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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

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.