Research Article

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Effect of convection heat transfer on thermal energy storage unit

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Abstract: Latent heat storage represents a promising technique to achieve net zero energy buildings. This work investigates the behaviour of phase change material (PCM) inside a rectangular enclosure, which represents the geometry of a latent heat storage system. The left side of the unit is exposed to a constant temperature (T_h), while the other three walls are exposed to convection heat transfer boundary condition [$h = 5, 10$, and $15 \text{ W/(m}^2 \text{ K)}$] and different ambient temperatures ($T_\infty = 297^\circ$ and 307°K). The ambient temperatures were selected to be at/above the melting temperature of the studied PCM (coconut oil). To study the melting process of the PCM, the continuity, Navier-Stokes and energy equation were used. The Navier-Stokes equations were modified using the Carman-Kozeny relation. The finite element method was utilized to produce numerical results. The results are presented in terms of flow and thermal fields, Nusselt number (Nu), and the melt fraction (MF) of the PCM. The results show that, when $T_\infty = T_m$, the melting rate of the PCM slows down with increasing the convection heat transfer coefficient. While the melting rate accelerates with increasing the convection heat transfer coefficient when $T_\infty > T_m$.

Keywords: PCM, convection, Carman-Kozeny, melting process, Nusselt number

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Nomenclature

$A(T)$ Parameter is defined in Eq. (6)

$B(T)$ Parameter is defined in Eq. (7)

C Arbitrary constant in Eq. (6)

c_p Specific heat at constant pressure (J/(kg K))

D Melting interface position from the left wall (m)

$D(T)$ Gaussian function

g Gravitational acceleration (m/s^2)

h Convection heat transfer ($\text{W/(m}^2 \text{ K)}$)

h_f Latent heat of fusion (J/kg)

k Thermal conductivity (W/(m K))

L Enclosure height (m)

MF Melt fraction

Nu Average Nusselt number

p Pressure (Pa)

q Arbitrary constant in Eq. (6)

T Temperature (K)

ΔT Range of melt temperature of the PCM (K)

t Time (s)

u Velocity component of the liquid PCM in the x -direction (m/s)

v Velocity component of the liquid PCM in the y -direction (m/s)

x Horizontal coordinate (m)

y Vertical coordinate (m)

Greek symbols

β Coefficient of volumetric thermal expansion ($1/\text{K}$)

μ Dynamical viscosity (Pa s)

ρ Density (kg/m^3)

∞ Ambient

Subscripts

h Hot

l Liquid

m Melting
s Solid

1 Introduction

Conventional energy resources are currently diminishing because of a growing need for energy. For instance, substantial amounts of energy are required just for heating purposes. According to Natural Resources Canada, 63 % of the energy supply is used to heat spaces and 19% to heat water [1]. Additionally, it is these same CO₂-emitting sources that are considered by many to be the main reason behind global warming. As a result, scientists are zealously working on ways to reduce dependency on these resources by searching for cleaner, renewable sources of energy.

Most alternate sources of energy will require some form of thermal energy storage. Latent heat storage represents a promising technique to achieve net zero energy buildings [2].

Joulin *et al.* [3] numerically studied the thermal behavior of PCM installed within solar passive walls. The study included 1-D and 2-D analyses for different aspect ratios. The vertical walls were differentially heated, and the horizontal walls were insulated. The authors reported that conduction dominates in the early stage of melting process then convection takes a growing role throughout the melting process.

Mbaye and Bilgen [4] performed a numerical study to investigate the impact of heat flux and the aspect ratio of the enclosure on the melting process of PCM. The vertical walls of the enclosure were subjected to constant heat flux and constant temperature. The authors found that the ratio of the heat flux entering and leaving the enclosure is not impacted by the aspect ratio at the beginning of the melting process; as melting continues the heat flux ratio increases with an increasing aspect ratio. Also, they found that the melting process accelerates as the aspect ratio decreases.

The melting of PCM inside a tall enclosure, that was subjected to constant heat flux at one vertical side, was numerically and experimentally studied by Pala and Joshi [5]. The authors found that at the beginning of the melting process, conduction dominates; after that, convection plays a significant role in the melting process. At the final stage of the melting process, sensible heating plays a role in the thermal storage and increases the temperature of the PCM.

Alawadhi [6] numerically investigated the impact of PCM on reducing heat gain. The PCM-filled cylinders were

fixed inside a roof. The PCM type, quantity, and location inside a brick were studied. Convection boundary condition above and below the roof was applied. The authors found that using and locating the PCM in the center of the brick dramatically reduces the heat gain.

The main aim of this article is to study the effect of convection heat transfer conditions on the melting of PCM. The PCM fills a square enclosure. The left wall of the enclosure is isothermally heated, while the top, right, and bottom walls are exposed to convection boundary condition.

