Temperature moderation in a multistorey building by melting of a phase-change material

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Abstract   The current numerical study focuses on the feasibility of furnishing thermal comfort in a structure, by using paraffin wax stored on a plate below the ceiling in a multi-storey building. The method is aimed to reduce energy demands at the increasing thermal loads. In summer, in daytime, walls of the building are exposed to the ambient thermal load, and heat transferred inside is absorbed by the melting wax. The study is numerical. It relates to temperature variations outside and inside, coupled with heat conduction and accumulation in walls, with radiation between the surfaces, with natural convection of air inside and melting of the wax at the ceiling. Fins spacing on the storage plate, visualization of the melting process, and its parametric investigation provide an insight into the physical phenomena. Temperature and flow fields were investigated for 3 mm and 12 mm thick layers of wax. At the specified conditions of the present study a 3 mm layer provides thermal comfort for most of the day, while a 6 mm layer may suffice for the entire day. Fluent 6.3 software was used in the computations.

Keywords: Wax melting; Room cooling at ceiling; Numerical simulations; Thermal comfort

Nomenclature

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b_l –   final thickness of liquid layer on the tray, mm
b_s –   initial thickness of solid layer on the tray, mm
f_m –   melt fraction
h –   heat transfer coefficient, $W/m^2 K$
k –   thermal conductivity, W/m K
l –   distance between fins, m
q –   heat flux, W/m^2
s –   fin height, mm
T –   plate (tray) temperature, K, °C
T_{out} –   temperature of ambient, K, °C
T_{PCM} –   PCM temperature (solid fraction), K, °C
$T_{room\,av}$ –   average air temperature in the room, K, °C
$T_{wall\,av}$ –   average wall temperature, K, °C
$T_{wall\,inside}$ –   average temperature of the inside wall surface, K, °C
x_l –   height of melt layer between plate and solid interface, mm

1   Introduction

Thermal storage that utilizes latent heat of phase-change materials (PCM) is of interest, because of its large heat storage capacity. In summer, the phase-change materials are used in buildings as sinks, absorbing the heat that penetrates walls, ceiling or floor. For that application, the materials have to melt at temperatures lower than the desired thermal comfort temperature in the structure. The phase-change process is isothermal in melting or solidification. Materials that perform as sinks are stored either in walls, or in the vicinity of a ceiling (Mozhevelov *et al.* [1]).

Laouadi and Lacroix [2] conducted a theoretical study to assess performance of a PCM unit designed to level electrical energy demand for domestic space heating during peak hours. The studied storage unit was examined for its cyclic melting and solidification. Farid and Chen [3] numerically simulated storage of a phase-change material placed between an electrically heating surface and floor tiles. Khudhair and Farid [4] summarized their investigation and analysis of thermal energy storage systems incorporating phase change materials for use in building applications. Breesch *et al.* [5] studied natural night ventilation and an earth-to-air heat exchanger, which cools the ventilation air at daytime in summer. Zhang *et al.* [6] investigated thermophysical properties for free-cooling buildings. They validated their simulated results with experiments, and used them for selection of suitable building envelope materials. Henning [7] presented an overview of open and closed heat driven cooling cycles for applications in combination with solar collectors. They analyzed the control needs for such systems in summer.

Tyagi and Buddhi [8] reviewed the thermal performance of various types of systems like the PCM Trombe wall, PCM wallboards, PCM shutters, PCM building blocks, floor heating, ceiling boards and other devices.

Chowdhury *et al.* [9] simulated a system that uses a chilled ceiling, and concluded that it offers the best thermal comfort during summer. Pasupathy *et al.* [10] gathered information on developments of PCMs applications in buildings, and the methods used for space heating and cooling. The authors related to micro- and macroencapsulation methods, to PCM impregnation in building materials, to PCM-integrated space heating and cooling. Matens and Oliveira [11] aimed to evaluate the potential of integrated solar absorption cooling and heating systems for building applications. Baetens *et al.* [12] extensively reviewed the applications of phase-change materials in buildings. The authors discussed the performance of wallboards impregnated with PCMs, PCM enhanced concrete, and PCM-enhanced clay tiles, to provide thermal storage distributed throughout the building. The authors also pointed out the merits and demerits of those applications. Raj and Velraj [13] presented a review on free cooling and ventilation cooling, using phase-change materials. The free cooling was defined as being based on solidification at night, and melting in daytime, in both cases by natural convection. That was feasible in climates, where considerable temperature difference exists between day and night. The ventilation cooling was essential in cases of small temperature differences, like few degrees. Shatikian *et al.* [14] examined the effect of fins on the rate of melting of a phase-change material. The study was conducted using the enthalpy-porosity numerical model, as first presented by Voller *et al.* [15].

