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Dynamic Parameters to Characterize the Thermal Behaviour of a Layer Subject to Periodic Phase Changes

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Abstract

The paper addresses the issue of the dynamic characterization of a layer subject to phase change (PCM) with non-sinusoidal periodic boundary conditions, which are typical of the external walls of air-conditioned building.
The dynamic parameters used to characterize a monophase layer are not sufficient to describe how the temperature and heat flux trends in transfer through a layer subject to phase change are modified. Furthermore, a PCM due to the effect of latent heat associated with the phase change significantly modifies the heat storage capacity of the wall. The proposed parameters are determined by means of an explicit finite difference numerical model, considering PCM with different melting temperatures and thermophysical properties. The boundary conditions are such that one or more bi-phase interfaces originate in the layer. These parameters can be used for the thermal design of innovative walls in air-conditioned buildings with the aim of reducing power peaks entering the indoor environment, or to reduce thermal requirements, or to improve the thermal comfort within the building.

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Keywords: PCM; latent heat; external building wall; steady periodic regime; dynamic characterisation; multiple bi-phase interfaces

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1. Introduction

Phase change material (PCM) has been widely integrated in building envelopes with the aim of enhancing the thermal inertia of building components, improving both indoor thermal comfort and energy performance [1]. The presence of a layer of phase change material (PCM) in a wall of a building, due to the phenomena of storage and

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release of latent energy, change the dynamic thermal behaviour in both summer and winter air-conditioning. The external walls are subject to loadings, which are variable in time, mainly due to the solar irradiation, the air temperature and the apparent temperature of the sky. The variability of such loadings can be schematized by non-sinusoidal periodic fluctuations representative of the monthly average day, which give rise to a steady periodic regime in the wall. In such a regime, the variability of the boundary conditions compared to the PCM melting temperature can give rise, in the layer, to one or more bi-phase interfaces, or it is even possible that the entire layer does not undergo phase change and remains in a solid or liquid phase. The formation of a bi-phase interface at the melting temperature, moving inside the layer, gives rise to a discontinuity of the heat flux with storage or release of latent energy to a variable extent over time according to the advancement velocity of the bi-phase interface. The law of storage of latent energy in the layer differs from that of release because of the different boundary conditions during the two processes. The storage or release of energy at the melting temperature of the different abscissae modifies the form of the heat flux and temperature fluctuations in the layer. In such conditions, unlike a monophase layer, the dynamic characterization of a PCM layer requires the definition of new parameters to identify the thermal behaviour. In a monophase layer the dynamic characterization is obtained by the parameters containing in [2-5] in sinusoidal periodic conditions, while by those reported in [4-8] in non-sinusoidal periodic conditions. In the literature, for the dynamic characterisation of a phase change layer, new parameters have been proposed. Zhou et al. [9, 10] have studied the effects of PCM thermo-physical properties, of the inner surface convective heat transfer coefficient and of the thickness of a SSPCM wallboard on the time lag, decrement factor and phase transition keeping the time of the inner surface, when the layer is subjected to the action of a periodic sinusoidal temperature or heat flux on the outer surface. Ling et al. [11] have proposed and evaluated three indicators, namely, thermal storage coefficient, thermal resistance and thermal inertia index of PCM useful to evaluate the thermal inertia performance of a building component with a PCM heated with periodic fluctuation. Evola et al. [12] have introduced a series of indicators in dynamic regime that allow a precise description of both the PCM behaviour (frequency of melting, storage efficiency) and the intensity and duration of the thermal comfort perceived by the occupants.

In this work, the issue of dynamic characterisation of a PCM layer is addressed, in the hypothesis that the thermal regime is a steady periodic regime. The boundary conditions considered are typical of building external walls in continuous air-conditioning and modelled by means of non-sinusoidal periodic fluctuations. The boundary conditions are such that one or more bi-phase interfaces originate in the layer. The definition of the parameters is obtained using the trends of the heat flux and of the temperature, to identify the thermal transfer through the layer, and the total and latent energy stored in the layer in order to define the heat capacity of the layer. Such parameters are evaluated on a monthly basis for a PCM layer with different melting temperatures and thermophysical properties, subject to phase change, and compared with the parameters of the same layer evaluated in the months in which the phase change is absent. The dynamic simulations were obtained with a finite difference numerical model, implemented in a calculation algorithm [13], validated by means of a comparison with the results determined with an analytical model that resolves the heat transfer in a PCM layer in a steady periodic regime [14]. The trend in time, in the different months, of the temperature and heat flux fields in the PCM layer, of the positions of bi-phase interfaces and of the associated latent energy are reported in a more extended form in a previous work by the authors [13].