2 Physical and mathematical models

The energy storage system can be approximated by a 2-D enclosure. A schematic diagram of the enclosure system is shown in Figure 1. Initially, the solid form of the PCM occupies the enclosure. The initial temperature of the PCM is assumed to be equal to its melting temperature. The left vertical wall of the enclosure is maintained at constant temperature (T_h) which is above the melting temperature (T_m) of the PCM. The remaining three walls are applied to convection boundary condition. The following assumptions are applied: the liquid phase of PCM is a Newtonian and incompressible fluid, all thermophysical properties of the PCM are assumed to be constant, the Boussinesq model is used in the buoyancy force term. In addition, in the energy equations, the internal heat generation and the viscous dissipation effect are neglected, and laminar fluid motion is assumed.

Figure 1: Schematic illustration of (a) the thermal storage system, (b) the physical model of the thermal storage unit

Conservation equations of mass (continuity), momentum, and energy (in the liquid and solid regions) are used to model the complete flow and thermal fields as shown below [3, 7].

$$\frac{\partial \rho_l}{\partial t} + \frac{\partial (\rho_l u)}{\partial x} + \frac{\partial (\rho_l v)}{\partial y} = 0 \quad (1)$$

$$\begin{aligned} \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \\ = \frac{1}{\rho_l} \left[-\frac{\partial p}{\partial x} + \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) - A(T)u \right] \end{aligned} \quad (2)$$

$$\begin{aligned} \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} \\ = \frac{1}{\rho_l} \left[-\frac{\partial p}{\partial y} + \mu \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) + g(\rho\beta)(T - T_m) - A(T)v \right] \end{aligned} \quad (3)$$

$$\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \frac{k_l}{(\rho c_p)_l} \left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right] \quad (4)$$

$$\frac{\partial T}{\partial t} = \frac{k_s}{(\rho c_p)_s} \left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right]. \quad (5)$$

In the above equations, ρ_l is the density of the liquid PCM, t is the time, u and v are the velocity components of the liquid PCM in the x and y -directions, p is the pressure, μ is the dynamic viscosity of PCM, g is the gravity, β is the coefficient of thermal expansion of the liquid PCM, T is the temperature, T_m is the melting temperature of the PCM, k_l is the thermal conductivity of the liquid PCM, c_{p_l} is the specific heat at constant pressure of the liquid PCM, k_s is the thermal conductivity of the solid PCM, ρ_s is the density of the solid PCM, and c_{p_s} is the specific heat at constant pressure of the solid PCM.

In the momentum equations Eqs. (2) and (3), Kozeny-Carman relation is used to model the flow within the interface. The parameter $A(T)$ in Eqs. (2) and (3) is defined to achieve a gradual reduction of the velocities of the liquid PCM from a finite value in the liquid zone to zero in the solid zone. To implement Kozeny-Carman relation, parameter $A(T)$ is defined as [8]

$$A(T) = \frac{C(1 - B(T))^2}{(B(T)^3 + q)} \quad (6)$$

where C and q are arbitrary constants of value of 10^5 and 10^{-3} , respectively. $B(T)$ can be defined as [8]

$$B(T) = \begin{cases} 0, & T < (T_m - \Delta T) \\ \frac{T - T_m + \Delta T}{2\Delta T}, & (T_m - \Delta T) < T < (T_m + \Delta T) \\ 1, & T > (T_m + \Delta T) \end{cases} \quad (7)$$

where ΔT is the range of temperatures over which the melting process occurs. If the PCM is a pure material, ΔT is zero, and the mushy zone is thin. On the other hand, if the PCM is an impure material, ΔT is greater than zero, and the mushy zone is wider than that for pure material.

$B(T)$ is zero when the temperature is lower than T_m , while it is one when the temperature is higher than T_m . Equations (6) and (7) can be used to calculate the thermo-physical properties of the PCM, as follows [8]

$$\rho(T) = \rho_s + (\rho_l - \rho_s)B(T) \quad (8)$$

$$k(T) = k_s + (k_l - k_s)B(T) \quad (9)$$

$$c_p(T) = c_{p_s} + (c_{p_l} - c_{p_s})B(T) + h_f D(T) \quad (10)$$

$$\mu(T) = \mu_l(1 + A(T)). \quad (11)$$

s and l stand for the solid and liquid phases of the PCM, respectively, and h_f is the latent heat of fusion of the PCM. $D(T)$, which is a Gaussian function, is used to determine the latent heat over a temperature range ΔT . $D(T)$ can be calculated from [8]

$$D(T) = \frac{e^{-\frac{T(T-T_m)^2}{\Delta T^2}}}{\sqrt{\pi\Delta T^2}} \quad (12)$$