Our current work simulates temperature moderation in a structure at mid-storey on a typical subtropical summer day [16]. Paraffin wax, chosen as the phase-change material, is stored over a plate at the ceiling. The heat accumulated and transferred by the walls is naturally conveyed up by air in the analyzed structure. As the heat is absorbed by the melting wax at the ceiling, thermal comfort within the structure is achieved.

2   Physical model and numerical procedure

In our current study the physical model of the analyzed structure, and the phase change material stored at its ceiling, are being considered as an entity. The numerical procedure differs, and is described separately for the structure and for the storage space.

2.1 Physical model

A structure inside a multi-storey building 8 m long, 8 m wide, and 2.5 m high is considered. Heat from the surroundings penetrates the four walls, which are 0.15 m thick, and made of construction materials, having a density of 1300 kg/m3, specific heat of 0.9 kJ/kgK, and thermal conductivity of 0.45 W/mK. The choice of a structure in a multi-storey building means a concrete adiabatic floor and a concrete adiabatic ceiling. In our case temperature moderation in the structure is demanded, therefore, a heat sink in summer, and a heat source in winter have to be mounted.

In the current study a summer day is chosen, and a paraffin wax, being a phase-change material, serves as a heat sink. The paraffin wax is stored over the aluminum plate, installed parallel to the ceiling, about 0.01–0.02 m below it. The plate, being horizontal, is 8 m long and 8 m wide. It has end walls, like a tray, which are a few millimeters higher than the stored wax melt. The tray is open at its top, to the air passage, which extends from the wax, up to the concrete ceiling.

The wax properties are partly based on commercially available paraffins. The one chosen for our study melts at $21\,^{\circ}$C, with latent heat of 100 kJ/kg, density of the solid wax is 800 kg/m^3, density of the liquid wax is 750 kg/m^3, specific heat is 2.5 kJ/kgK, and the thermal conductivity is 0.2 W/mK. The solid-liquid zone, i.e., the mushy zone, is assumed to extend within the range of $0.2\,^{\circ}$C, or rather $21\pm0.1\,^{\circ}$C, as in the almost pure material.

The following processes are expected: heat from the surroundings is conducted across the walls. Part of it accumulates in the walls, while the other part enters the structure. The air inside heats up at the walls and moves inside by natural convection. The warm stream moves up to the aluminum plate. Simultaneously heat is transferred by radiation between the inside surfaces. Heat is absorbed by the plate and the wax stored on it. The wax melts, and liquid is formed on the plate. The solid-liquid interface moves up, and the liquid layer thickens. The thermal resistance to transfer of heat increases. The solid phase, which is heavier, floats over the liquid layer. As long as the solid layer is perfectly uniform, it would stay on top of its melt, till it completely disappears by melting. In practice, as the layer becomes thinner and thinner, it may fracture and collapse down. At night the wax has to solidify, by rejecting its latent heat to a stream of cold air, which may flow on top of the wax, inside the free passage at the ceiling. Currently, the night cooling by air has not been considered quantitatively, with regard to the air flow rate, its temperature, the passage cross-section size, or the rate

of solidification.

The end walls of the tray are 8 m apart. Longitudinal fins are constructed on the plate between those walls, and have to be as high as the height of the final melt. The fins being based on the plate, and made of aluminum, reach the plate temperature being isothermal, due to their geometry and properties. The fins are installed on the plate, at the bottom of the tray. They are straight and longitudinal, 8 m long, 12 mm thick, 4 mm or 16 mm high, as the height of the tray end walls. The thermal conductivity, k, of the aluminum fins and the plate is about 200 W/mK. The heat transfer coefficient in the wax, liquid or solid, on the fin interface is $h = 10-20$ W/m^{2}K, as obtained from the Fluent software. Introducing into the common equation of fin efficiency the fin height of 16 mm, the aluminum thermal conductivity, k, and the heat transfer coefficient, $h = 20$ W/m^{2}K, results in a fin efficiency of unity, indicating temperature uniformity in fins. The fins and plate temperature is higher than the melting point of the wax. Therefore, the adhering solid melts, forming 'openings' for free convection of the lighter liquid. As the liquid moves up, the fractured solid layer may settle down toward the plate.

The process of settling has two major effects: the solid layer becomes enveloped in liquid, and the resistance to heat transfer from the plate to the melting solid decreases. Both effects promote the rate of melting. With the increasing number of fins on the plate, those effects are further boosted.

2.2   Numerical procedure

Due to the large dimensions of the structure, and relatively very small thickness of the wax layer, coupling between the two is rather complex. Instead, the thermal resistance, between the plate and the solid layer, was assessed for the structure computations.

