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Research Article

Numerical investigation of an amalgamation of two phase change materials thermal energy storage system

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ABSTRACT

In the last three decades, many researchers have published their findings on the storage of thermal energy using various phase transition materials (both organic and non-organic). One of their goals was to have a higher heat storage capacity with a shorter heat charging cycle for thermal energy storage. This study looked into a floating capsule thermal energy storage system (TESS). A number of spherical capsules filled with beeswax were placed in a paraffin-filled cylindrical shell. With heat transfer fluid flowing through three hexagonal tubes arranged at 120° inside the TESS core, the two phase change materials (beeswax with a thermal conductivity of 0.25 W/mK and paraffin with a thermal conductivity of 0.23 W/mK) were charged and discharged. For the proposed TESS, a mathematical model was created and utilised to forecast thermal energy storage capacity and charging/discharge times for various configurations. In TESS, a 70–30% mixture of the two PCMs results in a 21.5 percent increase in heat storage capacity when beeswax alone is used, and an 8.4 percent decrease in storage capacity when paraffin alone is used. For a heat storage capacity of 7300 kJ, the model estimates charging and discharging times of around 2.6 and 3.2 hours, respectively.

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INTRODUCTION

One of the components of sustainable development is the demand for clear energy, such as solar energy. Many researchers have focused on different ways to store this solar energy in the form of heat inside a device which is commonly called a thermal storage device or system (TESS). It helps balance energy supply and energy demand. The energy required [1] is mostly used for the purpose of heating and cooling. Industrial processes requiring heating indicate that approximately 30% of energy is used to heat processes below 100 °C and only 13% of energy is used to heat processes above 400 °C.

PCMs are commonly employed as a heat storage medium in TESS in a number of Solar Energy Systems. This stored heat can be used [2] during their demand, for example, in industrial units, thermal comfort applications, drying, etc. In her experimental and numerical analysis [3] for the energy storage device (shell and tube) for charging or discharging suggested that melting of PCM is temperature sensitive and occurs isothermally, both during

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melting and solidification phase. In their numerical investigation analysed the heat transfer rates for u-tube, u-tube with in-line fins, u-tube with staggered fins and with PCM festoon channel configuration [4]. They suggested that the festoon channels with phase change material configuration offered a higher heat transfer rate during both the charging and discharging phases.

Recent developments in TESS research using phase change materials to improve thermal conductivity has been discussed in their experiments [5]. Their experiments with placing inserts / structures with high conductivity in the PCM material resulted in a higher thermal conductivity of TESS. There is little published data on using two phase change materials inside a single thermal device without mixing them. There is few published data on TESS that combines the advantage of two PCM's in a single shell system. It's worth noting that while paraffin has a high heat storage capacity, it has low thermal conductivity. Beeswax, on the other hand, has a lower heat-storage capacity but a higher thermal conductivity. In order to increase thermal conductivity (which impacts charging and discharging time) and boost the heat storage capacity of the proposed TESS, a mixture of paraffin and beeswax is used in the TESS. There is very little published data available where a combination of the two characteristics of (thermal conductivity and heat storage capacity) is being modelled for thermal storage systems. In this research, a TESS model with a number of copper spherical capsules filled with beeswax as a secondary thermal energy storage medium was put in a shell filled with paraffin (A-53 grade) as the primary thermal energy storage medium. With a case study for a specific thermal energy storage system (charging and discharging), the suggested mathematical model was validated with the experimental results of [6].

BACKGROUND

Phase change materials (PCMs) are widely used in energy storage devices due to two fundamental features. These characteristics are enhanced heat storage density and homogeneous heat energy distribution [7]. In TESS, the two basic heating/cooling modes of PCM are sensitive and latent heat. In a TESS, PCMs store energy as sensible or latent heat, or as a combination of the two. Because PCM has a greater capacity for heat storage, it can retain heat energy for a longer period of time. Researchers in [8] investigated the parallel heat transfer fluid (HTF) flow direction of PCMs and found that the energy storage or release rates increased by up to 5% when compared to the counter HTF flow direction. They attributed their findings to the larger temperature difference at the fluid's inlet as hot and cold fluids meet the parallel flow from the same end. They also said that a bigger temperature differential resulted in a greater depth at the PCM phase change during TESS storage and release.

Numerical investigations were conducted in [9] and compared the flow field and heat transfer performance of slurry from a biogas plant using computational fluid dynamics (CFD) inside twisted hexagonal, circular, octagonal, triangular and square tubes. They concluded that, relative to other formed ducts or cross sections of pipes, twisted hexagonal tubes had the highest heat enhancement factor. In his experimental investigation explained as to why hexagonal columns are formed in the volcanic remains of Ireland's Giant's Causeway. It was suggested in [10] that the volcanic cooling cracks are formed at approximately 120 degrees. He has attributed this to nature's phenomenon of a greater surface area of hexagonal shapes to increases heat dissipation. This suggests that the charging and discharging time of thermal energy storage can be enhanced by using hexagonal tubes placed at 120 ˚C.

Researchers in [11] developed a theoretical model of a shell and tube TESS using several PCMs. They suggested that the fraction of PCM in a mixture and its melting temperature play a vital role in the design and performance of any TESS. According to [12] paraffin are a straight chain of n-alkanes (CH3-(CH2)-CH3). They further stated that paraffin was less expensive, non-corrosive, chemically inert (stable below 500 °C) and their crystallization (CH3 chain) stores larger amounts of latent heat. In [13] researchers investigated heat storage system unit using a staggered heat exchanger using different organic PCMs. They found that due to heat convection, the PCM require lesser time for melting than that for its solidification. Furthermore, they explain the need for TESS with a uniform solidification process to reduce solidification time. As PCM thermal conductivity is increased, melting and solidification time can be reduced.