The boundary and initial conditions of the thermal storage unit can be written as:

lower horizontal wall : (13)

$$-k \frac{\partial T(x, 0, t)}{\partial y} = h(T(x, 0, t) - T_\infty), u = v = 0,$$

upper horizontal wall,

$$-k \frac{\partial T(x, L, t)}{\partial y} = h(T(x, L, t) - T_\infty), u = v = 0,$$

right wall :

$$-k \frac{\partial T(x, L, t)}{\partial y} = h(T(L, y, t) - T_\infty), u = v = 0,$$

left wall :

$$T(0, y, t) = T_h, u = v = 0,$$

interface condition : $T(D, y, t) = T_m$,

$$\rho h_f \frac{\partial D}{\partial t} = -k \left(\frac{\partial T(D, y, t)}{\partial x} - \frac{\partial D}{\partial y} \frac{\partial T(D, y, t)}{\partial y} \right),$$

initial condition :

$$T(x, y, 0) = T_m, u = v = 0.$$

where h is the convection heat transfer coefficient, T_∞ is the ambient temperature, L is the height of the unit, and D is the position of the melting interface starting from the left wall.

The averaged Nusselt number is calculated from [9]

$$Nu = \frac{1}{\Delta T} \int_0^L -\frac{\partial T}{\partial x} \bigg|_{x=0} dy \quad (14)$$

3 Numerical procedure

The governing equations, Eqs. (1-5), with the boundary and initial conditions are numerically solved using the finite element method. For this purpose, a numerical scheme was built using the commercial software COMSOL 4.3b. To avoid the results dependency on the mesh size, a careful examination is conducted. Four element sizes were tested, 2522 (fine), 6580 (finer), 16986 (extra fine), and 26544 (extremely fine) elements, as shown in Figure 2. The independency test is conducted for the case at $h = 10 \text{ W/(m}^2 \text{ K)}$ and $T_\infty = 297^\circ \text{K}$. Insignificant differences are observed among the four cases. However, for the lower numbered elements, 2522, the solution witnesses a slight fluctuation. The two higher numbered cases, 16986 and 26544, consume more time to complete the solution. As a result, the finer meshing of 6580-elements is selected in the present work. The proposed discretization numerical scheme consists of 5964 triangular elements and 616 quadrilateral elements. The time step is 10 s. The simulation is aborted when the relative tolerance is smaller than 10^{-3} for the continuity, momentum, and energy equations.

Figure 2: The mesh independency test at $h = 10 \text{ W/(m}^2 \text{ K)}$ and $T_\infty = 307^\circ \text{K}$

4 Results and discussion

In the present work, a numerical study was conducted to investigate the impact of convection heat transfer condition on the melting process of PCM. Individually, the impact of the convection heat transfer coefficient and ambient temperature were investigated. Carman-Kozeny relation was used to simulate the liquid-solid interface. Coconut oil was chosen as the PCM because its melting temperature is close to the comfortable temperature range of occupied spaces, in air conditioning sector, of $293.5^\circ - 296.5^\circ \text{K}$ ($20.5^\circ - 23.5^\circ \text{C}$) [10]. The thermophysical properties of coconut oil are listed in Table 1.

Table 1: Thermophysical properties of coconut oil

Properties (units)	Coconut oil	
	Solid	Liquid
$\rho \text{ (kg/m}^3\text{)}$	920	918
$\mu \text{ (Pa s)}$	-	0.0268
$c_p \text{ (K/(kg K))}$	3.750	1.670
$k \text{ (W/(m K))}$	0.166	0.166
$\beta \text{ (1/K)}$	0.7×10^{-3}	
$h_f \text{ (J/kg)}$	103.000	
$T_m \text{ (K)}$	297	

A validation was performed to confirm the capability of the built model. The present model was validated by comparing the liquid-solid interface evolution gained from this model with the experimental results of Gau and Viskanta [11]. As shown in Figure 3, a good agreement

Figure 3: Comparison of interface position during melting of gallium between Gau and Viskanta [11] and the present study

Figure 4: Flow (arrows) and thermal fields (contours) for different convection heat transfer coefficient ($h = 5, 10$, and $15 \text{ W}/(\text{m}^2 \text{K})$) at 1500 s (a) $T_\infty = 297^\circ \text{K}$, (b) $T_\infty (= 307^\circ \text{K}) > T_m$

was achieved. The insignificant discrepancies may have resulted from the theoretical assumptions.