For the computational procedure, the structure was divided by two vertical planes of symmetry. The origin of the coordinate system was taken at the intersection of the two planes. This division yielded a quarter of the original space, namely $4 \times 4 \times 2.5$ m, defined as the three-dimensional computational domain. Free convection of air inside was coupled with radiation, with time-dependent accumulation and conduction in the walls, and conduction through the plate at the ceiling. The computational grid consisted of $50 \times 80 \times 80$ cells, for the height, length and width of the structure respectively. The time step varied along the day. At first it was 1 s, and later on, up to 10 s. The computation was conducted for 12 hours of physi-

cal time, from 7:00 till 19:00. Similar grid was used previously in structures
of about the same size [1,17,18]. Grid refinement was applied [17], without
any further significant effect.

In the space of the structure, turbulent free convection of air is com-
puted, using k-ε model. Although the air movement in the space is slow,
the criterion expressed by the Rayleigh number for turbulent flow is sat-
isfied, namely Ra $> 10^9$. In our case, it is obtained at a temperature
difference of 1.0 °C between the inside wall temperature and the average
room temperature, yielding Ra $=$ GrPr $= 1.59 \times 10^9$, where Gr and Pr
are the Grashof and Prandtl numbers, respectively. At 7:00 and 19:00 the
temperature difference is smaller, and the flow may change from turbulent
to laminar.

The governing equations for the air inside the structure have been pre-
sented by Mozhevelov *et al.* [1]. The surface-to-surface radiation inside the
structure is computed by applying the discrete transfer radiation model,
referred to as DTRM.

The entire process is transient, and is actually monitored since 6:00.
Then, the ambient, the walls, the room space and the solid wax are at
21 °C. Cooling of the wax is maintained till 7:00, preserving it as a solid at
21 °C. Thus, for the current study, the initial conditions are: $t = 0$ (7:00):
$T_{PCM} = 21$ °C, $f_m = 0$. The other temperatures have increased till 7:00 to:
$T_{out} = 23$ °C, $T_{wall\,av} = 22$ °C, $T_{wall\,inside} = 21.6$ °C, $T_{room\,av} = 21.5$ °C.

The boundary conditions are: at the adiabatic floor and ceiling, $q = 0$.
At all surfaces, no slip and no penetration are assumed. The structure has
no ports, and no windows. Ports to the cold air passage at the ceiling are
shut-down at 7:00. Pressure inside the structure is atmospheric, as outside.

Averaging of temperatures by volume is done in the room space and in
the walls. Averaging on the surface is performed at the storage plate, and
on the inside walls. All those computations are performed in Fluent 6.3
software [1,14].

The transient ambient temperature adapted in our study, has been mea-
sured for several years, collected and averaged [16]. It reflects evolution of
daily temperature in July in a subtropical climate.

The heat transfer coefficient on the outside walls was taken as $h =$
15 W/m^{2}K, for the free convection and thermal radiation of the surround-
ings. Solar irradiation on the walls has not been accounted for.

The processes in the room and over the storage plate at the ceiling, are
computed separately, thus sharing the plate temperature. For the compu-

tational procedure, the tray at the ceiling was divided by a vertical plane of symmetry between two end walls, or between two longitudinal fins. The space was defined as the computational two-dimensional domain.

Two wax layers were investigated: 3 mm thick, having end walls 4 mm high, and 12 mm thick, having end walls 16 mm high. The free space above the wax was occupied by air. For the description of the wax-air system, with a moving internal interface, and without interpenetration of the two media, a volume of fluid (VOF) [14] model was used. In the melting wax the enthalpy-porosity method was applied (Shatikian *et al.*, [14], Voller *et al.*, [15]): the liquid fraction in each cell was expressed by the porosity of that cell. Thus, in a solid zone the porosity was zero, while in a liquid zone it was equal unity. In the mushy zone at the liquid-solid interface, a mixture of solid and liquid was represented by their respective fractions. The full set of governing equations was presented by Shatikian *et al.* [14].

The computational grid varied with the height of the tray walls, and with the distance between fins along the tray. For a distance of 0.1 m between the fins, and 4 mm high walls, the grid consisted of 200×20 cells, for length and height respectively. The time step varied from 1×10^{-3} s up to 0.1 s. For fins 4 m apart, and 4 mm high walls of the tray, the grid consisted of 500×20 cells. The time step varied from 1×10^{-3} s up to 0.5 s. For fins 4 m apart, and 16 mm high walls, the grid consisted of 500×64 cells, for length and height respectively. The time step varied from 1×10^{-3} s up to 0.5 s.

The heat conducted across the plate is absorbed in the melting wax. The temperature of the three-dimensional plate is averaged over the surface, and as such is applied to the two-dimensional layer of wax. All the numerical calculations were performed using the Fluent 6.3 software.

