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Thermal field and heat storage in a cyclic phase change process caused by several moving melting and solidification interfaces in the layer

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ABSTRACT

This work determines the effective thermal fields in a non-sinusoidal periodic regime, which form in a layer of phase change material (PCM) within which multiple solidification and melting bi-phase interfaces are present.

The physical model used describes heat conduction in the solid phase and the liquid phase and the phase change at the melting temperature with the equation of thermal balance at the bi-phase interface. The resolution of the physical model, obtained by means of the finite difference numerical model, leads to equations for calculation of the temperature in the nodes in the solid phase and in the liquid phase, and the liquid fraction in the nodes in phase change at the melting temperature. The numerical model and the resolution algorithm were obtained by extending those proposed by Halford et al. (2009). In addition, the numerical model and the resolution algorithm proposed in this paper foresee: (i) the presence of one or more bi-phase interfaces in the layer; (ii) a non-uniform spatial discretization of the sub-volumes of the layer in order to obtain a more accurate representation of heat flux discontinuity in the sub-volumes involved in the phase change; (iii) the variability in space and time of the thermal resistances and the areal heat capacities as a function of the position of the bi-phase interfaces; (iv) the use of temperature and of the liquid fraction values in a node at two previous time instants to determine the thermodynamic state at the successive time instant; (v) different thermo-physical properties in the solid phase and in the liquid phase. The numerical model is validated by means of a comparison with an exact analytical solution, which resolves the Stefan problem in a finite layer in a steady periodic regime.

The calculation procedure is employed for the study of the thermal behaviour of PCM layers, with different melting temperatures and thermo-physical properties, with boundary conditions typical of those operating on the external walls of air-conditioned buildings. This procedure allows for the determination, at different time instants of the period P = 24 h, of the position of the bi-phase interfaces present in the layer, the field of temperature and heat flux and the instantaneous energy released and stored by each interface. The numerical results reveal interesting phenomena that, for such boundary conditions and in such detail, have never been reported previously in the literature.

1. Introduction

The mathematical formulation of the heat exchange in a PCM layer is known as the Stefan problem and its exact analytical solution is available only for semi-finite or infinite mono-directional geometries and temperature or heat flux boundary conditions that are constant in time [1–4]. The complexity of the resolution is due to the discontinuity of the heat flux at the bi-phase interface whose position is variable in time with consequent variation of the solid and liquid phase domain. For this reason, several authors have proposed analytical solutions of the model obtained introducing approximations and numerical solutions to describe the phase change and the relative latent storage. The heat balance integral method [5] is frequently used as an analytical approximation technique; instead, the effective thermal capacity method [6–8], the apparent heat capacity method [9–12] and the enthalpy method [13–19] are the most widespread numerical methods, which use a nodalisation that is fixed or variable in time [20–23]. These numerical models allow for obtaining a solution to the thermal exchange problem without directly resolving the equation of discontinuity of the heat flux at the bi-phase interface on which the Stefan problem is based.

The previous methodologies have mainly been used to study the thermal transient in a PCM layer, while there are few studies related to their use in steady periodic regime. The problem of the determination

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of the thermal field in PCM layers subject to boundary conditions variable in time in the case of a steady periodic regime is of particular interest. Such a regime, for example, owing to the daily periodicity of the loadings that act on the external surface of the walls, such as solar radiation, is representative of building wall behaviour. The analytical solution of the Stefan problem in a finite layer subject to periodic boundary conditions has recently been provided by Mazzeo et al. [24]. Such a solution is valid in the case in which, during the period, the boundary conditions of temperature or heat flux ensure a temperature oscillation with values on a face always less than the melting temperature and on the other face with values that are always greater. In these conditions, a sole bi-phase interface originates which oscillates within the layer with the same frequency as the thermal oscillations on the layer boundary. A numerical study of the periodic phase change in a PCM layer, initially in solid phase, subject to a sinusoidal surface temperature, in all time instants above the melting temperature, on one face while the other face is kept isothermal below the melting temperature, was reported by Ho and Chu [25], who adopted the enthalpy method. Casano and Piva [26] presented a numerical and experimental investigation of a phase change process in a plane slab of PCM periodically heated from above, while the bottom is kept at a temperature lower than the melting temperature by means of a refrigeration system. For all the tests conducted, the presence of an interface separating an upper zone, where the material is liquid, from a lower zone in solid phase, is clearly evidenced.

