typical week 16/8-23/8) and Brisbane (QLD, typical week 22/6-28/6) representing the mild-hot and subtropical climate (respectively zones 5 and 2 of BCA [4]);
- Alice Springs (NT, typical week 12/7-18/7) representing the hot dry climate (zone 3 of BCA [4]).

In Fig. 1 a schematic section of the modelled test room is shown. It is a 25 m^2 room (square plant of 5m x 5m), with two walls exposed to north and south. All the remaining surfaces are adiabatic, thus simulating the effects of a room placed in an inner position inside the building. South wall has been modelled as an insulated lightweight wall (own weight less than 100 kg/m^2), with a double-glazed window; the ratio between floor area and transparent surface is 8.

On north surface, directly exposed to solar radiation, a lightweight Trombe Wall has been implemented; it is composed by an external window (with a 6 mm single glazing unit) separated from the internal test partition by a 100 mm ventilated air gap. The air gap is connected with both outdoor and indoor through operable vents. An external blind is used to shade the north transparent facade during summer in order to avoid overheating in the air cavity.

The simulated test partition is a lightweight wall finished with superficial plasterboard panels, with a core composed by a mineralized wood layer. As detailed in Table 1 and in Table 2, 25 different test partitions have been modelled, integrating PCMs either in layer 2 or in layer 4.

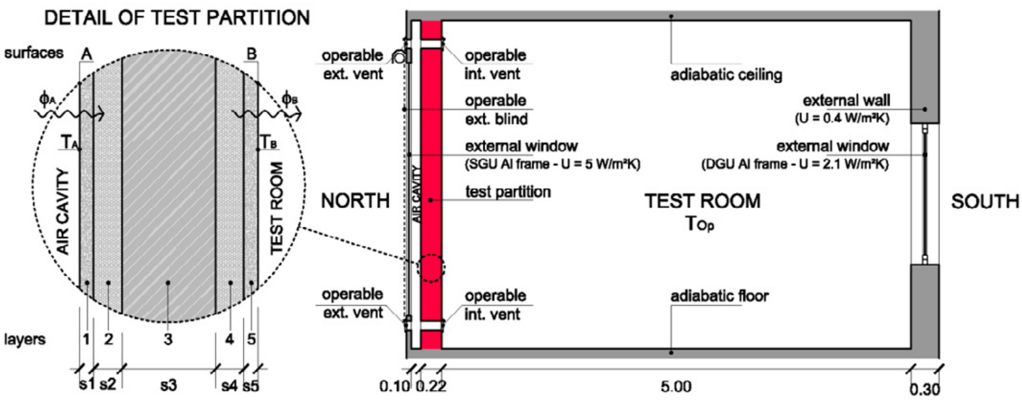

Fig. 1. Test room section and details of test partition. ϕ_A is considered positive if absorbed, while ϕ_B is considered positive if released by the partition.

4 different PCMs produced by Rubitherm® and based on n-paraffin and waxes have been used. They could be stored in aluminium modules, and a total combined thickness between 30 and 90 mm has been modelled. The effects of different melting areas (18-23 °C for RT 21, 25-28 °C for RT 27, 27-31 °C for RT 31 and 38-43°C for RT 42) have been simulated. In the following paragraphs each PCM is described

through its crystallization temperature (T_C), corresponding to the highest enthalpy peak obtained during the cooling process (21°C for RT21, 27°C for RT27, 29°C for RT31 and 42°C for RT42). In order to minimize the effects of the changing of thermal capacity and of thermal transmittance during the non-transition phase, the thermal parameters of the core layer (k, ρ and C_p) have been chosen similar to the PCM's ones and a total thickness of 220 mm have been considered for all the 25 partitions.

