Study on PCM Assisted Constant Temperature Water Heating System

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Abstract. Spread of novel coronavirus across the globe creates panic situations internationally. Major challenge of this pandemic situation is the absence of a specific treatment or vaccine for curing the disease. As per published report of WHO, temperature above 55 °C is potentially kill Corona virus. This study focuses on design a water heating system that could provide water above the required temperature with minimal input power even during the off-sunshine hours. The thermal performance of Phase Change Material (PCM) integrated solar water heating system providing water temperature above 56 °C both during the day and the off sunshine hours has been discussed in this present study.

The phase change behaviour of paraffin-wax-6035 confined within a copper tube of 100 mm diameter and 1000 mm length and 1 mm thickness, has been studied using CFD analysis. The analysis is carried out for three different cases viz. conventional solar water heating system, modified solar water heating system integrated with bare PCM tube and finned PCM tube of 1 mm fin thickness. The thermal storage capacity of solar water heater is compared based on the thermal storage capacity factor which is calculated to be 1.1149 & 1.1586 for bare PCM tube and finned PCM tube case, respectively with respect to the conventional solar water heater.

Keywords: Phase Change Material; COVID-19; energy efficiency; CFD; solar water heater

| Index | Description | Abbreviation | Description |
|-------|-------------|--------------|-------------|
| Cu    | Copper domain | CFD | Computational Fluid Dynamics |
| Fin   | Fin | HTF | Heat Transfer Fluid |
| PCM   | Phase Change Material | PCM | Phase Change Material |
| Steel | Storage tank wall | WHO | World Health Organization |
| Wall  | Isothermal inner wall | SWH | Solar Water Heater |
| Water | Water filled in storage tank | FCC | Face Centre Cubic-structure |
Table 2. Symbols used in present article

| Sign | Description                                                                 | Sign | Description                                                                 | Sign | Description |
|------|-----------------------------------------------------------------------------|------|-----------------------------------------------------------------------------|------|-------------|
| $T_b$ | Boiling temperature (K)                                                     | $h_{mol}$ | Molar enthalpy (kJ/mol)                                                  | $\vec{j}$ | Unit vector in Y direction |
| $t$  | Duration (s)                                                               | $M_o$  | Molecular weight (g/mol)                                                  | $u$  | Velocity component in X direction (m/s) |
| $b$  | Correlation coefficient                                                     | $T_{wall}$ | Temperature of considered wall (K)                                       | $v$  | Velocity component in X direction (m/s) |
| $z$  | Carman-Kozeny constant for the source term (kg/m³/s)                        | $\tau$ | Thermal status maintenance time (s)                                        | $\vec{v}$ | Velocity field of fluid (m/s) |
| $\varepsilon_{sc}$ | Duration for water to touch solidus temperature of PCM (s) | $r$  | Small supportive constant in source term for solid domain | $T_{ref}$ | Reference temperature (K) |
| $\varepsilon_s$ | Duration required for complete solidification (s) | $T_S$ | Solidus temperature (K)                                                  | $\rho$ | Density (kg/m³) |
| $T_f$ | Final temperature (K)                                                     | $C$  | Specific heat (J/kgK)                                                    | $\lambda$ | Liquid fraction |
| $\beta$ | Gravity (m/s²)                                                            | $A_s$ | Surface area (m²)                                                        | $\sigma$ | Root mean square deviation (%) |
| $Q$  | Heat (J)                                                                   | $\Delta T$ | Temperature difference (K)                                               | $\phi$ | Source term |
| $\dot{Q}$ | Heat transfer coefficient (W/m²K)                                          | $T$  | Temperature field (K)                                                    | $\xi$ | Thermal storage capacity factor |
| $T_i$ | Initial temperature (K)                                                   | $P$  | Pressure (pa)                                                             | $\mu$ | Viscosity (Pas) |
| $L$  | Latent heat (J/kgK)                                                       | $k$  | Thermal conductivity (W/mK)                                              | $\beta$ | Volumetric coefficient of thermal expansion (K⁻¹) |
| $T_l$ | Liquidus temperature (K)                                                  | $h$  | Total enthalpy (J)                                                       | $\psi$ | Melt fraction enrichment factor |
| $T_m$ | Melting temperature(K)                                                   | $\vec{i}$ | Unit vector in X direction | | |