It can occur that the boundary conditions give rise to more bi-phase interfaces in the layer and this renders the problem even more complex. The multiple bi-phase interfaces originate when the periodic temperature oscillation on the boundary face varies around the melting temperature. The presence of multiple bi-phase interfaces has been highlighted in the literature by Choi et al. [27], by considering sinusoidal boundary conditions that give rise to a surface temperature around the melting temperature on one face, and a constant temperature below the melting temperature on the other face. They found that during the heating process, the layer melts and the melting bi-phase interface moves from the boundary surface to the interior of the layer, while during the cooling process a solidification bi-phase interface appears on the same surface, which does not reach the first bi-phase interface, thus dividing the layer into three regions. Analysing only one cycle, the results of this analysis do not constitute the steady periodic regime solution, determining at the end of the cycle a gap between the two bi-phase interfaces and a stored energy different from that released. A similar result was also reported by Ho and Chu [28] who have highlighted that three solid-liquid interfaces might coexist, dividing the layer into four regions, according to the oscillating temperature amplitude on the boundary. In a recent work, with reference to boundary conditions characteristic of the building external wall, it was highlighted that the configuration of the phases in a PCM layer is variable over the course of the year [29]. The layer can be completely solid or liquid, there may be one bi-phase interface or two or three solid-liquid bi-phase interfaces might coexist.

From the literature, it appears that a detailed study of the thermal field and the heat storage in a PCM layer, in the presence of multiple bi-phase interfaces, subjected to the joint action of more non-sinusoidal periodic thermal loadings has not been addressed.

In this work, we studied the problem of the determination of the thermal field in PCM layers subject to periodically variable boundary conditions. The layer behaviour is schematised with a physical model that describes heat conduction in the solid phase and in the liquid phase, having different thermo-physical properties, and the phase change by means of the thermal balance equation at the bi-phase interface at the melting temperature. The finite difference numerical model and the resolution algorithm were obtained by modifying those proposed by Halford et al. [30], which allow for the position for the bi-phase interface to be evaluated explicitly. In particular, some simplifications, such as the uniformity of the spatial discretization of the sub-volumes of the layer, the invariance in space and time of the thermal resistances and the areal heat capacities, were removed in order to obtain a more accurate representation of heat flux discontinuity in the sublayer involved in the phase change. The model and algorithm developed contemplate the contemporaneous presence in the layer of several bi-phase interfaces and use the values of temperature and of the liquid fraction in a node at two previous time instant to determine the thermodynamic state at the successive time instant. Validation was achieved by a comparison with the results obtained with an analytical model available in the literature [24] that resolves the Stefan problem in a finite layer subject to periodic temperature or heat flux fluctuations on both boundary faces of the layer. The calculation procedure created was used to study the yearly thermal behaviour in different PCM layers available on the market, with melting temperatures ranging between 15 °C and 32 °C, subject to boundary conditions typical of building walls. The external loadings considered, relating to two climatically different locations and representative of the continental climate and of the Mediterranean climate, are the hourly values of the monthly average day of the air temperature, of the solar irradiation and of the apparent sky temperature. The air temperature, supposed as constant, was considered as an internal loading.

2. Methodology

2.1. Calculation model

2.1.1. Constitutive equation

The physical model was formulated under some common assumption in a thin PCM layer: one-directional heat transfer in the liquid and solid phase with the bi-phase interface flat; reversible and isothermal phase change with hysteresis, subcooling and phase segregation phenomena excluded [31–35]; thermo-physical properties constant with the temperature but different in the solid and liquid phases; negligible difference of density between the solid phase and the liquid phase; negligible convection phenomena in the liquid phase [26,36,37]. In these conditions, the equations describing heat exchange in a layer subject to phase change are the general equation of heat conduction in the solid phase and in the liquid phase, Eq. (1), and the Stefan conditions, Eqs. (2) and (3), expressed by the thermal balance equation at the bi-phase interface which is at the melting temperature.

$$\frac{\partial^2 T}{\partial x^2} - \frac{1}{a}\frac{\partial T}{\partial t} = 0 \tag{1}$$

$$\left[k_l \frac{\partial T_l}{\partial x} - k_s \frac{\partial T_s}{\partial x}\right]_{x=X_M} = \rho H \frac{dX_M}{dt} \tag{2}$$

$$T_l(X_M,t) = T_s(X_M,t) = T_M \tag{3}$$

with H latent heat of fusion, T_M melting temperature, X_M bi-phase interface position, ρ density, T_l and T_s temperature in the portion of the layer in liquid and solid phase, and k_l and k_s thermal conductivity in the liquid phase and in the solid phase.

The boundary conditions, on the external surface of the PCM layer are defined by the convective and shortwave and longwave radiative heat exchanges and, on the internal surface by the heat exchanges calculated by means of the surface heat transfer coefficient. The corresponding equations are:

$$\Phi_e = \Phi_{r,e} + \Phi_{c,e} + \alpha\Phi_s = h_{r,e}(T_{sky} - T_l) + h_{c,e}(T_{ea} - T_l) + \alpha_e\Phi_{s,e} = -k\left.\frac{\partial T}{\partial x}\right|_{x=0} \tag{4}$$

$$\Phi_{ia} = h_{s,i}(T_N - T_{ia}) = -k\left.\frac{\partial T}{\partial x}\right|_{x=L} \tag{5}$$

with Φ_e total heat flux from the outdoor environment, $\Phi_{r,e}$ longwave radiative heat flux exchanged with the sky, $\Phi_{c,e}$ convective heat flux