Table 1. Test Partitions: details of layers (1 to 5) and related thicknesses s

Partition ID	Plasterboard panel	PCM (RT 21, RT27, RT31, RT42)	Mineralized wood panel	PCM (RT 21, RT27, RT31, RT42)	Plasterboard panel
	s_1	s_2	s_3	s_4	s_5
No PCM (base case)	0.015	/	0.190	/	0.015
A3 (21 – 27 – 31 – 42)	0.015	0.030	0.160	/	0.015
A6 (21 – 27 – 31 – 42)	0.015	0.060	0.130	/	0.015
A9 (21 – 27 – 31 – 42)	0.015	0.090	0.100	/	0.015
B3 (21 – 27 – 31 – 42)	0.015	/	0.160	0.030	0.015
B6 (21 – 27 – 31 – 42)	0.015	/	0.130	0.060	0.015
B9 (21 – 27 – 31 – 42)	0.015	/	0.100	0.090	0.015

Table 2. Test partitions: layers' thermal properties

material	layer	k	ρ	C_p	α
Plasterboard panel	1 – 5	0.25	900	1000	2.78×10^{-7}
Mineralized wood panel	3	0.20	880	2100	1.08×10^{-7}
PCM (RT 21, RT27, RT31, RT42)	2 – 4	0.20	880	T dependant	T dependant

The partition's superficial temperatures (T_A and T_B) and thermal fluxes (ϕ_A and ϕ_B), as well as the operative temperature in the test room (T_{Op}) have been monitored during each simulated period in order to assess the comfort parameters' variation consequent the adoption of different technologies.

3. Theory and calculation

EnergyPlus™ software has been used in order to predict the relevant parameters for the simulation of PCM integrated solutions. The reliability of the software for the purposes of the here presented work has been widely demonstrated, as different research groups validated the simulations results with in-site measurements [5], [6]. Furthermore specific validations have been carried out for PCMs' simulations in hot and tropical climates [7].

The conduction finite difference (CondFD) algorithm, incorporated in EnergyPlus™, has been used and a fully implicit first order specific scheme has been adopted. This scheme is based on Adams-Moulton solution approach and the main equation is the following [8]:

$$C_p \rho \Delta x \frac{T_i^{j+1} - T_i^j}{\Delta t} = k_W \frac{T_{i+1}^{j+1} - T_i^{j+1}}{\Delta x} + k_E \frac{T_{i-1}^{j+1} - T_i^{j+1}}{\Delta x} \quad (1)$$

The values of thermal conductivities k_W and k_E in *(1)* are calculated as follow:

$$k_W = \frac{k_{i+1}^{j+1} - k_i^{j+1}}{2} \quad (2)$$

$$k_E = \frac{k_{i-1}^{j+1} - k_i^{j+1}}{2} \quad (3)$$

Where, the thermal conductivities listed in *(2)* and *(3)* of each node modeled could be time dependants. The CondFd algorithm allows also to set a different simulation grid discretization as a function of the thermal diffusivity of the material (α) and of the time step (Δt), by providing a space discretization constant C (inverse of the Fourier number). Therefore, for each layer, the spacing Δx between the nodes is: $\Delta x = \sqrt{C\alpha\Delta t}$.

In this work, a time step Δt of 120 s and a space discretization constant C of 3 have been set up; therefore the spacing Δx is respectively 0.010 m for layers 1 and 5 and 0.006 m for layers 2, 3 and 4.

4. Results and discussion

4.1. PCM integration in cold and mild climates (Hobart and Melbourne)

During the typical winter week the average values of the outside dry-bulb air temperatures in Hobart and Melbourne are respectively 8.9 °C and 10.6 °C, with peak minimum temperatures of 2.5 °C and 5.9 °C. Direct solar heat gains are able to increase the average superficial temperature on face A of the test partition respectively to 18.0 °C and 24.6 °C (Fig. 2(a) and Fig. 3(a)).

Integration PCMs on partition's A surface is greatly affecting the distribution of superficial temperatures, also producing beneficial effects on the distribution of internal surface temperatures. The most beneficial PCM is the RT 27 both in Hobart and Melbourne: the main positive effect is a consistent reduction of superficial temperature's variability both on A and on B surfaces.

Integration of PCMs on partition's B surface is almost irrelevant for the distribution pattern of outside surface temperatures, while tends to reduce the fluctuations of indoor surface temperatures. The most effective benefit is obtained by the adoption of a material a melting point area matches with the average values of indoor air temperatures (RT21).