2. Methodology

2.1. Calculation model

The equations that describe the heat transfer in a layer subject to phase change are the general equation of heat conduction in the solid phase and in the liquid phase (1), and the thermal balance equation at the bi-phase interface (2) at the melting temperature (3):

$$\frac{\partial^2 T}{\partial x^2} - \frac{1}{\alpha}\frac{\partial T}{\partial t} = 0 \quad (1) \qquad \left[k_l \frac{\partial T_l}{\partial x} - k_s \frac{\partial T_s}{\partial x}\right]_{x=X_M} = \rho H \frac{dX_M}{dt} \quad (2) \qquad T_l(X_M, t) = T_s(X_M, t) = T_M \quad (3)$$

with H latent heat of fusion, T_M melting temperature and X_M position of the bi-phase interface.

The boundary conditions on the external surface of the PCM layer are represented by shortwave and longwave radiative and convective thermal exchanges with the outdoor environment. On the internal surface, they are represented by the thermal exchanges with the indoor environment evaluated by surface heat transfer coefficient.
The system of equations (1), (2) and (3) with boundary conditions, is resolved by an explicit finite difference model. The discretization of the equations, obtained by evaluating the time derivative with the relative incremental ratio, leads to the relations for the calculation of the temperatures in the nodes that are not subject to phase change and of the liquid fractions λ present in the subvolumes of the nodes at the melting temperature. Such equations and the calculation algorithm used, which consists of three subprograms, are reported in [13]. The algorithm contemplates: the possibility that in the layer more solidification or melting bi-phase interfaces form, when the temperatures on the boundary surfaces of the PCM layer fluctuate around the melting temperature; a non-uniform spatial discretization; the updating at each instant of the thermal resistances between the nodes and the heat capacities in the nodes, different in the liquid phase and in the solid phase, as a function of the positions and the types of bi-phase interfaces. The k-th bi-phase interface $X_{M,k}$, positioned in subvolume j, is calculated summing the thicknesses Δx_i of the subvolumes preceding the node j at the portion of the subvolume in liquid phase $\Delta x_{j_k}\lambda_{j_k}$, if the bi-phase interface is of melting, and that in solid phase $\Delta x_{j_k}\left(1-\lambda_{j_k}\right)$, if the interface is of solidification.

$$X_{M,k} = \sum_{i=1}^{j_k-1} \Delta x_i + \Delta x_{j_k}\lambda_{j_k} \quad (4) \qquad\qquad X_{M,k} = \sum_{i=1}^{j_k-1} \Delta x_i + \Delta x_{j_k}\left(1-\lambda_{j_k}\right) \quad (5)$$

2.2. Definition of dynamic parameters

The parameters used for the dynamic characterization of the PCM layer are:

a) the fraction Λ_L of latent energy stored E_L compared to the total energy stored E_T in the layer in a period:

$$\Lambda_L = E_L/E_T \qquad (6)$$

b) the decrement factor of the maximum excursion in the period of the temperature f_T (Eq. 7) and of the heat flux f_Φ (Eq. 8), and the decrement factor of the transferred energy f_E (Eq. 9):

$$f_T = \frac{T_{si}^{max} - T_{si}^{min}}{T_{se}^{max} - T_{se}^{min}} \quad (7) \qquad f_\Phi = \frac{\Phi_{si}^{max} - \Phi_{si}^{min}}{\Phi_{se}^{max} - \Phi_{se}^{min}} \quad (8) \qquad f_E = \frac{\widetilde{E}_{si}}{\widetilde{E}_{se}} \quad (9)$$

c) the time lag of the maximum peak and of the minimum peak of the temperature $\Delta t_{T^{max}}$ and $\Delta t_{T^{min}}$ (Eqs. 10-11) and of the heat flux $\Delta t_{\Phi^{max}}$ and $\Delta t_{\Phi^{min}}$ (Eqs. 12-13):

$$\Delta t_{T^{max}} = \left(t_{T_{si}^{max}} - t_{T_{se}^{max}}\right) \quad (10) \qquad \Delta t_{T^{min}} = \left(t_{T_{si}^{min}} - t_{T_{se}^{min}}\right) \quad (11)$$