3 Results and discussion

Our current study tests the process of temperature moderation in a building by change of phase at prescribed conditions, and also investigates, visually and parametrically the phenomena associated with that process.

Figure 1 shows schematically the concrete structure, and the finned plate at the ceiling. Figures 2(a) and 3(a) depict the daily varying temperatures, inside and outside the building, and the thermal phenomena taking place on a summer day in the defined structure, located at a mid-storey in a multistorey building. Heat transferred from the surroundings across the walls
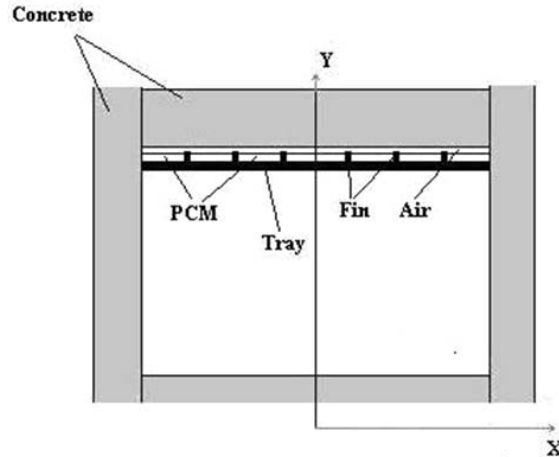
Figure 1. Schematic structure.

into the room is partly or mostly absorbed by the melting paraffin wax stored on an unfinned tray at the ceiling. The temperature is displayed for 12 hours, from 7:00 to 19:00. The ambient temperature varies from $23\,^{\circ}$C at 7:00, to $34\,^{\circ}$C at 13:00–14:00, and falls down to $27\,^{\circ}$C at 19:00. In both figures, the melt fraction is also presented. It is $f_m = 0$ at 7:00 in both cases. In the first case, where a 3 mm thick layer of solid wax is stored on the tray, the melting is completed at 15:00, $f_m = 1$. In the other case, the 12 mm thick layer melts in 12 hours to half of its thickness, $f_m = 0.5$. Thus, a 6 mm thick wax layer suffices for the entire day. The average wall temperature, in the first case, varies from $22\,^{\circ}$C in the morning, up to $28\,^{\circ}$C in the evening, due to heat accumulation. For the 12 mm thick layer the average wall temperature varies from $22\,^{\circ}$C to $27\,^{\circ}$C. The most relevant outcome for us is the temperature of air in the structure. In both cases it is $21.5\,^{\circ}$C at 7:00. For the 3 mm thick layer, the temperature rises from $23\,^{\circ}$C at 15:00, to $25\,^{\circ}$C at 16:00, and further to $27\,^{\circ}$C at 19:00. Thus, a solid layer so thin provides thermal comfort for 9 hours. For the 12 mm thick layer, the room temperature rises to $23.8\,^{\circ}$C at 19:00. At that time the melt fraction is only 0.5, meaning that a 6 mm layer may sustain thermal comfort in the room for 12 hours.

Figures 2(b) and 3(b) illustrate the temperature field at 19:00, at the plane of symmetry. In the first case, the wax liquefies already at 15:00. At that time, a distinct stratification of temperature is demonstrated. However, the range extends only over 0.25 $^{\circ}$C, which practically is negligible.

In the other case, segregated zones of temperature are apparent. The hot air accumulates at the walls, while in the central part of the room the temperature is 1 °C lower.

Figures 2(c) and 3(c) illustrate the air streamlines at the plane of symmetry at 19:00. In the first case the wax has melted earlier. The temperatures of the room and the inside wall are both 27 °C. Thus, the air is almost stagnant at that time. In the other case, melting is still on. A temperature difference of 1.2 °C is sustained between the room and the inside wall. Circulation of air is observed. In the center of the room, cooler air moves down, while warmer air rises up at the walls. In both cases the amount of paraffin wax is decisive with regard to all aspects of thermal comfort in the room.

Thermal comfort for humans in a subtropical climate is estimated within the range of 23–25 °C. To provide those conditions, the wax has to melt at a lower temperature. However, in commercial paraffins a mushy zone of several degrees extends between the melting and solidification points. In pure materials the change of phase is isothermal. Were the current study concerned with the design of a specific case, a commercial paraffin wax had to be used. If for example the melting point of the wax is chosen at 21 °C, then the solidification would be expected mostly at 18–19 °C. In the present case, where the feasibility is tested, a mushy zone of 0.2 °C was arbitrarily prescribed.