1. Introduction

Nowadays, the world is witnessing global pandemic situation due to novel Coronavirus-COVID-19. Almost all countries are affected by this virus since January 2020. Several actions including social distancing, use of mask and frequent sanitization, self-quarantine, taking immunity booster drink (kadha, hot water & herbal tea, etc.) have been prescribed by Government worldwide [1]. As a precaution use of warm water has also been prescribed. Studies show that viruses and bacteria are neutralized at exposure of temperature range (50⁰C to 70⁰C) [2]. For thermal disintegration of Corona virus, 20 min duration to expose at temperature range between 50⁰C to 55⁰C is required [3]. PCM integrated solar water heater system can be an energy efficient solution to provide a constant water temperature above 55⁰C.

PCM solar water heater is an attractive solution as it increase the heat storage capacity and thus, maintains an isothermal temperatures for longer duration [4], [5], [6]. Thus, it can be an energy efficient solution that can be implemented in hospitals, public places, restaurants, schools and house-holds [7], [8]. This study is mainly dedicated to modified solar water heater with PCM tube. A noticeable amount of heat can be stored by PCM during sun shine hours which can be further used for maintaining required temperature of water during off sun shine hours [9], [10]. Paraffin wax offers excellent characteristics among all different types of PCMs for solar water heating purpose. But it is suffered from low thermal conductivity [11], [10].

Solar water heating systems are principally classified as flat plat solar water heating system and evacuated solar water heating system. Solar water heating systems are secondary classified based on manner of water circulation, as active solar water system (external pump assisted) and passive solar water heater system (governed by natural circulation principle) [12]. However, passive system is more dominated over active system due to better thermal efficiency and no external power requirement [4], [13].
In-depth analysis on the solar water heating system and resisted heat transfer by suitable ceiling isolation materials inside the indoor construction is carried out by D Prakash et al. [14]. They gain the results as by improving the roof system, overall production of 25 L of hot water per day with 60\(^\circ\)C temperature rises is gained in the summer season. Also ceiling temperature maintained at 27\(^\circ\)C is throughout the day in summer.

The exhaustive study done by Manoj Kumar & Mylsamy [15] related to solar water heater included with a Nano fused phase alteration material with three various cases viz. with PCM, without PCM and with Nano fused PCM. They gain the result as, exergy efficiencies of the system were calculated as 19.6 \%, 22.0 \%, and 24.6 \%, for without PCM, with PCM, and with Nano fused PCM, respectively and energy efficiencies for the three cases were calculated to be 58.74 \%, 69.62 \%, and 74.79 \%, respectively.

2. Proposed model

As shown into the Figure 1, the PCM paraffin wax encapsulated copper tube is held at the core portion of the water storage tank. Thermopsyphonic convection characterized by circulation of fluid is mainly responsible for heating of water during day time. At each rotation, the warm water up surges in evacuated tubes of solar water heater and stored in to insulated storage tank. And cold water down surges for absorbing the heat.

![Schematic diagram of evacuated tube solar water heater with PCM encapsulated tube](image)