Fig. 4 and Fig. 5 show the distribution of thermal fluxes and superficial temperatures on both the two sides of the partition for the base case and for PCMs integrated on internal and external surfaces. A stabilization of thermal fluxes and of superficial temperatures is evident on both surfaces.

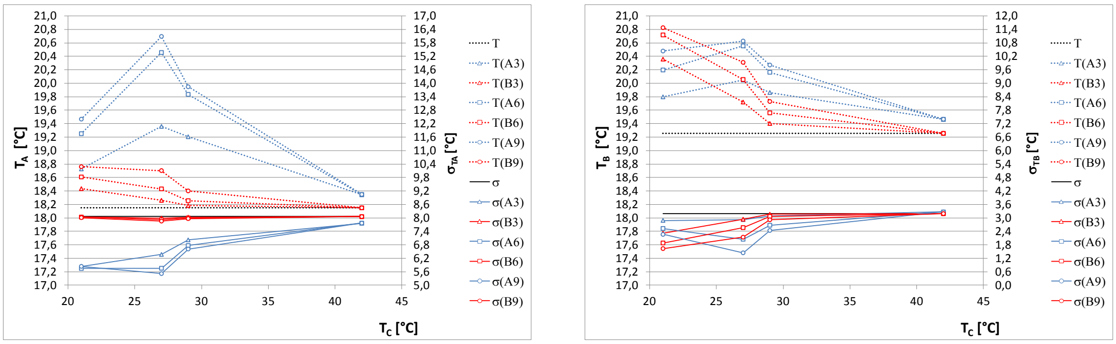

Fig. 2. Hobart: superficial temperature distribution (average and standard deviation) during the typical winter design week on: (a) A surface; (b) B surface

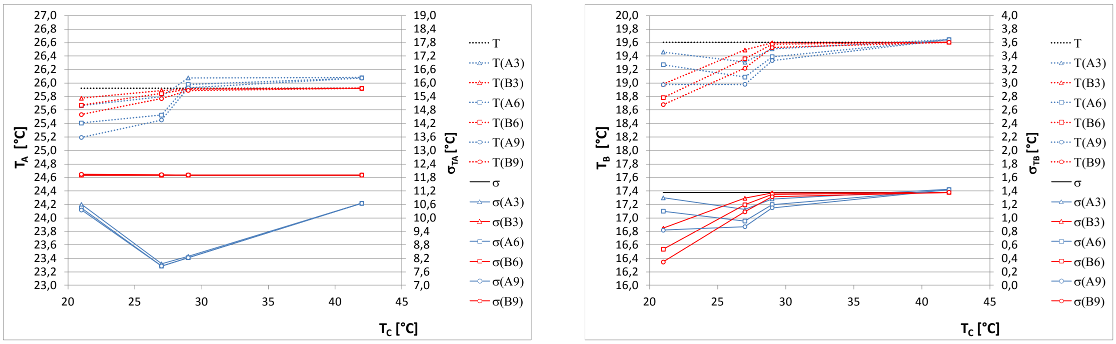

Fig. 3. Melbourne: superficial temperature distribution (average and standard deviation) during the typical winter design week on: (a) A surface; (b) B surface

The increase of thermal wave delay is another revealed benefit. Referring, for example, to the thermal fluxes distribution during July the 10th in Fig. 5, a shift of 5 hours of the peak of indoor thermal flux (moving from 2 am to 7 am) is noticeable. Similar results are evident also in the other climatic areas.

