Journal of Mechanical Engineering and Sciences
ISSN (Print): 2289-4659; e-ISSN: 2231-8380
Volume 13, Issue 3, pp. 5653-5664, September 2019

DOI: https://doi.org/10.15282/jmes.13.3.2019.27.0453

Latent heat storage for hot beverages

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ABSTRACT

Latent heat storage has shown a great potential in many engineering applications. In food industry, latent heat concept has been applied in food storage. One of its potential applications is to maintain hot beverages at a reasonable drinking temperature, i.e. 50-60 °C, for longer periods. In the present work, a numerical study was performed to investigate the impact of utilizing encapsulated phase change material PCM on the temperature of a hot beverage. To describe the phase change process, the Darcy's law damping term was integrated in the conservation of momentum equation that was applied for the PCM. Finite element method was used to solve the governing equations. The phase change material (PCM) was encapsulated in five rings which were immersed in a hot beverage filled a cup. As a PCM, Beeswax was used. As a beverage, coffee was used. The rings that contained the PCM were made of food grade stainless steel. The results showed that the encapsulated PCM maintained the hot beverage temperature at uniform and acceptable drinking temperature for a rational time. In the absence the PCM, the coffee dropped below 50°C within 1500 sec. While, in the presence of the PCM, it took 3120 sec to drop below 50°C.

Keywords: Latent heat; encapsulated PCM; hot beverages; food industry.

INTRODUCTION

The food industry is an important and large sector. Food storage maintains food for long periods under controlled and safe conditions to ensure the safety of the food. In hot and cold beverages sector, the temperature of the served drink is a key issue. The hot beverage undergoes three phases. The first phase starts after pouring the hot beverage into its container. At this phase, the beverage is very hot to be drunk since the water was boiling. The second phase starts when the beverage slowly cools down. In the second phase, the beverage reaches a desirable drinking temperature range. As the beverage keeps cooling down toward ambient temperature, the third phase starts. By reaching the third phase, the beverage is considered lukewarm. Many ideas have been applied to maintain the beverage at or around an acceptable drinking temperature for a longer time such vacuum thermos. The concept of using phase change materials PCMs has been widely used as a thermal storage in many applications [1–5] such as food industry [6] solar cooker [7,8] buildings [9,10], heating water [11], electronic cooling [12,13], power generation [14]. Due to its economic importance in industry, the research efforts on using PCM in food industry have been mostly focused on patent research. However, many published studies investigated the impact of integrating PCM in food storage system especially in terms of cooling and freezing. In terms of cooling, Gin and Farid [6] found that the temperature fluctuating of the frozen space was decreased when a PCM was used. In addition, the quality of the studied food, i.e. meat and ice cream, was better when the PCM was used. Also, Floros and Narine[15] found that using a PCM, i.e. diester, decreased the temperature of water from 85 ℃ to 60 ℃ within one minute and maintained the water temperature within a desirable temperature range for a longer time. In terms of heating, Rudy et al. [16] experimentally investigated using PCM in space heating through horizontal, vertical and inclined fin tube baseboard convector. The authors found that the horizontal orientation was associated with highest heat stored; while the highest heat released was associated with the vertical orientation. Lora [17] studied the impact of integrating PCM in the interior walls of a mug. It was found that by integrating the PCM, a desirable drinking temperature, i.e. 50-60 °C, was maintained 50% longer compared to without-PCM case.

The present study introduces a novel design of implementing latent heat storage in hot beverage cup. Usually, the PCM is integrated inside the walls of a container. In this study, the PCM is encapsulated in five rings emerged in a hot beverage.

MATHEMATICAL MODEL

The present problem is a 3-D truncated cone which represents a cup filled with coffee. Inside the cup there are five rings that contain a PCM. The five rings are connected with each other by a rod to maintain the distance between the rings and to be fixed in the centre of the cup. The rings and the rod are made of food grade stainless steel. Figure 1 shows the physical domain, the coordinate system, and the geometrical parameters of the present problem. The cup has the following dimensions: the top surface radius R_c= 0.04 m, the bottom surface radius r_c= 0.03 m, and the cup height H_c= 0.09 m. Each ring has the following dimensions: the tube radius r_t= 0.003 m, the ring inner radius r_{ri}= 0.012 m, and the ring outer radius r_{ro}= 0.018 m. Both the sidewall and the upper surfaces of the cup are exposed to air. The bottom surface is isothermally insulated.