**Figure 1.** Schematic diagram of evacuated tube solar water heater with PCM encapsulated tube

| Properties          | Water             | PCM               | Copper            |
|---------------------|-------------------|-------------------|-------------------|
| \( h_{mol} \)        | 285820 (kJ/mol)   | 14800 (kJ/mol)    | ---               |
| \( M_o \)            | 18.01528 (g/mol)  | 374 (g/mol)       | 29 (g/mol)        |
| \( T_\beta \)         | 373 (K)           | 595 (K)           | ---               |
| \( T_S \)             | 273 (K)           | 331 (K)           | ---               |
| \( T_I \)             | 273 (K)           | 333 (K)           | ---               |
| \( C \)              | 4186 (J/kg/K)     | 2100 (J/kg/K)     | 381 (J/kg/K)      |
| \( L \)              | 2260 (J/kg/K)     | 189000 (J/kg/K)   | ---               |
| \( k \)              | 0.6 (W/mK)        | 0.21 (W/mK)       | 387.6 (W/mK)      |
| \( \beta \)          | 0.21\times10^{-3} (K^{-1}) | 0.75\times10^{-3} (K^{-1}) | ---               |
| \( \mu \)            | 0.0017 (Pas) at 273 K to 0.00025 (Pas) at 273 K | 0.00689 (Pas) at 333 K to 0.00370 (Pas) at 363 K | ---               |
| \( \rho \)           | 1000 (kg/m³) at 273 K to 959 (kg/m³) at 373 K | 920 (kg/m³) at 293 K to 745 (kg/m³) at 363 K | 8978 (kg/m³)       |
| Chemical formula     | H\(_2\)O          | C\(_{20-40}\)H\(_{42-82}\) | Cu                |
| Structure            | Triangular (polar molecule) | iso chain (soft in nature) | FCC (Crystalline Solid) |
Three different cases are considered for CFD analysis viz. (1) Conventional solar water heater (2) Modified solar water heater with integration of PCM encapsulated bare tube and (3) Modified solar water heater with integration of PCM encapsulated finned tube. As soon as, the warm water gets in touch with the PCM encapsulated tube, it transfers thermal energy to PCM in sensible way. So, absorption of heat is done by PCM via sensible mode up to melting point and then via phase alteration process at isothermal condition. This produces localized drop in temperature of hot water. This low temperature water down surges towards evacuated tube for gaining the heat and fresh charge of heated water gets in touched with PCM zone. And next circulation initiated. Thus, storage of thermal energy is done in PCM encapsulated copper tube. This stored energy can be further utilized at night time for water heating.

| Component                  | Material | Dimensions                              |
|----------------------------|----------|-----------------------------------------|
| Storage Tank (insulated)   | Steel    | 570 mm diameter, 1020 mm length         |
| PCM encapsulation tube     | Copper   | 100 mm diameter, 1000 mm length & 1 mm thickness |
| Fins                      | Copper   | 86 mm height, 1000 mm length & 1 mm thickness |

### 3. Fluid Dynamics & Thermal Equations

Certain relevant assumptions which considered for CFD analysis are (1) Transportation of heat from the hot water to the PCM through tube wall and fin walls is done in two dimensional manners and also temperature field associated with PCM zone has two space co-ordinates. So, whole problem is considered as two dimensional [16]. (2) Copper has thermal conductivity considerably better enough to nullify the effect self-conductive resistance of 1 mm thick tube wall and fin walls. So, all copper walls are considered as diathermic in nature. (3) Molecular diffusion thermal energy transformation occurs in both solid and liquid phase of PCM. This is strictly true with thermo-physical properties that may differ. (4) The evacuated tube wall is diathermic in nature because wall is painted with good absorptivity material. So, glass wall is considered as diathermic wall. (5) Water is heated via natural convection and temperature-gradients are considerably small enough to neglect the radiation effects. (6) The liquid generated from its solid part is characterized as Newtonian, laminar, compressible, and viscous in nature. (7) All properties of paraffin wax are varying with respect to temperature and also the melting pattern displays less discontinuity. So, PCM is considered as pure, homogeneous and isotropic substance for thermodynamic calculations. (8) Mushy zone is saturated porous zone by the fluid portion of PCM and porosity of this porous zone is equal to fluid fraction of that particular instant.

Based on above assumptions following are the governing equations for all considered computational domains.