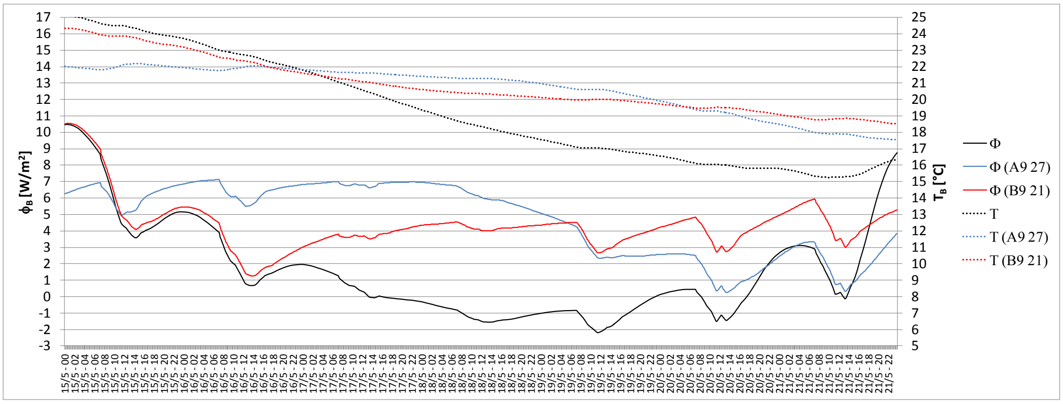

Fig. 4. Hobart: thermal fluxes and superficial temperatures (partition's B surface) during the typical winter design week

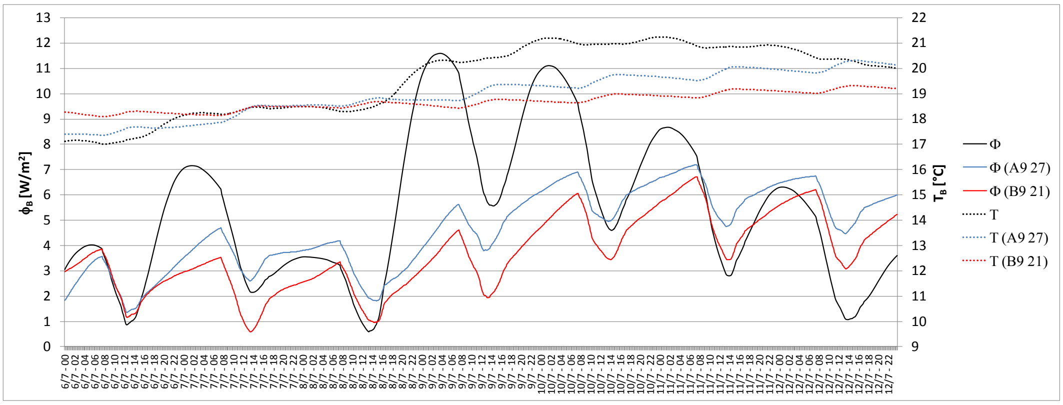

Fig. 5. Melbourne: thermal fluxes and superficial temperatures (partition's B surface) during the typical winter design week

4.2. PCM integration in mild-hot and subtropical climates (Sydney and Brisbane)

During the typical winter week the average values of outside dry-bulb temperature in Sydney and Brisbane are respectively 13.2 °C and 14.9 °C, with minimum temperatures of 6.1 °C and 8.2 °C, but the higher levels of solar irradiance produce an higher increase of the average superficial temperature (38 – 39 °C). The benefits (essentially regarding the reduction of superficial temperature variability) due to the adoption of PCMs on outside surfaces, in these climatic areas, are exponentially increasing with the increase of PCM's crystallization temperature (Fig. 6(a) and Fig. 7(a)), but remaining unchanged when the thickness is changing.