As a hot beverage, coffee is selected; and as a PCM, beeswax is selected. The thermophysical properties of coffee and beeswax are tabulated in Table 1. The beeswax is selected for its non-toxic nature. If any leakage accidently happens from the rings to the coffee, it is a safe to have the beeswax. Initially, the coffee is assumed to be at 80 °C, while the beeswax is assumed to be at 20 °C ($< T_m$). Since the melting temperature of the beeswax is 62 °C, then the beeswax initially is solid. The present numerical problem is based on the following assumptions:

- The beverage and the PCM are two different domains. The phase change behaviour of the PCM requires using especial term, the Darcy's law damping term, in the conservation of momentum equation. The Darcy's law damping term models the flow within the interface. By using this term, the velocities of the liquid PCM gradually increase from zero in the solid phase to finite values in the liquid phase.
- The beverage and the PCM are incompressible and Newtonian [18].
- The beverage and the PCM flows are transient and laminar.
- Radiative and viscous dissipation are neglected.
- Boussinesq approximation is considered for both the beverage and the PCM.
- No-slip condition is considered at all surfaces.
- The water thermophysical properties are considered for coffee in the present study.
- The thermophysical properties for both the beverage and the PCM are independent of temperature.
- The PCM is considered a homogeneous and isotropic.
- The evaporation from the beverage is ignored.

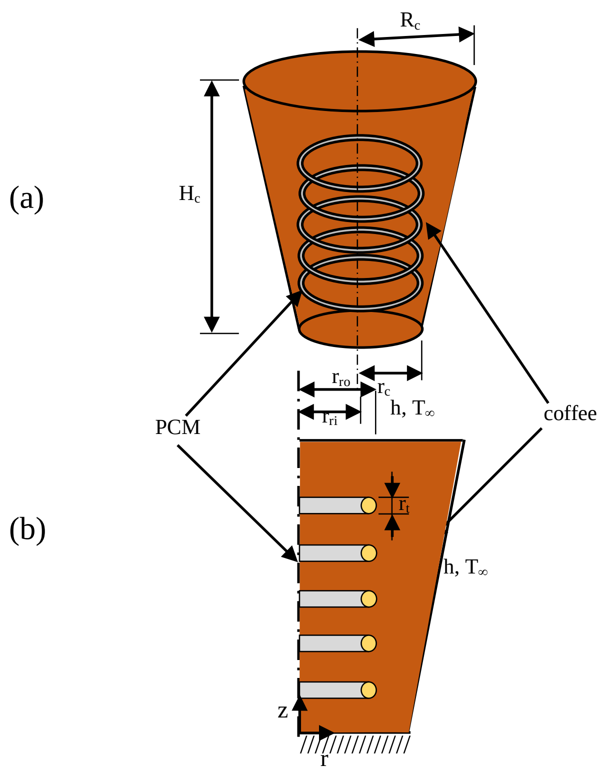

Figure 1. Schematic of (a) cup of coffee and encapsulated PCM, (b) a 2-D axisymmetric computational domain.

Table 1. Thermophysical properties of coffee and beeswax.

Thermophysical Property	Coffee [19]	Beeswax [20,21]	
		Solid	liquid
Melting temperature, T_m (°C)	----	62	
Density, ρ (kg/m^3)	988.1	827	869
Thermal conductivity, k (W/m K)	0.644	0.284	0.329
Specific heat, c_p (J/kg K)	4181.0	2.205×10^3	0.344×10^3
Dynamic viscosity, μ (kg/m s)	5.47×10^{-4}	----	2.59×10^{-4}
Latent heat of fusion, h_{sf} (kJ/kg)	----	177	
Thermal expansion coefficient, β (1/K) [12]	3.1×10^{-3}	3.44×10^{-4}	

The governing equations that describe the present problem are conservation of mass, momentum, and energy. The governing equations could be written based on the aforementioned assumptions as [10,22].