**Water Domain (Water portion of the system) & Liquid Domain (Liquid portion of PCM)**

**Continuity Equation**

\[ \nabla (\rho \vec{v}) + \left( \frac{\partial \rho}{\partial t} \right) = 0 \] (1)

**Navier stokes equation**

The momentum equation is given for the liquid domain of PCM is following

\[ \frac{\partial (\rho \vec{v})}{\partial t} + \nabla (\rho \vec{v}) = -\nabla P + \nabla (\mu \nabla \vec{v}) - \rho g \beta \Delta T + \phi \vec{v} \] (2)

The melt front is formed as porous media between solid and fluid domain with porosity equal to liquid fraction for the saturated porous zone termed as mushy zone. So, whatever fluid dynamics present in this zone is handled by enthalpy-porosity approach by providing the mushy zone parameter \( \phi \) in the momentum equation. In order to achieve this particular fluid dynamics, an appropriate definition of \( \phi \) is given as:
This is known as Carman–Kozeny relation. The constant $z$ has enough large value which can be able to suppress velocity and $r$ is a small constant used to avoid a division by zero when the two dimensional computational domain is under action of solid domain. The choice of the constants is arbitrary. In this work, $z = 161110$ kg/m$^2$s and $r=0.0003$ are used [17]. And for the water domain there is no phase transformation is done so, $\phi = 0$ for water.

\[
\phi = \left\{ \frac{x}{x} = \left( \frac{z(1-\lambda)^2}{\lambda^2 + r} \right); \lambda = f(T); \forall \lambda \in (0,1) & \forall T \in (T_s, T_l) \right\} 
\]

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**Figure 2.** Circulating flow field in water domain

**Figure 3.** Various Domains in PCM zone

**Energy Equation**

\[
C \left[ \frac{\partial (\rho h)}{\partial t} + \nabla (\rho \vec{V} h) \right] = k \nabla^2 T 
\]

Where $h$ is total enthalpy for both domains is defined as:

\[
h = \left( \int_{T_{ref}}^{T} C_d T \right)_{water} \quad \& \quad h = \left( \int_{T_{ref}}^{T} C_d T + \lambda L \right)_{PCM}
\]

Solid Domain (Solid portion of PCM) & Copper Domain (Tube Wall and Fin portion)

\[
C \left[ \frac{\partial (\rho h)}{\partial t} \right] = k (\nabla^2 T)
\]

**Equivalent temperature of water & Heat transfer rate equation**

For providing isothermal conditions, equivalent temperature of water gets defined as:

\[
T_f = \left( \sum_{p=0}^{n} \sum_{q=0}^{n} \frac{T_q \cdot \Delta t_p}{\sum_{p=0}^{n} \Delta t_p} \right)
\]

Where $T_q$ the temperature of water at particular time and $\Delta t_p$ is time duration between two sequential observations. And also $\forall T_q \geq T_m$ and $\Delta t_p$ is always taken after melting started.

\[
\left( \frac{\partial Q}{\partial t} \right) = \left\{ \frac{\partial (\rho V)}{\partial t} \int_{T_i}^{T_f} C_d T \right\}_{water} + \delta \left[ \frac{\partial (\rho V)}{\partial t} \left( \int_{T_i}^{T} C_d T + \lambda L \right) \right]_{PCM}; \delta = \{0; \lambda = 0 \quad 1; \lambda \neq 0 \}
\]

\[
Melt fraction enrichment factor (\psi) \& Thermal Storage Capacity Factor (\xi)
\]

Both are the performance parameters for comparing case-2 and case-3 configurations of water heater.

\[
\psi = \left( \frac{T_{Bare \ Tube}}{T_{Double \ Finned \ Tube}} \right) \quad \& \quad \xi = \left[ \left( \frac{\partial Q}{\partial t} \right)_{case-2 \ or \ 3} \right]^{1/3} \left( \frac{\partial Q}{\partial t} \right)_{case-1}
\]
Thermal Status Maintenance Time

It is duration up to which solar water heater can maintain the thermal status of water above 56\(^\circ\) C. So it is defined as following (\(\dot{\rho} \equiv 30\) W/m\(^2\)K for PCM [18]).