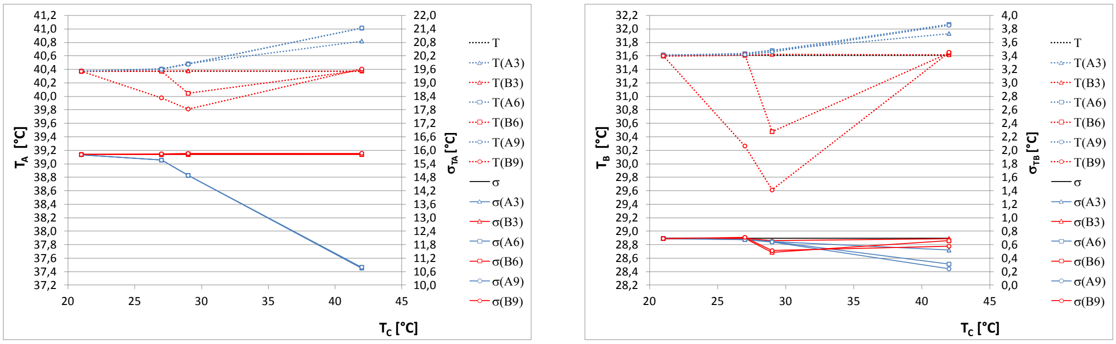

Fig. 6. Sydney: superficial temperature distribution (average and standard deviation) during the typical winter design week on: (a) A surface; (b) B surface

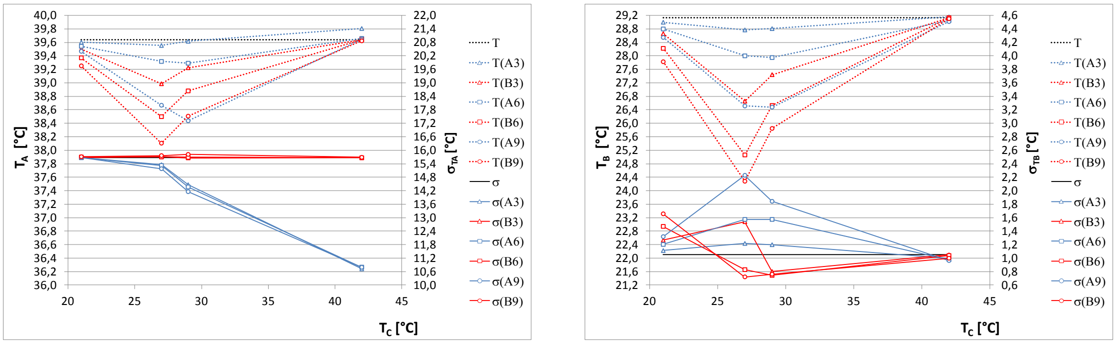

Fig. 7. Brisbane: superficial temperature distribution (average and standard deviation) during the typical winter design week on: (a) A surface; (b) B surface

The integration of PCMs in partition's B surface is affecting the distribution of internal surface temperatures. Choosing a product which melting point area includes the average value of superficial temperature (RT 31), a reduction of the average temperature of 2 °C and 3 °C respectively in Sydney and Brisbane is obtained. A decreasing of standard deviation of the population of superficial temperature values is another relevant benefit.

In the following Fig. 8 and Fig. 9 distributions of temperatures and thermal fluxes through B surface are shown. More regular distributions, obtained integrating PCMs either on A or on B surfaces, are able to prevent sudden changes of superficial temperatures (and thus of indoor operative temperature) due to weather fluctuations.

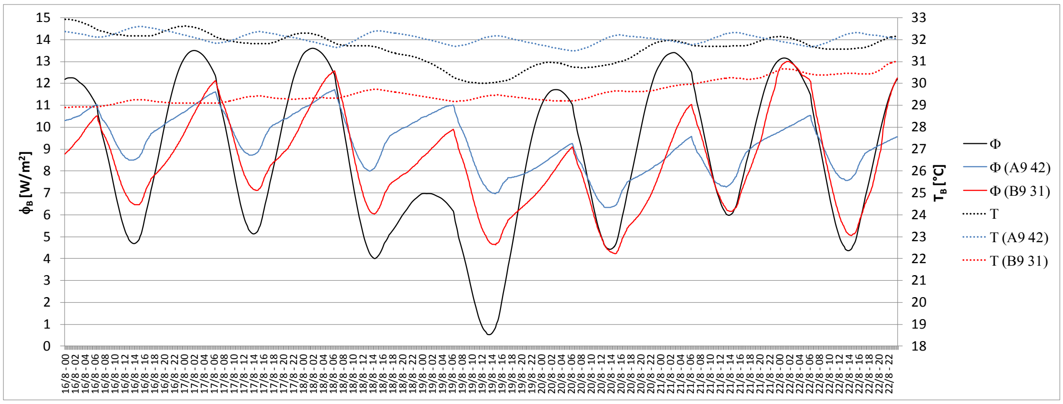

Fig. 8. Sydney: thermal fluxes and superficial temperatures (partition's B surface) during the typical winter design week