$$\frac{D\rho}{Dt} = 0 \tag{1}$$

$$\rho\frac{DV}{Dt} = -\nabla p + \mu\nabla^2 V + \rho g\,\beta(T - T_{ref}) + S \tag{2}$$

$$\rho\, c_p\left(V\frac{DT}{Dt}\right) = k\,\nabla^2 T \tag{3}$$

where ρ; is the density, t is time, V is the velocity, p is the pressure, μ is the dynamics viscosity, g is the gravitational acceleration, β is the thermal expansion coefficient, T is temperature, S is the Darcy's law damping term which is defined in Equation 4, c_p is the specific heat, and k is the thermal conductivity. The term S in Equation 2 is solely devoted to solving the phase change problem, and it can be defined as [23].

$$S = \frac{C\,(1-f)^2}{f^3}V \tag{4}$$

where c; is the mushy zone constant (10^5 kg/ m^3 s), f is the melt fraction which can be defined for isothermal phase change as [23]

$$f = \begin{cases} 0 & if\;\; T < T_s \quad \text{solid phase} \\ \frac{T-T_s}{T_l-T_s} & if\;\; T_s \le T \le T_l \quad \text{mushy zone} \\ 1 & if\;\; T > T_l \quad \text{liquid phase} \end{cases} \tag{5}$$

To express the conversion of energy for a PCM that has constant thermophysical properties, Equation 6 is considered [23]

$$\frac{DH}{Dt} = k\nabla^2 T \tag{6}$$

H represents the total enthalpy. The total enthalpy represents the summation of the PCM sensible and latent heats [23]

$$H = h_s + f\ h_{sf} \tag{7}$$

where h_s; is the sensible enthalpy, and h_{sf} is the latent heat of fusion.

The sensible enthalpy can be defined as [23]

$$h_s = h_{ref} + \int_{T_{ref}}^{T} c_p \tag{8}$$

To solve the governing equations of the present problem, the following boundary and initial conditions are considered

$$\begin{aligned}
&\text{bottom surface: } -k\frac{\partial T(r,0,t)}{\partial z} = 0, u = v = 0\\
&\text{top surface, } -k\frac{\partial T(r,H_c,t)}{\partial z} = h(T(r,H_c,t) - T_\infty), u = v = 0\\
&\text{sidewall surface: } -k\frac{\partial T(r_z,z,t)}{\partial r} = h(T(r_z,z,t) - T_\infty), u = v = 0\\
&\text{interface condition: } T(s,z,t) = T_m, \rho_{PCM} h_{sf}\frac{\partial s}{\partial t} = -k\left(\frac{\partial T(s,z,t)}{\partial r} - \frac{\partial s}{\partial z}\frac{\partial T(s,z,t)}{\partial z}\right)\\
&\text{initial condition: } T(r,z,0) = T_{ini}, u = v = 0
\end{aligned} \tag{9}$$

MESH DEPENDENCY TEST AND THE MODEL VALIDATION

The governing equations were solved using commercial package COMSOL Multiphysics. The solution computed from COMSOL Multiphysics is based on the Finite Element Method. To ensure mesh dependency results, a mesh dependency test was performed. Three numbers of elements were tested, i.e. 165 (grid 1), 4345 (grid 2), and 6647 (grid 3). The mesh dependency test was based on the temperature of the coffee at the half height of the cup. In Table 2, the three tested grids properties are tabulated. The mesh dependency test results are shown in Figure 2. As can be seen from Figure 2, the results obtained from grids 1 were less than these obtained from the other two tested grids. The results obtained from grid 3 suffered from fluctuation at the beginning of the calculation. Figure 2 depicts that grid 2 satisfied the independence condition. As a result, grid 2 was selected to run the simulation with.

Table 2. The tested grids with their properties.

Grid	number of elements	Max. element size, mm	Min. element size, mm	Max. element growth rate	Curvature factor
1	165	0.88	0.028	1.4	1
2	4345	0.14	0.004	1.13	0.3
3	6647	0.112	0.0016	1.1	0.25

