dimensionless amplitude of the total energy, ΔE, the dot-dash line for the dimensionless amplitude of the latent energy, ΔE_L. The dimensionless amplitude of total and latent energy is zero for $\tau_2 = 0$ (steady heating with a low power) and for $\tau_2 = 1$ (steady heating with a high power). Both distributions show a maximum in the interval $0 < \tau_2 < 1$.

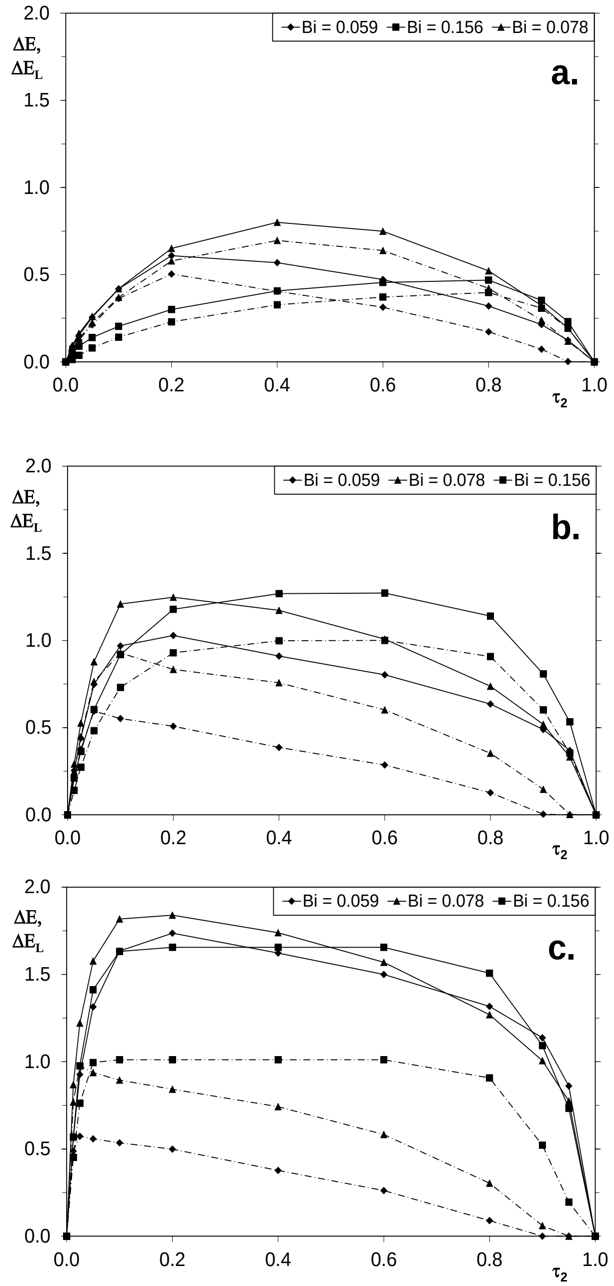

Figure 5. Dimensionless amplitude of total, ΔE (—), and latent, ΔE_L (---), energy for *Ste* = 0.012, as a function of τ_2; a.: $\Omega = 2$; b. $\Omega = 4$; c. $\Omega = 8$

For increasing values of Ω, the maximum of ΔE_L tends to move towards low values of τ_2 when *Bi* decreases. This is due to the fact that the latent term is able to give a significant contribution to the energy storage just for short durations of the high power heating (Fig. 3). For higher values of *Bi*, the sensible term is as high as to be prevailing over the latent one, in particular for high values of τ_2. For longer durations of the high power heating, low values of *Bi* mean low external heat transfer and thence a lower variation of energy storage, because the system tends to stay in the solid phase *S*2.