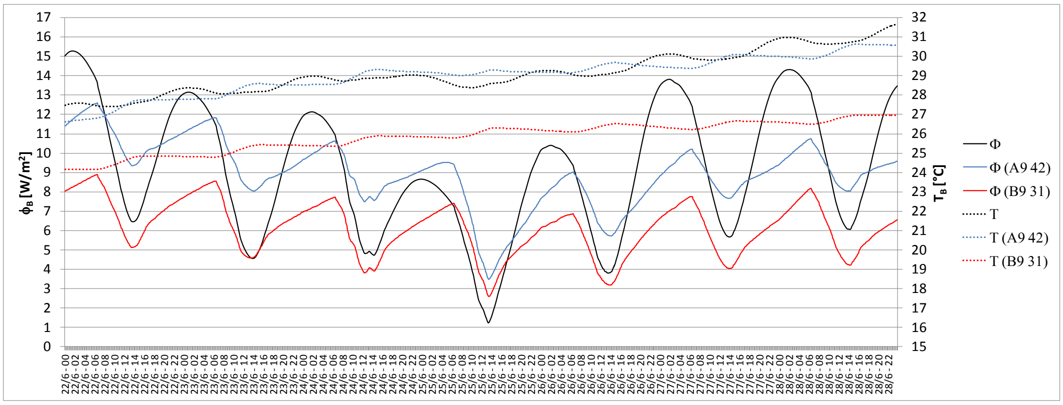

Fig. 9. Brisbane: thermal fluxes and superficial temperatures (partition's B surface) during the typical winter design week

4.3. PCM integration in hot arid climates (Alice Springs)

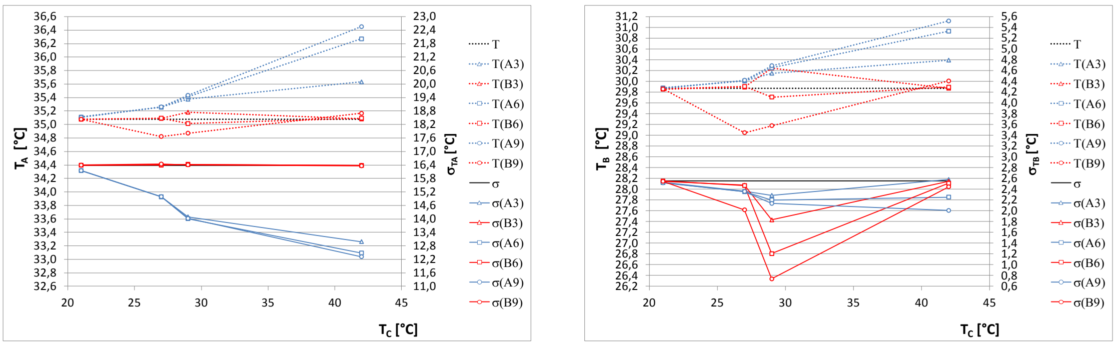

Fig. 10. Alice Springs: superficial temperature distribution (average and standard deviation) during the typical winter design week on: (a) A surface; (b) B surface

In hot arid climatic area, represented by the city of Alice Springs, great diurnal temperature fluctuations are expected during winter season. During the typical design week, high average values of dry-bulb outdoor air temperatures (14.0 °C), comparable with the ones registered in subtropical climates, are coupled with low values of minimal outdoor temperatures (4.2 °C), comparable with the ones registered in cold regions. In the base case (without the integration of PCMs in the partition), due to the effect of high levels of solar heat gains in the air cavity, the average value of superficial temperature of partition's A face exceeds 35 °C, while the corresponding value on B face is slightly below 30 °C.

The integration of PCMs in partition's A surface is greatly reducing the superficial temperature's fluctuation (the standard deviation of the population of temperature values is decreasing from about 16 °C to about 12 °C), while an increase of 1°C is obtained on the average value of A superficial temperatures. This effect is also evident on B surface, but mitigated in its intensity (especially for the reduction of standard deviation).