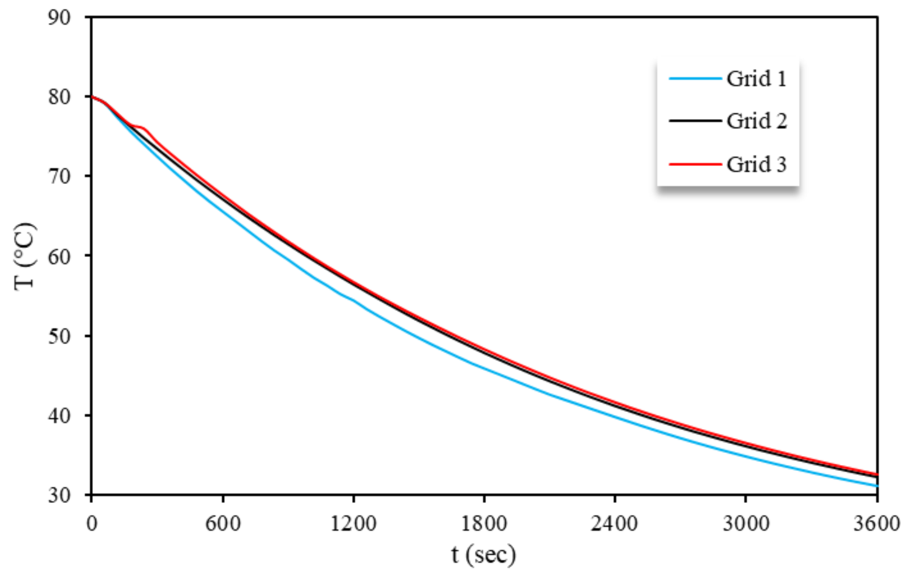

Figure 2. Mesh independency test.

To validate the present model, a comparison was performed with those obtained by Pitts and Sissom [24]. Pitts and Sissom [24] studied natural convection in cylindrical enclosure and presented their results in terms of Gr.Pr and Nu, where Gr is the Grashof number, $Gr = g\ \beta\ \rho^2\ 2{R_c}^3(T_s - T_{ini})/\mu^2$, Pr is the Prandtl number, $Pr = \mu\ c_p/k$;, and Nu is the Nusselt number, $Nu = \ h\ 2R_c/k$. Using dimensionless parameters gives a good capability to compare results under different temperature ranges and geometry dimensions. The present validation was performed for the case of natural convection in a vertical cylindrical enclosure. In Figure 3, a reasonable agreement can be noticed between the numerical data from the present model and those of Pitts and Sissom [24] with maximum deviation of 5%.

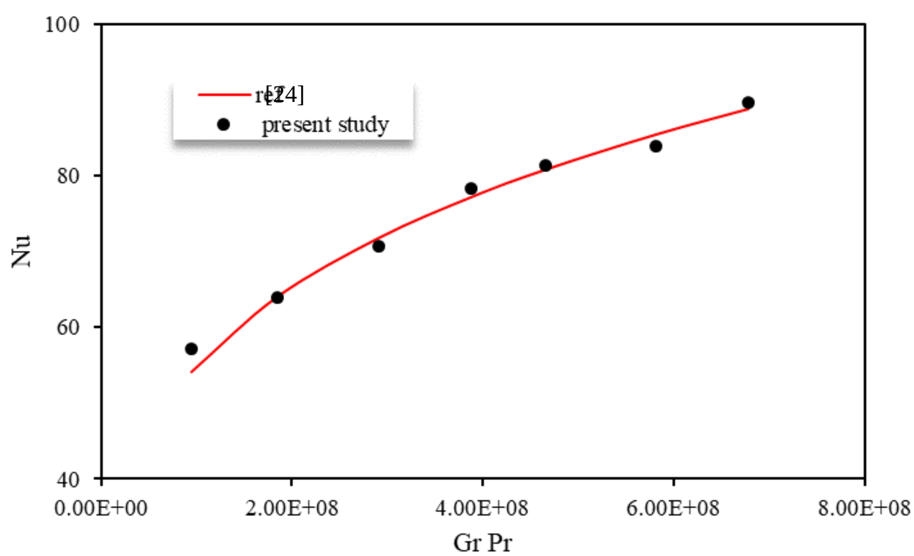

Figure 3. Validation comparison between the present and [24] results.

RESULTS AND DISCUSSION

In the present study, a numerical investigation was performed to study the impact of utilizing encapsulated PCM on hot beverage temperature. Initially, i.e. t= 0 sec, the entire coffee was at 80 ℃; while the PCM was at 20 ℃. Since the present study focuses on the thermal behaviour of a hot beverage in the presence of a PCM, the results are presented in terms of the hot beverage temperature.