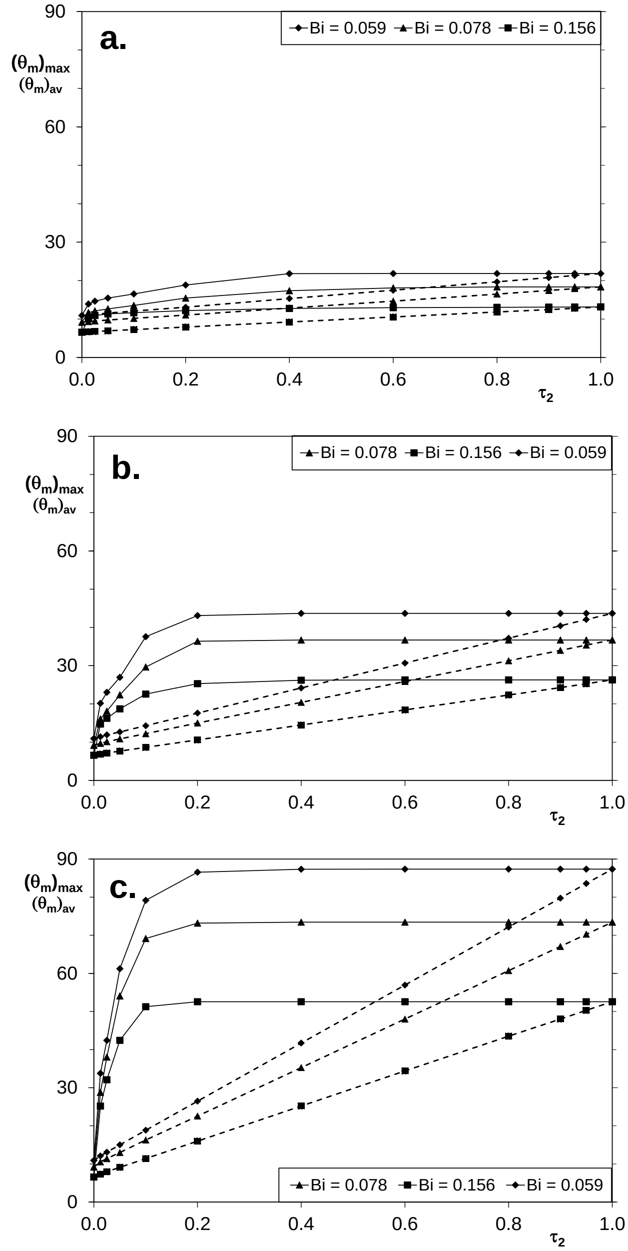

Figure 6. Maximum, $(\theta_m)_{max}$ (—), and average, $(\theta_m)_{av}$ (- -), dimensionless mean temperature, for *Ste* = 0.012, as a function of τ_2; a.: $\Omega = 2$; b. $\Omega = 4$; c. $\Omega = 8$

The maximum amplitude of the total energy variation is well evident for low values of Ω; this maximum increases for increasing values of Ω. Conversely, for high values of Ω, the distributions tend to become flat, and independent of τ_2. This is mainly due to the latent term, which tends to be very efficient ($\Delta E_L \approx 1$), with the maximum possible contribution in terms of charge and discharge of the thermal storage. For the highest value of Ω the distributions of the amplitude of dimensionless total energy storage are quite independent of *Bi*. In this range of Ω the two components, sensible and latent, of the energy storage seem to compensate their effects. A low *Bi* means a high temperature and a high sensible contribution; conversely, a high *Bi* means a low temperature and a high latent contribution.

For the same values of *Ste*, *Bi* and Ω of Fig. 5, in Fig. 6 is shown the maximum, $(\theta_m)_{max}$, and the average, $(\theta_m)_{av}$, dimensionless mean temperature on the heated surface as a function of the dimensionless time τ_2.

The distributions of $(\theta_m)_{max}$ are characterized by a growing trend for increasing values of Ω, the opposite for increasing values of Bi. This reflects that a high energy input during a period (high Ω), coupled to a constant "intensity" of the ambient heat transfer (same Bi), is the reason of an increase of the temperature. Conversely, a better heat transfer due to larger surfaces of the fins in air or a more intensive convection (high Bi), coupled to the same energy input (same Ω), is the reason of a decrease of the temperature.

For the whole set of data shown in Fig. 6, for increasing values of τ_2 a value of $(\theta_m)_{max}$ independent of the value of τ_2 is rapidly reached; this is exactly the value of the high power steady state reached for $\tau_2 = 1$.