$$\Delta t_{\Phi^{max}} = \left(t_{\Phi_{si}^{max}} - t_{\Phi_{se}^{max}}\right) \quad (12) \qquad \Delta t_{\Phi^{min}} = \left(t_{\Phi_{si}^{min}} - t_{\Phi_{se}^{min}}\right) \quad (13)$$

d) the fraction of the period P in which the maximum or the minimum peak of the temperature Π_{T_i} (Eq. 14) and of the heat flux Π_{Φ_i} (Eq. 15) on the internal surface are constant:

$$\Pi_{T_i} = \Delta P_{T_{si}^{p}=const}/P \quad (14) \qquad\qquad \Pi_{\Phi_i} = \Delta P_{\Phi_{si}^{p}=const}/P \quad (15)$$

In the preceding equations, the subscripts s*i* and s*e* indicate respectively the internal and external surface of the layer, while the apexes *p, max* and *min* identify the generic peak, the maximum value and the minimum value in the period of the considered thermal quantity. If the parameter Π, relative to the temperature or heat flux trends, is different from zero, for the determination of the time lags (Eqs. 10 - 13) the time *t* to consider is that relative to the start of the fraction of time in which the peak of the thermal quantity is constant.

These parameters can be used to identify the dynamic behavior of a PCM layer with boundary conditions characteristic of summer and winter air conditions, both in the absence and presence of a phase change. In the first case, Π_{T_i}, Π_{Φ_i} and Λ_L are null and the dynamic parameters are reduced to those characteristic of a monophase layer. In the second case, the parameters Π_{T_i}, Π_{Φ_i} and Λ_L identify the layer both in energetic terms that of damping of thermal fluctuations.

3. Dynamic characterization of PCM layers

3.1. Description of the case study

The dynamic characterization was realized considering a layer with a thickness equal to 6 cm consisting of three different types of PCM. The melting temperatures and latent heat of fusion are, respectively, 15, 23 and 32 °C and 160, 185 and 162 kJ/kg; the thermal conductivities are 0.43, 0.815 and 0.60 W/m K, the specific heat capacities 1900, 3060 and 3600 J/kg K, and the densities 1510, 1690 and 1420 kg/m^3. We used hourly climatic data relative to the monthly average day [15] of the different months of two climatically different locations: Turin (Lat = 45° 7', Long = 7° 43') and Cosenza (Lat = 37° 30', Long = 15° 05'). In the numerical simulations: the solar absorption coefficient of the external surface of the wall, exposed to South, is equal to 0.6; the internal heat transfer coefficient and the external convective and radiative heat transfer coefficients are equal, respectively, to 7.7, 20 and 5.35 W/m^2 K. We considered an indoor environment set point temperature of 26 °C in the summer season, of 23 °C in the intermediate season, and of 20 °C in the winter season. The layer was discretized with 19 nodes and the integration step Δt is equal to 5 seconds.

3.2. Results and discussion

The calculation algorithm permitted the determination of the number and the position of possible bi-phase interfaces and of the temperature fields in the layer, during different months of the year, upon variation of the PCM and the locality. Thus, configurations of the phases in the layer were defined and the heat flux field and the instantaneous energy stored, sum of the latent and sensible contribution, were calculated. In each point of the layer, the trends of the temperature and of the heat flux can be considered as the sum of a steady component and of a fluctuating component. The monthly average daily fluctuating energies on the internal surface $\widetilde{E}_{si}$ and on the external surface $\widetilde{E}_{se}$ were calculated by means of the numerical integral in time of the fluctuating surface heat fluxes $\widetilde{\phi}_{si}$ and $\widetilde{\phi}_{se}$ extended only to positive or negative values. The fluctuating energies were used for the calculation of the decrement factor of the energy f_E. The total stored energy E_T is calculated by means of the numerical integral in time, extended only to positive or negative values, of the difference of the heat flux entering and exiting the layer (Eq. 16). Similarly, the advancement velocity of the k-th bi-phase interface, given by the relation $(X^{n+1}_{M,k} - X^{n}_{M.k})/\Delta t$, was used to evaluate the stored latent energy E_L by means of Eq. (17).

$$E_T = \sum_{n=0}^{P} (\phi_{si} - \phi_{se})^{+}\,\Delta t \qquad (16) \qquad\qquad E_L = \sum_{n=0}^{P} \left(\rho H \frac{\left(X^{n+1}_{M,k} - X^{n}_{M.k}\right)}{\Delta t}\right)^{+} \Delta t \qquad (17)$$

The sensible energy E_S is given by the numerical integral in time, extended only to positive or negative values, of the difference between the instantaneous total energy stored and the instantaneous latent energy.