\[
t = t_e + \left(\frac{Q}{\dot{\rho}A_{e}\Delta T}\right)_{PCM}
\]

\[(10)\]

4. Boundary conditions & Computational Methodology

Initial boundary conditions for the CFD analysis of conventional solar water heating system are (1) At the hot surface of Glass tube, wall temperature \(T_{wall} = T_{f} = 70\) \(^\circ\) C; (2) Initial temperature of the water is considered as \(T_{i} = 27\) \(^\circ\) C; (3) At the cold wall (back side of glass tube) and side wall (end portion of glass tube) of Glass tube, \([k_{glass}(\partial T_{glass}/\partial t)]_{wall} = 0\); (4) At the tank wall \([k_{steel}(\partial T_{steel}/\partial t)]_{wall} = 0\). And initial boundary conditions for the CFD analysis of remaining both cases are (1) At the outer surface of Copper tube, wall temperature \(T_{wall} = T_{f} = 70\) \(^\circ\) C; (2) Initial temperature of the PCM is considered as \(T_{i} = 27\) \(^\circ\) C; (3) At the PCM and fin surface interface conjugate heat transfer is done so \([k_{steel}(\partial T_{steel}/\partial t)]_{wall} = [k_{PCM}(\partial T_{PCM}/\partial t)]\); \(T_{fin} = T_{PCM}\); (4) At the outer wall of Copper tube is held at constant temperature so, at the wall \([k_{Cu}(\partial T_{Cu}/\partial t)]_{wall} = 0\). (5) At the tank wall \([k_{steel}(\partial T_{Steel}/\partial t)]_{wall} = 0\).

Complete simulation of phase alteration process and the fluid dynamics incorporated with the melting process is carried out by ANSYS-FLUENT-16.0. Second order upwind differencing scheme is used for solving both momentum and energy equations and SIMPLE scheme is considered for pressure–velocity coupling with 0.1 second is considered as time step for calculations. The grid size with 31293, 36258 and 38355 cells is checked to evaluate grid independence case of bare tube. Finally grid size with 36258 cells is selected, and further refinement doesn’t show any remarkable improvement in accuracy of liquid fraction. While, the grid size with 785293, 805424 and 925683 cells is checked to evaluate grid independence case of finned tube. Finally grid size with 805424 cells is selected, and further refinement doesn’t show any remarkable improvement in accuracy of liquid fraction.

5. Validation

CFD simulation result of bare Copper tube is validate against experimental data taken of average temperature of PCM after phase alteration event started at the day time from thermally equivalent model for phase alteration process presented by Manoj Kumar & Mylsamy, [15]. Root mean square \(\sigma\) (\%) deviation and correlation coefficient \(b\) are calculated to validate the CFD simulations according to following expressions [8] respectively.

Here \(b > 0\) indicates positive linear relationship, \(b < 0\) indicates negative linear relationship and \(b = 0\) indicates no relationship between two variables. Also \(X_i\) is CFD simulation data and \(Y_i\) is experimental data.

\[
\sigma(\%) = \sqrt{\frac{\sum\left((\frac{X_i - Y_i}{X_i}) \times 100\right)^2}{N}}
\]

\[
b = \left(\frac{N \sum X_i Y_i - (\sum X_i)(\sum Y_i)}{N \sum X_i^2 - (\sum X_i)^2} \right) \sqrt{\frac{N \sum Y_i^2 - (\sum Y_i)^2}{N \sum X_i^2 - (\sum X_i)^2}}
\]

\[(11)\]
6. Results and Discussion

Consider the Figure 5, which indicates the simulated profile of the average water temperature of the water with respect to time which approximately near to the experimental profile obtained by Manoj Kumar & Mylsamy, [15] for same time interval. Water gets heated from gaining the heat from the evacuated tube. Then, this heated water up surges due to density gradient in to the evacuated tube towards the storage tank. So, overall clockwise circulation cycles are generated in the system.