The distributions of $(\theta_m)_{av}$, for increasing values of τ_2 , are characterized by a linear increase between the values corresponding to the low and high power steady heating, This average temperature is clearly related to the dimensionless input energy into the system, equal to:

$$\Pi = \Pi_1\left[1-\left(\Omega-1\right)\tau_2\right] \tag{36}$$

where:

$$\Pi = \frac{q_1 t_1 + q_2 t_2}{\left(\Delta H_L\right)_{\max}} \tag{37}$$

$$\Pi_1 = \Pi\left(t_1 = P, t_2 = 0\right) = \frac{q_1 P}{\left(\Delta H_L\right)_{\max}} \tag{38}$$

In Figure 7 some results are shown of the amplitude of the dimensionless total, ΔE, and latent, ΔE_L, energy storage as a function of the Stefan number, Ste, for $\tau_2 = 0.6$ and for three Biot numbers, $Bi = 0.059$, 0.078 and 0.156. The solid line is used for the amplitude of dimensionless total energy, ΔE, the dashed one for the amplitude of dimensionless latent energy, ΔE_L. For the whole set of calculations, ΔE increases with Ste and with Ω. Differently, ΔE_L tends to a constant value for increasing values of Bi. This constant value, for increasing values of Ω, tends to its limiting value, $\Delta E_L = 1$, occurring when the change of phase is extended to the whole volume filled by the PCM. This situation occurs only for contemporary high values of Bi, Ω and Ste. This means that at high values of Ω and Ste, a large fin able of a good heat transfer with the ambient (high Bi) is helpful for the exploitation of the PCM in the TCU. However, it also means that, from a certain point, the system is unable to take advantage of the phase change process. Going deeply into the process, for the chosen value of τ_2, during the time of high power input (Fig. 3), high values of Ω and Ste favour the complete phase transition and the consequent energy storage. During the time of low power input, a high value of Bi facilitates the complete release of the stored latent energy (see for an example, Fig. 4). In these cases, the storage of total energy is significantly linked to that of latent energy. This behaviour explains Fig. 7.a, where a high Bi ($Bi = 0.156$) inhibit the phase change of the whole volume filled by the PCM and a further increase of latent storage is not possible. This behaviour explains also Fig. 7.c, where for $Bi = 0.156$ the distribution of ΔE crosses that of $Bi = 0.059$ and 0.078. For $Bi = 0.156$ the whole volume filled by the PCM changes its phase and a further increase of latent storage is not possible.

For the same values of τ_2, Bi and Ω of Fig. 7, in Fig. 8 is shown the maximum, $(\theta_m)_{max}$, and the average, $(\theta_m)_{av}$, dimensionless mean temperature on the heated surface as a function of the Stefan number, Ste. Both $(\theta_m)_{max}$ and $(\theta_m)_{av}$ are quite independent of Ste, though they strongly increase with Ω. The effect of Bi is such that the dimensionless temperature decreases with Bi. The decrease is larger for larger values of Ω. When combining the results of Figure 7 and 8, it is confirmed that efficient fins help to ensure low values of the maximum dimensionless mean temperature on the surface exposed to the heat flux, coupled to a good exploitations of the phase change process.