3.2.1. Surface temperatures and heat fluxes in the absence and in the presence of phase change

Figure 1 shows examples of trends of the temperatures and heat fluxes on the internal and the external surfaces, in the case of absence of bi-phase interface (a), of the formation of one (b), of two (c) and of three bi-phase interfaces (d). In the images we also report the melting temperature T_M of the PCM, the trend of the internal air temperature T_{ia} and of the equivalent temperature of the outdoor environment $T_{e,eq}$ [4, 5] representative of the three external loadings. The vertical lines allow for the identification of the time instants in which the phase change process associated with each bi-phase interface starts and ends. Figure 1a is relative to a PCM layer in liquid phase, not subject to phase change. Figure 1b regards a layer, which is the location of the formation of a melting bi-phase interface, starting from the internal surface, which penetrates in the layer, reaches a maximum depth, inverts the process and extinguishes itself on the internal surface. Figure 1c is relative to a layer, which is the location, in successive time instants, of two bi-phase interfaces. Both the interfaces, the first of solidification and the second of melting, originate on the external surface, penetrate with different velocities and re-join within the layer, restoring to the initial liquid phase. Figure 1d regards a layer in which three bi-phase interfaces form. The first interface is of melting and the second is of solidification, both originate on the external surface. The third, for half of the period is of melting and for the other half is of solidification; it fluctuates within the layer close to the internal surface. In the latter case, similarly to case 1c, the two interfaces that form on the external surface penetrate in the layer and join together again within the layer.