Along with the assessment of temperature moderation in the chosen structure, the investigation proceeds also into the analysis of the related physical phenomena. The visualization of melting in Figs. 4 and 5 shows the thinning of the solid layer, the change of its shape, the formation of melt at the plate, the settling and collapse of the solid. It illustrates the melting of a 3 and a 12 mm layers of wax over a finned plate. The fins are 4 m (a), and 0.1 m (b) apart. As shown in those figures, an open passage is formed at the fin surface (left), across which liquid moves up, enveloping the solid layer. The shorter distance between the fins (b) enhances the rate of melting and settling of the solid. It is indeed obvious, that in case (a) there is one fin and two end walls on the tray, which expose surfaces at temperatures above the melting point of the solid. In case (b) there are 79 fins dividing the 8 m wide tray. On each fin there are two open passages formed. The solid melting and settling are accelerated in comparison to case (a). The visualization demonstrates the physical phenomena which dominate the process. That insight has been achieved due to the enthalpy-porosity
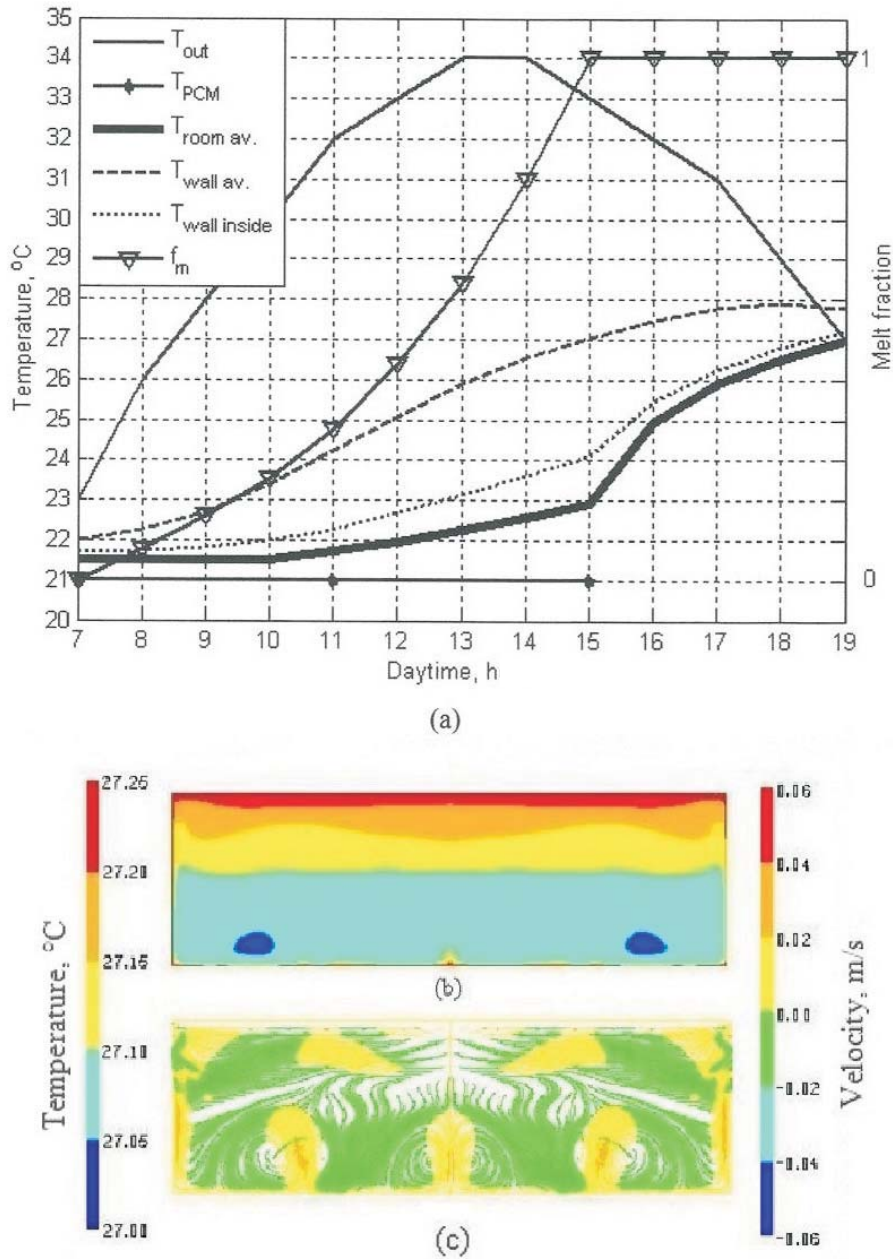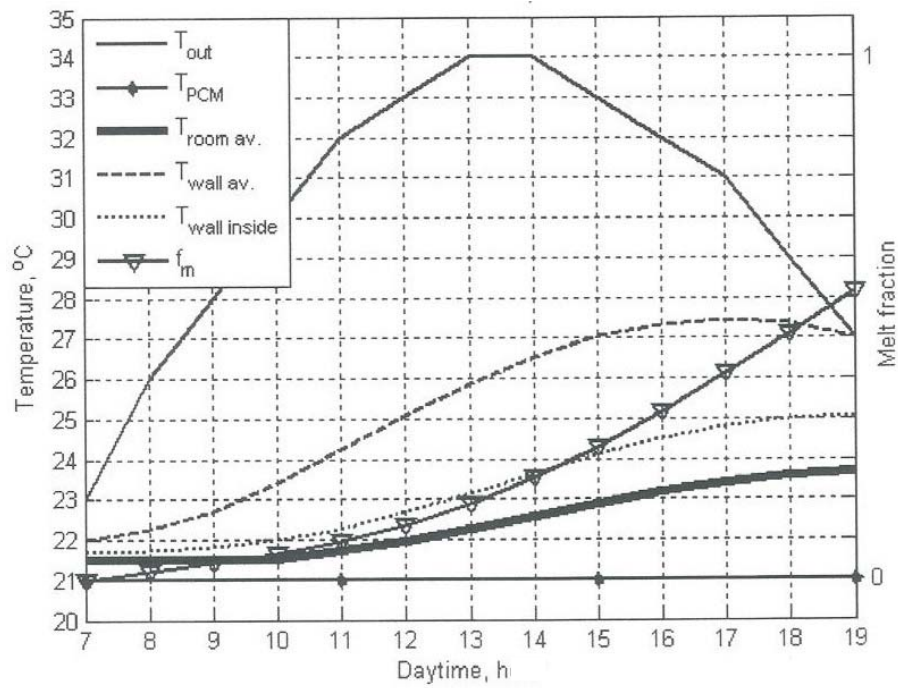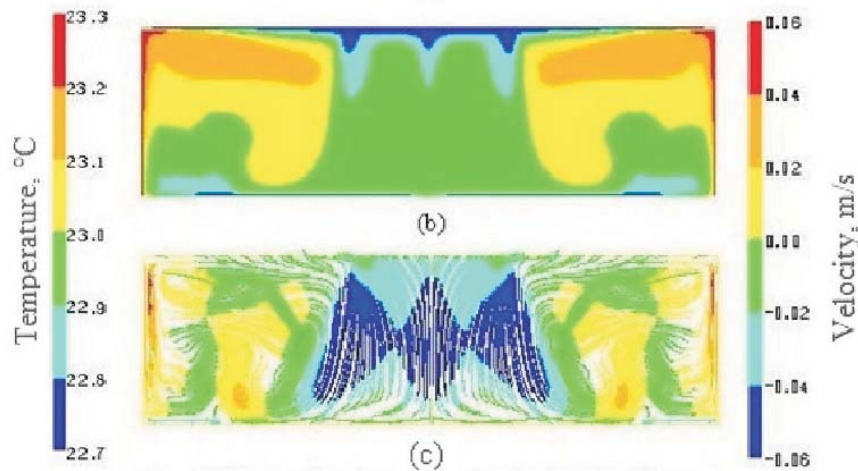
Figure 2. Wax layer, 3 mm thick: (a) temperature and melt fraction variation along the day, (b) temperature field at the plane of symmetry at 19:00, (c) air streamlines at the plane of symmetry at 19:00.