Figure 4 describes the temperature contours for both cases, i.e. with and without PCM, at t= 0, 0.5, 120 and 1800 sec. Initially at 0 sec, Figure 4(a), the temperature of the entire coffee was 80 ℃. The same temperature for the coffee was found with the presence of the PCM. However, the PCM temperature was ranged from 20 ℃ at the centre of the ring to about 70 °C at the surface of the ring. After 0.5 sec, Figure 4(b), the temperature of the coffee without the PCM was still high, i.e. ~ 80 °C. At the same time, the temperature of the coffee, especially close to the PCM rings, in the presence of the PCM decreased to around 65 °C. The reduction in the coffee temperature happened because some of the heat was absorbed by the PCM. At this time, the PCM temperature increased above its melting temperature especially the PCM in the upper rings due to the high heat. At 120 sec, Figure 4(c), the temperature of the coffee without PCM dropped to around 70 °C. While in the presence of the PCM, the coffee temperature dropped to around 65 °C. Then after half an hour, 1800 sec, Figure 4(d), the coffee, without the PCM, cooled down to around 40 °C. The coffee in the upper portion cooled faster because the heat was lost to the surrounding of the cup from top as well as from sidewall. However, the coffee with the PCM maintained its temperature around 60 °C. The PCM compensated the lost heat from the heat that it previously absorbed and maintained the coffee temperature. It can be concluded from Figure 4(d) that the coffee in the presence of the PCM maintained its drinkable temperature even after half an hour after pouring the coffee in the cup. The drinkable coffee temperature was not gained in the absence of the PCM.

The impact of using PCM extended to the temperature distribution along the cup. Figure 6 illustrates the impact of using PCM rings on the coffee temperature at the centre of the cup at four different heights starting from bottom, i.e. 1- Hc/4, 2- 2Hc/4, 3- 3Hc/4, and 4- Hc. The temperature increased as the location was closer to the bottom of the cup. This temperature distribution was similar for both cases, i.e. with and without PCM. For instance, at 1800 sec for the case without PCM, the temperature of point 1 was 50.3 °C, point 2 was 48 °C, point 3 was 44 °C, and point 4 was 35. While, with the presence of PCM, the temperatures were 58°C at points 1, 2, and 3, and 53 °C at point 4. The coffee temperature in the absence of the PCM dropped to below desirable drinkable temperature in most levels of the cup. Also, it can be noticed that in the absence of the PCM, the temperature differences between different heights were obvious. When the PCM rings were employed, the temperature difference along the cup diminished. However, the upper portion of the coffee was an exception from the other parts of the coffee. The upper portion had less temperature because it lost its heat to the surrounding from the top surface and the sidewall. While, the other parts lost their heat solely from the sidewall of the cup. In addition, the coffee at different levels along the cup in the presence of the PCM was at drinkable temperature, 50 °C, after 2340 sec for point 4 and 3120 sec for points 3, 2, and 1.