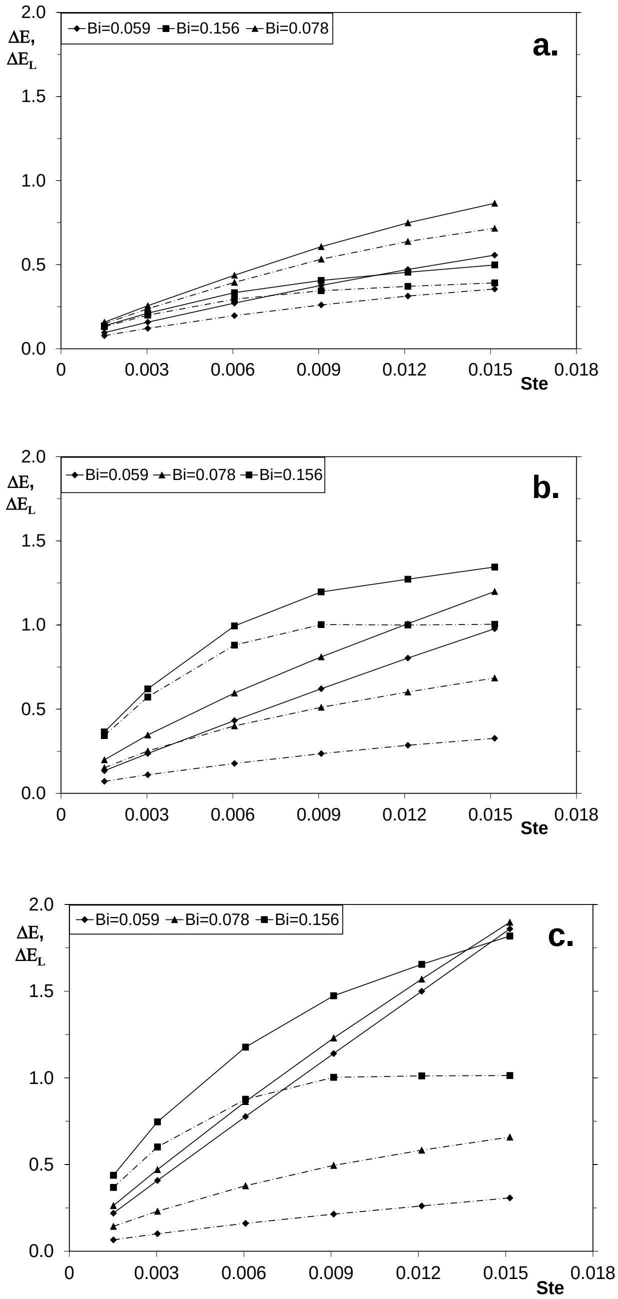

Figure 7. Dimensionless amplitude of total, ΔE (—), and latent, ΔE_L (- - -), energy for $\tau_2 = 0.6$, as a function of Ste; a.: $\Omega = 2$; b. $\Omega = 4$; c. $\Omega = 8$