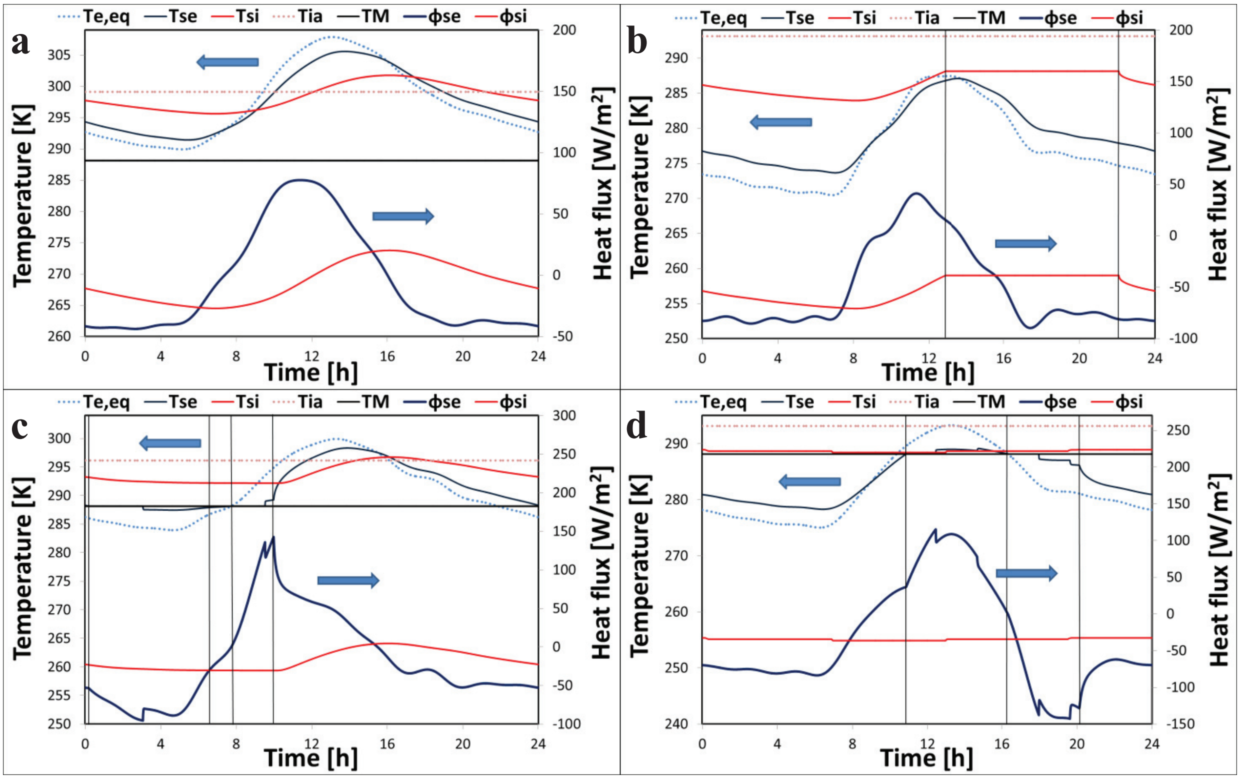

Fig. 1. Surface temperatures and heat fluxes, melting temperature, internal air temperature and equivalent temperature of the outdoor environment: a) in absence of phase change, August; b) with one bi-phase interface, February; c) with two bi-phase interfaces, May; d) with three bi-phase interfaces, March. Turin, PCM S15.

In the absence of a phase change (figure 1a) the temperature and heat flux fluctuations in the transfer through the layer, are attenuated and undergo a time lag proceeding from the outside towards the inside. In the presence of phase change, differing from a monophase material, it was shown that, with regards to the surfaces thermal fluctuations: for a fraction of the period the relative maximum or minimum peak is constant; the daily maximum excursion, the fluctuating energy in the period, and the time instant in which the maximum or the minimum peaks occur are modified; discontinuities at the start and at the end of the process are present; on the internal surface the maximum excursions can be completely dampened in presence of three bi-phase interfaces.

3.2.2. Evaluation of dynamic parameters

For the PCM and the considered localities, the number of bi-phase interfaces and the disposition of the phases in the layer proceeding inwards from the outside, in different months, are evaluated. The phase changes occur: for PCM S15 from September to May for Turin with the exception of the month of January, and from October to May for Cosenza; for PCM HS22P from May to September in Turin and from April to November in Cosenza; for PCM C32, due to the high melting temperature, in Turin no phase changes occur, while in Cosenza occur from July to September. The quantity of latent energy stored, in the months in which the phase change is recorded, depends on the number of bi-phase interfaces, on the extension of the portions of the layer involved in the phase change, on the density and on the latent heat of fusion. In Turin, the highest values of stored latent energy occur in April and in October for PCM S15 and in June for PCM HSSP22. Instead, in Cosenza the highest values of stored latent energy occur in March and November for PCM S15, in June and September for PCM HSSP22 and in August for PCM C32.

Figures 2 and 3 report the values in the different months of the dynamic parameters evaluated with Eqs. (6-13).

The values of the fraction Λ_L of stored latent energy compared to the total energy stored in the layer in a period calculated with Eq. (6), allows for the identification of the months in which the latent storage is prevalent over the sensible one. The decrement factor of the maximum excursion of the temperature f_T in the presence of phase changes it reduces and, in the months with the highest stored latent energy, is annulled. The decrement factor of the maximum excursion of the heat flux f_Φ and the decrement factor of the energy f_E exhibit similar trends and values, and in the presence of a phase change present analogous behavior of f_T.