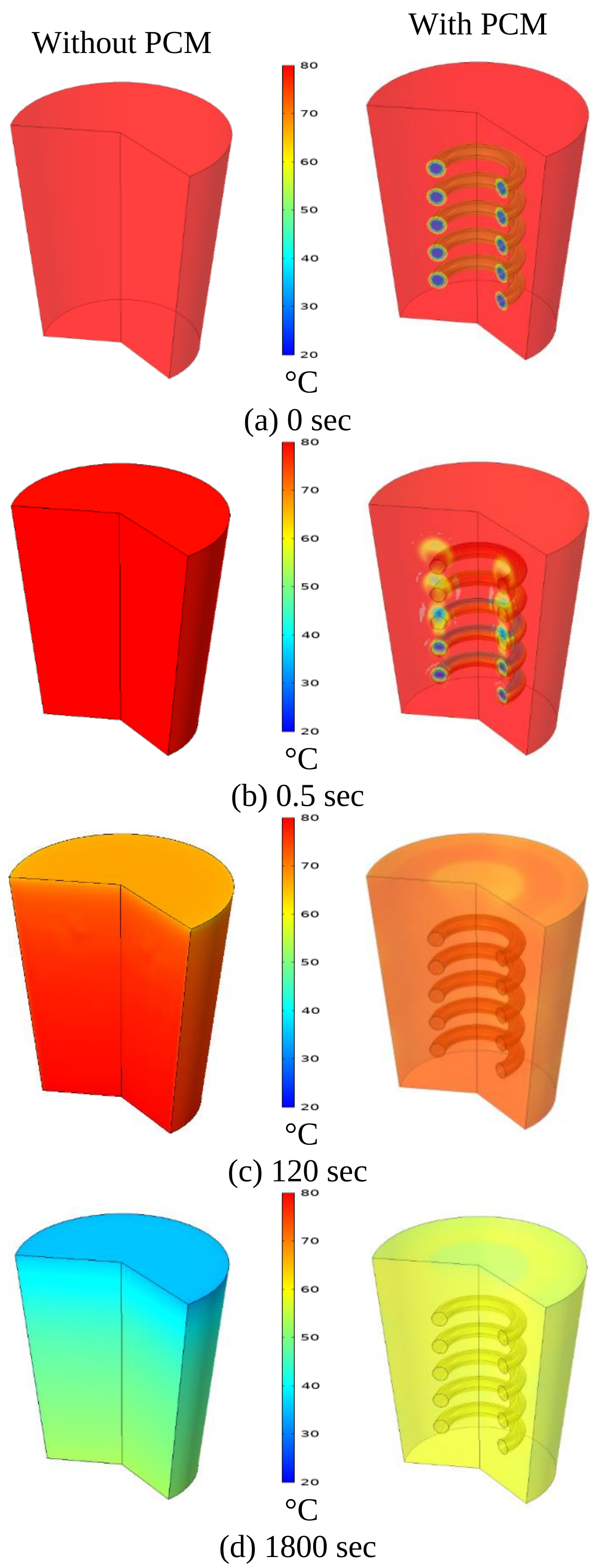

Figure 4. Temperature contours for with and without PCM cases at (a) t=0, (b) 0.5 (c) 120 sec, and (d) 1800 sec.

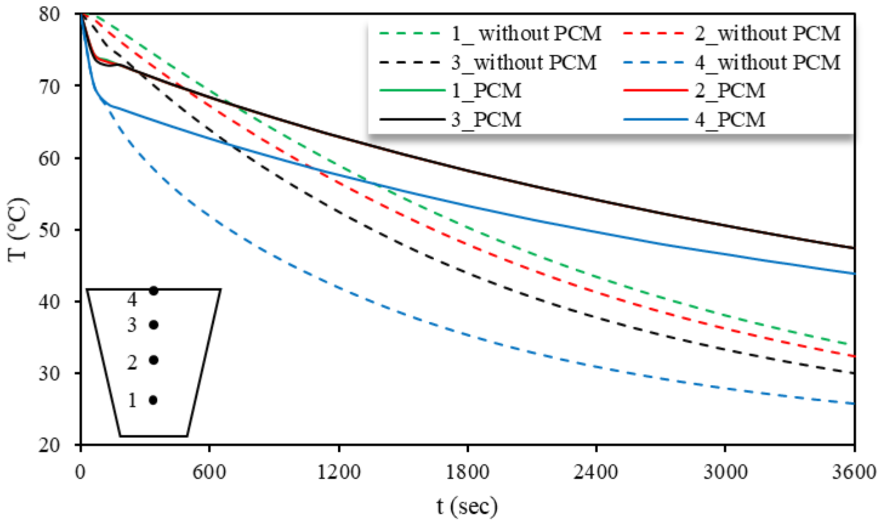

Figure 5. Coffee temperature history for both cases, i.e. with and without PCM at different heights along the cup of coffee.

Figure 6 depicts the volume average temperature of the coffee with time for 3600 sec. It could be noticed that the coffee volume average temperature in the absence of the PCM, the coffee temperature dropped below the drinkable temperature, 50 °C, within 1560 sec. As for the case in the presence of the PCM, the volume average temperature dropped below the drinkable temperature within 3120 sec. A sharp reduction in the volume average temperature could be observed in the first 120 sec in the presence of the PCM. This reduction happened because the PCM absorbed the excess heat from the coffee. This absorbed heat was later released from the PCM to the coffee. The released heat ensured the warmness of the coffee for a longer time compared to the case without PCM as mentioned above.