Figure 4 shows the effect of the convection heat transfer coefficient on the flow and thermal fields at 1500 s , when $T_\infty = T_m = 297^\circ \text{K}$, Figure 4(a), and $T_\infty > T_m = 307^\circ \text{K}$, Figure 4(b). The studied convection heat transfer coefficients were [$h = 5, 10$, and $15 \text{ W}/(\text{m}^2 \text{K})$]. The arrows in Figure 4 represent the flow field, and the counters represent the thermal field where the blue region is the solid PCM and the colored region is the liquid PCM. As the PCM that is adjacent to the hot walls heats up and melts, it

becomes lighter due to low density. The relatively low-density melted PCM rises along the hot wall assisted by the buoyancy force, then it heads right. The impermeability of the upper wall forces the melted PCM to move to the liquid-solid interface, convecting the thermal energy with it. As the warm melted PCM hits the cold liquid-solid interface, it transfers thermal energy to the solid PCM. As a result, the liquid PCM becomes less warm, and its density increases. The increment in the PCM density drives the melted PCM down along the liquid-solid interface. While flowing along the liquid-solid interface, the melted PCM

keeps transferring the thermal energy to the liquid-solid interface [12]. However, the amount of transferred thermal energy to the liquid-solid interface from the melted PCM decreases along the liquid-solid interface. The non-uniform heat transferred results in a higher amount of melted PCM in the top of the unit. The value of convection heat transfer coefficient and the ambient temperature play a significant role on the rate of the melting process and the shape of the solid PCM throughout the melting process. For the same h , when $T_\infty = 297^\circ\text{K}$ ($= T_m$), Figure 4(a), the melting process solely starts from the left wall. However, when $T_\infty = 307^\circ\text{K}$ ($> T_m$), Figure 4(b), the melting process occurs starting from the left, top, and right walls. Although the unit was also exposed to ambient temperature from the bottom, insignificant effects result from exposing the bottom wall. The high temperatures of the side and top walls assist in initiating the melting of the PCM from the top and the right walls besides the melting due to heating from the left wall. With changing h , the rate of melting of the PCM differs according to T_∞ . When T_∞ equals T_m , the rate of dissipating heat from the unit to the ambient increases with increasing h . As a result, the melting rate decreases with increasing h , as shown in Figure 4(a). The left wall of the unit is heated at a temperature that is higher than the melting temperature of the PCM. When the PCM melts, the melted PCM temperature becomes higher than the melting temperature. In the case when T_∞ equals T_m , a heat loss occurs from the hot melted PCM to the ambient. The heat loss is increased by increasing h , which subsequently deaccelerates the melting rate. Figure 4(b) shows the acceleration in the melting process when increasing h under the condition of T_∞ is higher than T_m . In this case, the rate of heating the PCM from the ambient increases due to increasing h . When the ambient temperature T_∞ is higher than T_m , the ambient becomes a heat source to melt the solid PCM. As T_∞ is higher, the melting becomes faster [13]. In addition, as h increases, the heat transfers faster from the ambient to the unit, and subsequently the PCM melts faster.

The effect of convection heat transfer coefficient h and the ambient temperature T_m on Nu , along the left wall of the unit, is shown in Figure 5. As soon as the melting starts, a thin layer of liquid PCM is formed, and conduction becomes the dominant heat transfer mode. Conduction is dominant in this stage of the melting process because the viscous force overcomes the buoyancy force due to the scant liquid PCM layer [14]. In this stage, the heat transfer decreases with time due to increasing the temperature of the vicinity liquid along the left wall. Then Nu arises when the liquid PCM layer becomes wider, and the viscous force decreases while the buoyancy force increases. As heating

progresses, the temperature of the liquid PCM increases leading to a drop in the convection heat transfer rate, and as a result Nu reduces. Figure 5 shows that at the beginning of the melting process, both h and T_∞ have an insignificant effect on Nu . After that, there is a positive effect of increasing h on improving Nu for both T_∞ values. A similar improvement in Nu is obtained with increasing T_∞ for all the studied values of h .

Figure 5: Effect of convection heat transfer coefficient and ambient temperature on Nu

Figure 6 shows the effect of the convection heat transfer coefficient h and the ambient temperature T_∞ on the

Figure 6: Effect of convection heat transfer coefficient and ambient temperature on the melt fraction of the PCM

melt fraction of the PCM, MF . The PCM melts faster at the early stages of the melting process because of the high temperature difference between the hot walls and the melted PCM adjacent to the hot walls [15]. However, the melting rate decreases with time as the liquid PCM temperature increases which reduces the heat transfer rate to the unit. When T_∞ equals T_m , reducing h assists the PCM to melt faster. Where by reducing h , the heat losses from the unit decreases. While increasing h , in the case of T_∞ is higher than T_m , the heat transfer rate to the unit increases. As a result, the melting rate increases.

5 Conclusions

A numerical study was performed to investigate the behavior of the melting process under convection heat transfer condition. Besides the governing equations of the fluid flow and energy, Carman-Kozeny relation was applied to simulate the liquid-solid interface. COMSOL 4.3b software, which is based on finite element method, was used to build the numerical model of the present study. It can be concluded that the melting rate increases with increasing h when T_∞ is higher than T_m . In this case, the unit is exposed to a higher heating rate. When T_∞ equals T_m , increasing h leads to increasing the heat loss from the unit. As a result, the melting rate of the PCM decreases.

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