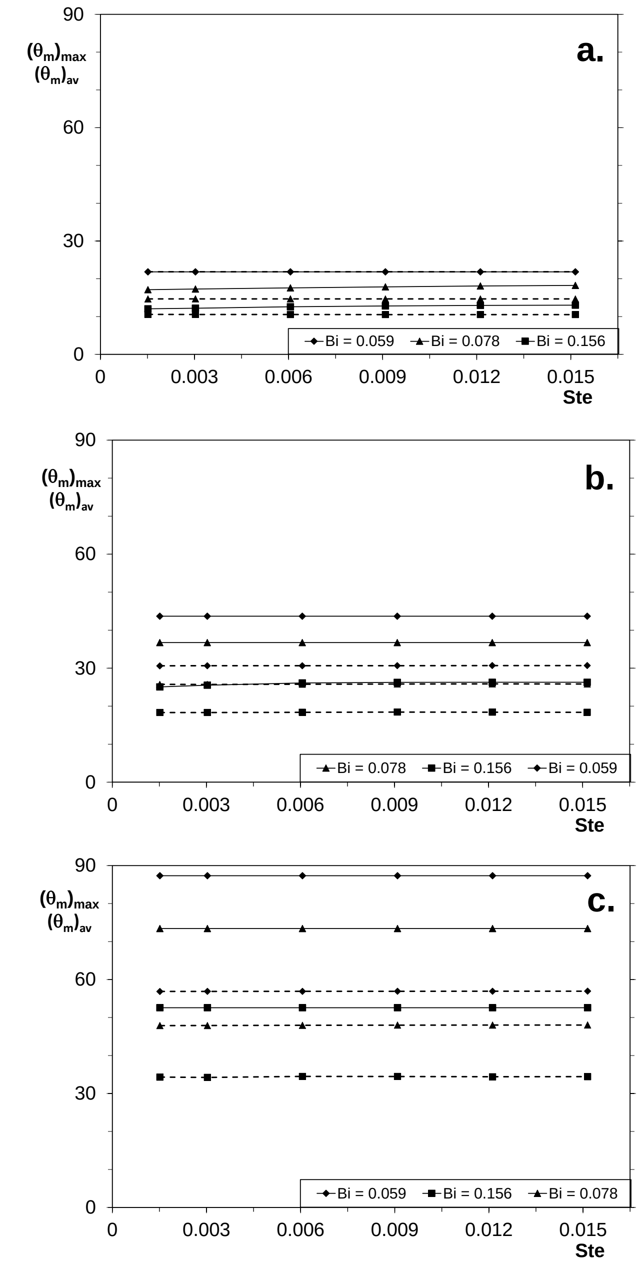

Figure 8. Maximum, $(\theta_m)_{max}$ (—), and average, $(\theta_m)_{av}$ (- -), dimensionless mean temperature on the heated surface, for τ_2 = 0.6, as a function of *Ste*; a.: Ω = 2; b. Ω = 4; c. Ω = 8

4. CONCLUDING REMARKS

A TCU with a PCM energy storage system, designed for the thermal control of electronic devices, has been investigated numerically. Conduction heat transfer is the prevailing heat transfer process. The application is characterized by a periodic heating on two levels of power.

The analysis of the energy behaviour of the system shows that the storage of energy varies periodically in time with the two levels of the heating boundary condition.

The main design parameter is the maximum value of the mean temperature on the heated surface, where the electronic components to be cooled are placed.

In general it can be observed that a TCU based on PCM is suitable to be used when a high power heating acts in short times. During the peak of heating, the phase change can occur; afterwards, it is important that the storage system could release the stored energy in a freezing process.

For this hybrid heat storage system, in order to exploit the presence of the PCM, it is important to store and to release an amount of latent energy lower than the maximum latent energy storable.

Since the dimensionless parameters governing the steady periodic process are thirteen, we concentrated our attention on two parameters useful to describe the thermal load (Ω and τ_1) and on two more parameters useful to characterize the thermal behaviour of the TCU (*Bi* and *Ste*).

When Ω is low, a high value of *Bi* helps to control the temperature, but the contribute of the PCM can be very low, because the most of the energy input during the high power heating phase is dissipated in the ambient. In the opposite case, when Ω is high, a low value of *Bi* is not enough to avoid a sensible heating of the TCU, protracted also after the complete phase-change of the PCM. In this situation the TCU is not useful for the control of temperature.

A complete exploitation of the PCM requires therefore an accurate design of the system on the base of the parameters affecting the performance of the TCU.

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NOMENCLATURE

Symbol

B	m	Thickness of the basement
Bi		Biot number $(h_e{*}L)/\lambda_F$
c	J/(kg K)	Specific heat at constant pressure
Fo		Fourier number $\alpha_F P/L^2$
h_e^*	W/m^{2}K	Equivalent heat transfer coefficient
H	J/m^3	Specific enthalpy
L	J/kg	Enthalpy
P	s	Period
q	W/m^2	Heating power
r	J/kg	Latent heat of fusion
Ste		Stefan number $c_{S1}T_R/r$
t	s	Time
T	K	Temperature
T_R	K	Reference temperature q_1L/λ_F
w	m	Thickness of the fin
W	m	Half width of the fin-PCM system
x	m	Cartesian coordinate
X	m	Solid-solid interface position
y	m	Cartesian coordinate

Greek symbols

α	m^2/s	Thermal diffusivity
A_{Si}		Thermal diffusivity ratio α_{Si}/α_F
E		Dimensionless energy $\Delta H/(\Delta H_L)_{max}$
η		Dimensionless coordinate x/L
θ		Dimensionless temperature $(T-T_0)/T_R$
λ	W/(m·K)	Thermal conductivity
Λ_{Si}		Thermal conductivity ratio λ_{Si}/λ_F
ξ		Dimensionless coordinate y/L
Ξ		Dimensionless position of the interface X/L
ρ	kg/m^3	Density
Π		Dimensionless input of energy $qt/(\Delta H_L)_{max}$
τ		Dimensionless time t/P
τ_1		Time ratio t_i/P
Ω		Power ratio q_2/q_1

Subscripts

a	Ambient
av	Average over a period
B	Basement
f	Phase change
F	Fin
m	Mean on the heated surface
max	Maximum
min	Minimum
L	Latent
PCM	Phase change material
$S1$, $S2$	Different phases of the solid PCM
W	Half width of the fin-PCM system
0	Initial condition
1, 2	Low and high power