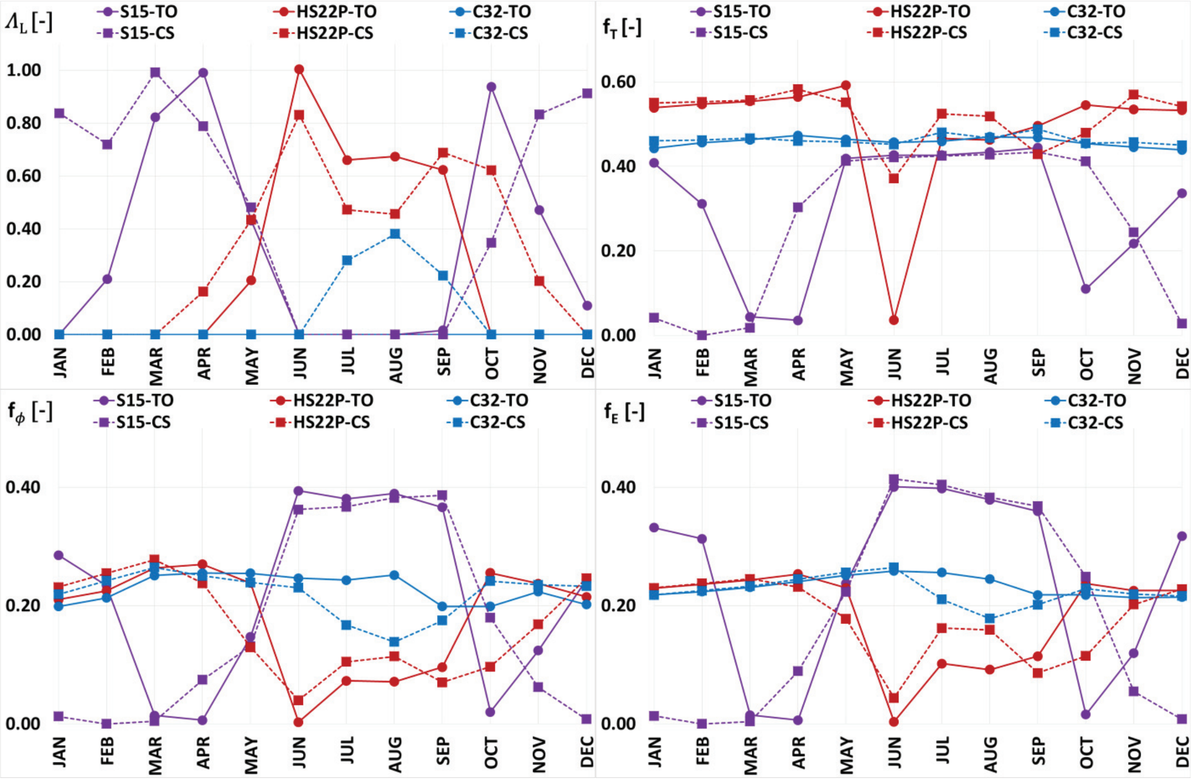

Fig. 2. In the different months, fraction Λ_L of latent energy stored compared to the total energy stored in the layer in a period, decrement factor of the maximum excursion of temperature f_T, decrement factor of the maximum excursion of heat flux f_Φ and decrement factor of energy f_E.

In the absence of phase change, time lags (figure 3) are almost constant, with the exception of that of the minimum peak of the heat flux, which presents a seasonal variability. In the presence of one or more bi-phase interfaces, the time lags undergo abrupt variations. In particular, in the absence of phase change, for both localities and for the different PCM, upon variation of the month, the variation range of $\Delta t_{T^{max}}$ and $\Delta t_{T_{min}}$ is between 1 and 3 hours while that of $\Delta t_{\Phi^{max}}$ is between 4 and 5 hours. Time lag $\Delta t_{\Phi_{min}}$ varies between 4 and 6 hours in summer and between 14 and 16 hours in winter. In the presence of a phase change, the entity of the abrupt variations is a function of the PCM, of the locality and of the month.