Figure 3. Wax layer, 12 mm thick: (a) temperature and melt fraction variation along the day, (b) temperature field at the plane of symmetry at 19:00, (c) air streamlines at the plane of symmetry at 19:00.

numerical model [14,15], even if the mushy zone is arbitrarily limited. In
other studies the mushy zone was eliminated by adapting the effective heat
capacity (EHC) method which has considerably simplified the numerical
procedure [1]. However, the EHC method does not reflect all the physical
phenomena which accompany phase change, like convective motion of the
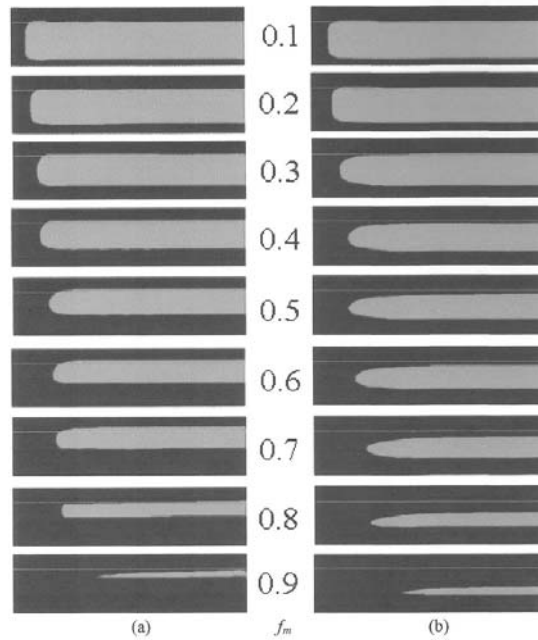liquid phase, or the solid settling in the melt, as indeed observed in Figs. 4
and 5.