As shown in to Figure 6, 7 & 11, the growth of liquid fraction is higher in case of the finned tube as compare to bare tube but physical nature of both curves get restored. This restoration of physical nature of curves is the indication of same fluid field gets generated in to fluid domain. But thermal response of the finned tube higher compare to bare tube because two fins provide extra nucleating sites for localized circulating child roll cell growth.

While in case of bare tube, only tube wall is participated in this process. As time progresses, these new born circulating roll cells became matured. So their size get increased and due to that the tangential velocity gets increased as admiring more fluid particles in to self for circulation around the eye of self. So, most of the fluid domain is dominated by advection heat transfer mode instead of conduction heat transfer mode. But still some regions of the fluid domain such as tube & fin walls and mushy zone get dominated by this molecular conduction heat transfer mode due to activation of no slip condition and self-nature as saturated porous media with porosity equal to liquid fraction respectively.

As shown in to Figure 8, 9 & 11, in fully developed fluid domain whatever child roll cells generated became more matured as participating more fluid particles and during this process, their localized temperature increases, velocity also gets increases and density gets decreases as $\rho \propto 1/T$. So, due to density difference considered local circulating roll cell tries to up surge by overcoming solid domain. And get settle down at the top portion of the tube, resulting in two large circulating roll cells observed at the top portion of fluid domain in to tube. But during this up surging process, fins act as the resistance by providing small space between self and solid domain. Also due to presence of various active nucleating sites on the fin wall, child roll cells born and the fluid particles join these child roll cells’ circulating field by leaving the matured roll cell circulating field. In addition to this, also activation of no slip condition and diffusion fluid
films supports molecular thermal excitations instead of advection which creates zone which termed as diffusion fluid film.

Figure 8. Matured fluid domain in case-2

Figure 9. Matured fluid domain in case-3

Figure 10. CFD Results of conventional solar water heater

Table 5. Thermal Status Maintenance Time of various cases

| Case  | Thermal Status Maintenance Time  |
|-------|----------------------------------|
| Case 1| Up to midnight                  |
| Case 2| Up to 8:00 am                   |
| Case 3| Up to 4:30 am                   |
So, overall fluid field of matured roll cell gets destroyed up to certain considerable extent by combine effects provided by fin walls, solid domain & diffusion fluid film. So, destroyed large roll cells are observed in Figure 9. This phenomenon gets reflated in all three profiles of the finned tube as slight depression. This is not happen in bare tube due to more space available in fluid domain, and roll cells get perfect pattern in bare tube fluid domain. So, all three profiles of bare tube case are not depressed. According to Figure 6 & 7, it is concluded that the physical nature of fluid domain is remain same in both cases but thermal response of the finned tube is batter as compared to bare tube because of thermal supports provided by the fins to the fluid domain. But due to depression in to the thermal profiles of finned tube, this advantage of fins is became slight darker. As in view of reverse temperature profile of water throughout off sun shining hours [14], water touches 55 ° C at middle of the night. \( t \) is calculated for both cases by using equation (26).

7. Conclusions
Present study illustrates Phase alteration pattern for three different cases viz. conventional solar water heating system, PCM assisted solar water heater under different configurations. Following inferences are drawn from this study:

1. Thermal storage capacity of solar water heater gets increased due to integration of PCM tube inside the water storage tank. Thermal Storage Capacity Factor is calculated to be 1.1586 and 1.1149, for PCM SWH with and without fin case, respectively. (2) PCM encapsulated bare tube failed in completion of stored thermal energy delivery which causes lacking of post sensible heat transfer is observed in bare tube case which is not the scenario in finned tube case. (3) Overall performance of PCM encapsulated bare tube is better than finned tube among all considered physical and thermal constrains. (4) Modified evacuated solar water heating system integrated with finned tube can able to provide hot water above 56 ° C throughout the day and night time. Thus, it can be treated as better compassionate choice for defending present COVID-19 pandemic situation.
In this present article, two configurations of PCM integrated tube incorporated inside conventional water heater are studied. Another configuration of PCM integrated tubes viz. single vertical finned tube, crossed finned tube, triple finned tube will be studied.

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