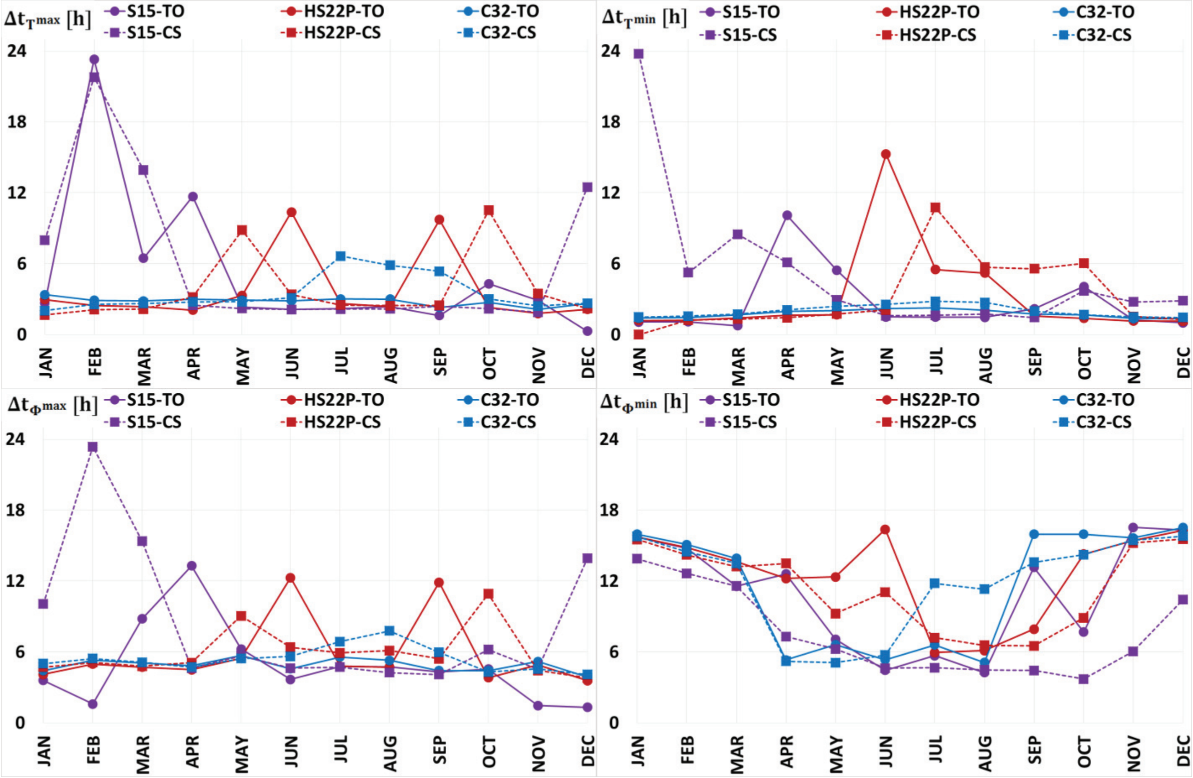

Fig. 3. In the different months, time lag of the maximum peak of temperature $\Delta t_{T^{max}}$, time lag of the minimum peak of temperature $\Delta t_{T_{min}}$, time lag of the maximum peak of heat flux $\Delta t_{\Phi^{max}}$ and time lag of the minimum peak of heat flux $\Delta t_{\Phi_{min}}$.

The maximum or the minimum peak of the internal surface heat flux is constant in the fraction of the period in which also the relative peak of the internal surface temperature is constant, as the temperature of the indoor environment is fixed and is equal to the set-point value. For this reason, in continuous regime of air-conditioning $\Pi_{T_i} = \Pi_{\Phi_i}$. In the considered cases, only for PCM S15 is it possible to observe that for Turin, from November to March except January, and for Cosenza from December to February, the peaks of temperature and heat flux on the internal surface remain constant for a fraction of the period. For such PCM, the values that assume the parameter $\Pi_{T_i} = \Pi_{\Phi_i}$ vary between 0.149 and 1.

4. Conclusion

The dynamic characterization of a PCM layer, obtained through the definition of new parameters, has allowed for the evaluation of the effects produced by the phase change on the heat transfer of the thermal fluctuations coming from the outdoor environment and on the thermal storage in the layer. The dynamic parameters can be used for the dimensioning of the layer and to identify the thermal behavior in situ. In particular, regarding the temperature fluctuation, the decrement factor of the maximum excursion, the time lag of the maximum peak and minimum peak, and the time fraction in which the peak of the internal surface temperature remains constant can be used to quantify the thermal discomfort in the indoor environment both in winter and in summer. If the heat flux is considered, similar parameters can be used to evaluate the entity of the attenuation and time lag of the power peak, entering in the summer and exiting in the winter, in order to determine the maximum thermal loads operating on the indoor environment, for dimensioning the air-conditioning system. If, instead, the fluctuating energy in transit in the wall is considered, the associated decrement factor allows the estimation of the fraction of energy transferred to the indoor environment in the two air-conditioning periods, in order to determine the thermal requirements. Finally, the fraction of stored latent energy allows for the evaluation of the correct use of the layer as a latent heat storage system.

The analysis developed on a monthly basis with reference to a PCM layer with different melting temperature, subject to different climatic conditions, has shown that the phase changes give rise to different dynamic characteristics, as a function of the quantity of stored latent energy. Such energy depends on the number of bi-phase interfaces, on the extension of the portion of the layer involved in the phase change, on the density and on the latent heat of fusion. In particular, compared to a monophase layer, the decrement factor of the maximum excursion of the temperature is reduced, also by an order of magnitude, while that of the heat flux and the energy are reduced by even two orders of magnitude. The phase changes give rise to abrupt variations of temperature and heat flux time lags, both of the maximum peak and of the minimum peak. In particular, those of the temperature and that of the maximum peak of the heat flux increase, even by 20 hours, while that of the minimum peak of the heat flux decreases in winter and increases in summer with variations of even 12 hours. Lastly, a correct thermal dimensioning of the PCM layer can lead, in a fraction of the period, to a complete attenuation of the temperature and heat flux fluctuations coming from the outdoor environment.

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