However, in this climatic area, the most beneficial PCM's position is on B surface. Even if the partition's outside superficial temperatures are not really affected by this integration (Fig. 10(a)), a decrease of 1°C of the inside average superficial temperature and a decrease of about 2°C of the standard deviation of the population of superficial temperature are obtained. As shown in Fig. 11, this beneficial effect is also noticeable by a levelling of T_B curve (dotted red line).

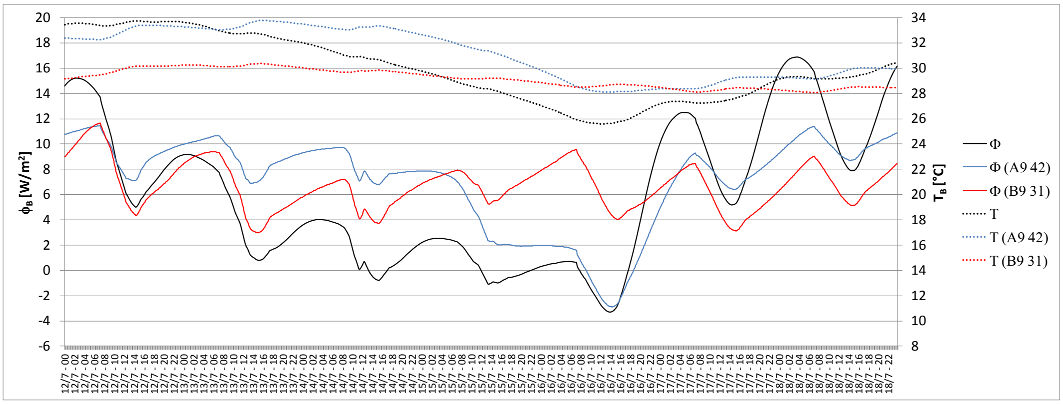

Fig. 11. Alice Springs: thermal fluxes and superficial temperatures (partition's B surface) during the typical winter design week

5. Conclusions

PCMs' integration in lightweight building components is highly beneficial and able to minimize the fluctuation of temperatures (both radiant and operative) due to the lack of thermal storage mass. These beneficial effects are even more evident if the thermal flux is forced by solar radiation, which is an extremely variable heat source. Previous studies demonstrated the benefits of PCMs integration in Trombe walls in different climatic areas, but an integrated parametrical assessment was needed, in order to evaluate the effects of material's properties and integration strategies in several climatic areas.

For this reason 5 different Australian cities, representative of 5 different climatic areas have been chosen.

The results of this study show that:

- In mild-cold and temperate climates, the integration of PCMs on the outside surface of the intermediate partition of a Trombe wall produces an optimal reduction of the fluctuation of inside temperatures, which remain steady on comfortable values. In this case the adoption of a phase change material with melting point area that includes the average value of outside superficial temperatures is showing the highest benefits.

- In mild-hot and subtropical climates the integration of PCMs in the inside surface of the intermediate partition of a Trombe Wall helps to reduce the superficial temperature's variability. Also in this case a matching between the melting area and the average values of superficial temperatures is highly beneficial.
- In hot and dry climates, with high diurnal temperature range, the integration of PCMs either on the outside or on the inside surface of the intermediate partition greatly reduces the variability of superficial temperatures. The adoption of PCMs on the inside surface tends also to reduce the superficial temperature, preventing overheating effects caused by high solar gains.
- The PCM's thickness variation is affecting both inside and outside temperature distribution. While on the inside surface both the average value and the standard deviation of the population of superficial temperature are affected by the increase of PCM's thickness, on outside surface only the average values of superficial temperature are influenced. Furthermore the adoption of the highest PCMs thickness shows the highest benefits, due to the increase of the global partition's thermal capacity.
- In all climatic areas, the adoption of PCMs contributes also to increase the dephasing between absorbed and released thermal fluxes by the partition, restoring thermal inertia to lightweight constructions.

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