Figure 4. Solid (bright) and melt (dark) wax on a finned plate, 3 mm thick wax layer:
(a) fins 4 m apart, (b) fins 0.1 m apart.

In Figs. 6-8 the above described effects are quantified. The three figures
show how the melt layer between the plate and the solid changes in height
versus. the melt fraction, being affected by fin spacing, thickness of solid
layer, and plate temperature. The settling and nonsettling solid layers are
analyzed. The nonsettling layer touches the plate at $f_m = 0$. As melting
proceeds, the solid interface moves up. As the melt approaches $f_m = 1$, the
remaining solid interface approaches the height of the final melt, $x_l = b_l$,
floating on its top. Figure 6 illustrates the effect of fin spacing, for a 3 mm
thick layer of wax, and plate temperature of 22 ºC. For fins 1–4 m apart, the
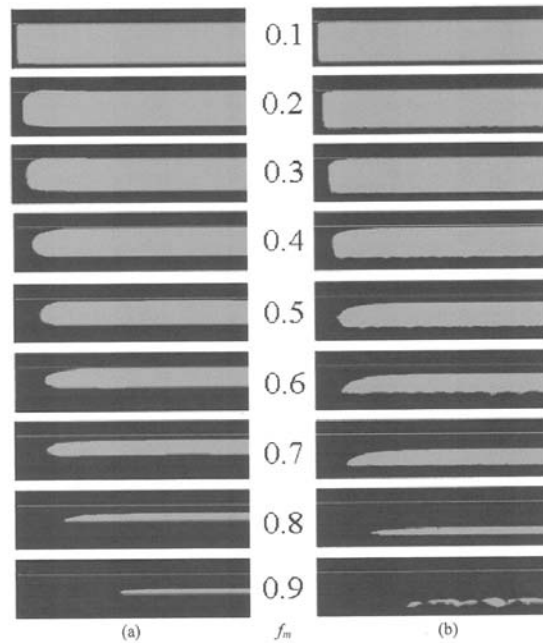melt layer, x_l – solid layer thickness, rises with the melt fraction. As the fin

Figure 5. Solid (bright) and melt (dark) wax on a finned plate, 12 mm thick wax layer:
(a) fins 4 m apart, (b) fins 0.1 m apart.

spacing is reduced from 0.5 to 0.1 m at $f_m = 0.7-0.9$, the melt layer on the plate thins down due to the enhanced convection across the open passages at fin surfaces. Figure 7 shows the effect of solid layer thickness, b_s, upon the melt height, x_l, versus f_m. The case is examined for fins 0.5 m apart, and plate temperature of $22\,°C$. It may be observed that the thicker the initial solid layer, the more pronounced its settling in the melt. The same effect has been clearly seen in Figs. 4 and 5. Figure 8 illustrates the effect of plate temperature on the growing melt layer vs. melt fraction. At plate temperatures of 22, 23, and $25\,°C$ the same performance is observed, up to a melt fraction of 0.4. At higher melt fractions, the melt height grows with the plate temperature. This phenomenon is due to the faster melting at higher temperatures, and the relatively slow settling rate of the remaining solid.