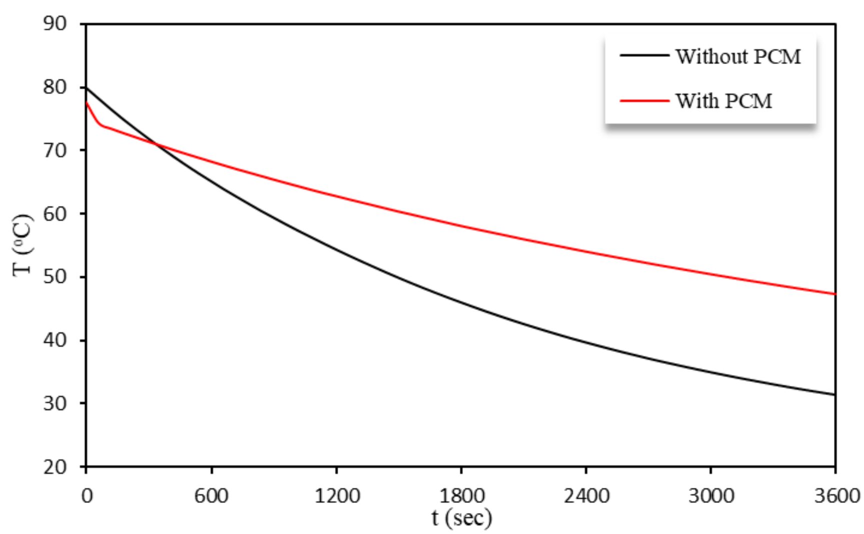

Figure 6. Coffee volume average temperature history for both cases, i.e. with and without PCM

CONCLUSIONS

A numerical study was performed to investigate the impact of integrating an encapsulated PCM in rings on the temperature of hot beverage. The hot beverage was coffee, and the PCM was beeswax. Initially, the coffee was at 80 °C and the beeswax was at 20 °C. The PCM was encapsulated in five rings along the cup of coffee. Finite Element method was used to solve the governing equations of the problem. The present model was validated with literature, and good agreement was found. Two cases were studied and compared, without PCM and with PCM. The computational calculations showed that by utilizing PCM, encapsulated in rings, in comparison with without-PCM case, the following advantages were obtained:

1. The temperature of the coffee dropped faster to 60 °C in the absence of the PCM, within 840 sec; while it took 1440 sec to reach 60 °C with PCM.
2. The temperature of the coffee was uniform in most parts of the cup contained the coffee. A slight temperature difference was noticed between different heights along the cup of coffee.
3. In addition, the coffee average volume temperature was maintained at an acceptable drinking temperature range for a longer time, 60 °C-50 °C for 1680 sec. While it was 660 sec without the PCM.

NOMENCLATURE

c	Mushy zone constant
c_p	Specific heat (J/kg K)
f	melt fraction
g	Gravitational acceleration (m/s^2)
Gr	Grashof number, $Gr = g\ \beta\ \rho^2\ 2{R_c}^3(T_s - T_{ini})/\mu^2$
H	Specific enthalpy (J/kg)
H_c	Cup height (m)
h	Convection heat transfer coefficient (W/m^2 K)
h_s	Sensible enthalpy (J/kg)
h_{sf}	Latent heat of fusion (kJ/kg)
k	Thermal conductivity (W/m K)
Nu	Nusselt number, $Nu = h\ 2R_c/k$
PCM	Phase change material
Pr	Prandtl number, $Pr = \mu\ c_p/k$
p	Pressure (N/m^2)
R_c	Cup top surface radius (m)
r	Radial coordinate (m)
r_c	Cup bottom surface radius (m)
r_{ri}	Ring inner radius (m)
r_{ro}	Ring outer radius (m)
r_z	Cup sidewall radius (m)
S	Source term
s	Liquid- solid interface location (m)

t	Time (min)
T	Temperature (^oC)
V	Velocity vector (m/s)
u,v	Velocity in the radial and axial directions, respectively (m/s)
z	Axial coordinate (m)
Greek Symbols	
β	thermal expansion coefficient, (1/K)
μ	Dynamic viscosity (N s/m^2)
ρ	Density (kg/ m^3)
Subscripts	
ini	Initial
l	liquid PCM
m	Melting
s	Solid
∞	Ambient

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