In Figs. 6-8 the height of the melt actually expresses the thermal resistance to heat transfer from the plate to the melting solid layer. In each case aforementioned, the solid fraction $(1 - f_m)$ represents the remaining stored capacity of the wax layer to absorb heat from the structure. The insight
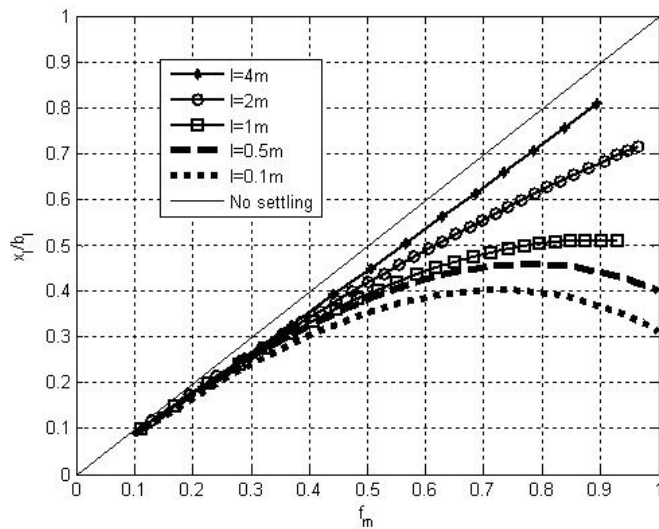
Figure 6. Effect of fins on melt height vs. melt fraction: 3 mm, wax layer thickness, plate temperature 22 °C.
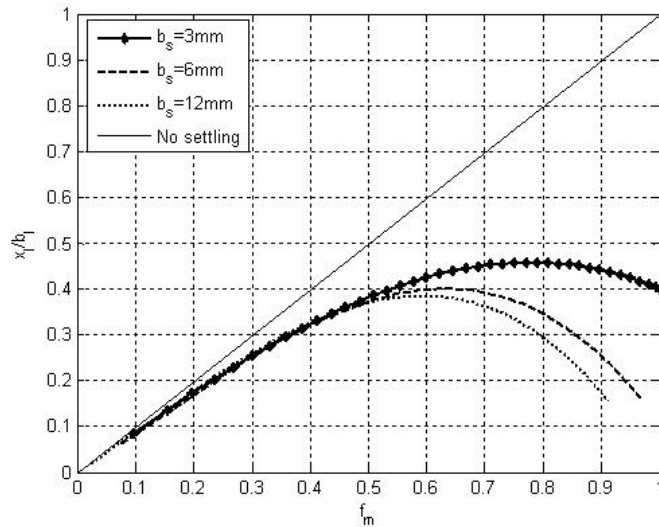

Figure 7. Effect of wax layer thickness on melt height vs. melt fraction: plate temperature 22 °C, fins 0.5 m apart.
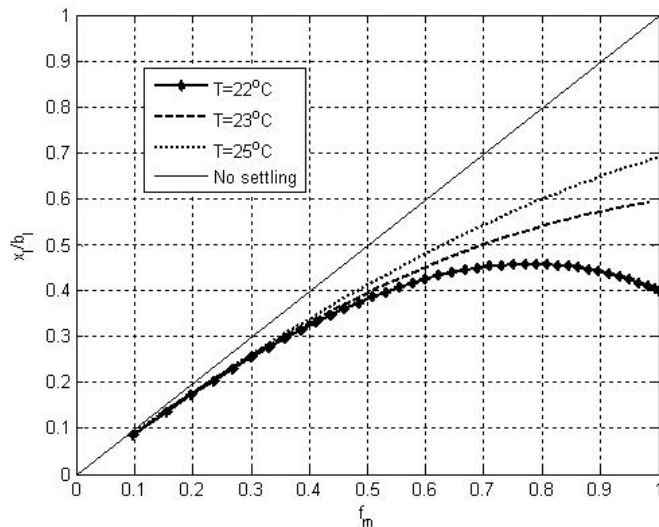
Figure 8. Effect of plate temperature on melt height vs. melt fraction: 3 mm thick wax
layer, fins 0.5 m apart.

into those phenomena may guide the researcher and designer to construct
efficient, thermally comfortable systems, which may also reduce energy de-
mands at hours of high thermal loads.

Our choice of a structure cooled from the ceiling by melting wax has
practical applications, although in each case the specifics have to be an-
alyzed. Our structure has been examined as a vacant apartment, not in-
habited, having no ports or windows. The real structure may have walls
thicker or thinner, may be insulated inside or outside. The walls may be
exposed to asymmetrical solar irradiation. The floor and ceiling could have
low thermal conductivity, but may be not necessarily adiabatic, as defined
in this study. The phase change material has to be commercially available,
having a mushy zone of several degrees. The night solidification could be
achieved in several ways imposed by the locally available means. It may be
air flowing over the melt, or water flowing in pipes installed within the melt.
All those variables may be computed for an optimal design of a thermally
comfortable building, adjusted to its local conditions.

4   Conclusions

Thermal comfort in a structure, at the presently prescribed conditions, is achievable on a summer day via the use of a phase-change material. Paraffin wax, stored over a conducting plate at the ceiling of the structure, absorbs by melting the heat transferred across the walls of the structure. At our prescribed conditions, a solid layer of paraffin wax, 3 mm thick, furnishes thermal comfort for most of the day. A 6 mm thick layer suffices for the entire day. Fins on the storage plate enhance the rate of melting of the phase-change material by opening passages at the fin surfaces for the melt to move up across the solid layer. Visualization of the melting displays the motion and shape of the solid wax. The position of the solid interface shows the effects of fin spacing, solid layer thickness and plate temperature on the process.

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