There are a number of organic PCMs like beeswax, volcanic rock, activated charcoal, gypsum, etc. Many researchers have looked at the first method but due to a direct contact of heat with PCM, the characteristics of PCMs gets affected. Researchers in [14] studied composite thermal storage that consisted of a PCM with an encapsulation material (a solution of sodium, potassium eutectic salts and diatomite encapsulation materials). The required characteristics of an organic PCM for TESS are which will give an optimum combination of heat storage and charging/discharging time. With organic PCMs, higher the heat storage capacity lower is their thermal conductivity and vice versa. It is difficult to find a single organic PCM with combined characteristics of higher heat storage capacity and higher thermal conductivity. Alternatively, it is possible to achieve higher heat storage capacity and higher thermal conductivity by using a combination of two or more PCMs. A combination of 70% PCM provide maximum compressive strength and volume density of 393.3 J/g of effective energy density.

In [15], researchers used encapsulated paraffin wax spheres inside water in the shell in their experiments to measure energy storage capacity of paraffin. They immersed 150 encapsulated paraffin wax spheres inside the tank full of water in their TESS and found an increase in energy absorption by water by about 20 percent in their experiments. A spherical shape has a greater surface area for the same given volume, and thus spherical containers are more desirable than cylindrical containers in TESS. Paraffin as a PCM has poor thermal conductivity which is its primary drawback. This causes the process of melting and solidification to take a long time. Therefore, any device that uses paraffin, requires a wider surface area [16]. Therefore, to increase charging and discharge speeds, more advanced heat transfer techniques are needed to be applied. In their experiments [17] inserted carbon fibre brushes into PCM placed inside their TESS. They concluded that improved heat transfer rates in thermal storage which in turn reduced tank size, costs and facilitated saving in required space. Researchers in [18] experimented with inserting aluminium foils in paraffin wax inside TESS. They observed that the thermal conductivity of aluminium foils doubled without substantial statistical change inside the two phase material (aluminium foils and paraffin wax).

Some attempts have been made in this direction in recent years to boost the heat transfer rates in the paraffin wax-based storage unit. Few of the methods those are experimented with are using finned tubes, multiple tubes, and multiple PCMs in TESS design to increase the heat transfer rates. In their experiments suspended pipes with fins were used for storing latent heat energy. They found that the heat pipe with suspended fins enhanced heat storage and reliability of TESS. In [19] researchers mainly focused on the melting and solidification of PCM with heat pipe and metal foil in their experiments. They found that melting and solidification rates increased by around 200% and 600% respectively as compared to rates using non-foil heat pipe PCM. A number of heat transfer improvement strategies are suggested [20] such as use of fins, heat pipes, etc. along with the addition of high conductivity materials. The combined technique improved the heat exchange and the thermal conductivity of PCM.

The team of researchers in [21] investigated the effect of fin shape on the thermal performance of horizontal latent heat thermal energy storage (LHTES) systems using longitudinally finned tubes. In the horizontal shell-and-tube LHTES system, longitudinal fins of various heights, thicknesses, and numbers were used, and paraffin was packed in the annulus. For charging procedures, the melting fronts, average temperatures, and velocity profiles of Phase Change Material (PCM) were graphically depicted and compared. In comparison to the bare-tube structure, they discovered that incorporating longitudinal fins in a minor quantity (2.85% of total volume) might shorten the complete melting time by 34%.

MATHEMATICAL MODELLING AND PROPOSED TESS

A TESS which provide a 60-70 ˚C temperature range has its applications in industries like pasteurization, washing, cleaning, distillation, metal pre-treatment processes, paint shop flash-off zones, etc., [22]. Many mathematical models are published for TESS with circular tubes. Hexagonal pipes placed at 120°, a combination of PCM_1 (paraffin) in shell and PCM_2 (beeswax) in spherical capsules floating in the shell is considered to thermal heat storage. A general layout of the proposed TESS is as shown in Figure 1.

To obtain the design dimensions of various components, a cloth drier of a dry cleaning shop with a capacity

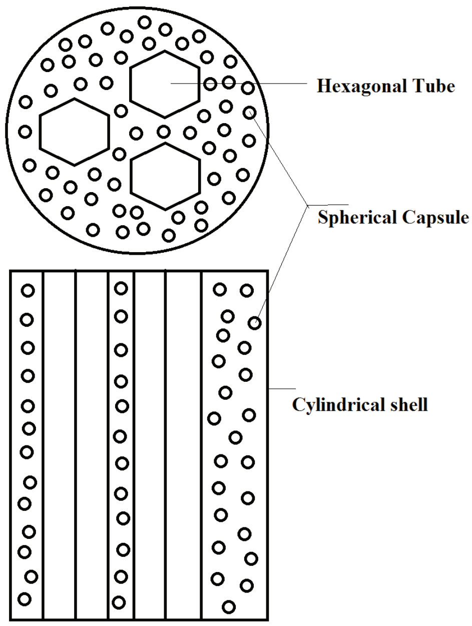

Figure 1. Layout of the proposed TESS. The 3-pass hexagonal tubes are placed at 120° angle. Spherical capsules contains (PCM_2) and cylindrical shell contains (PCM_1).

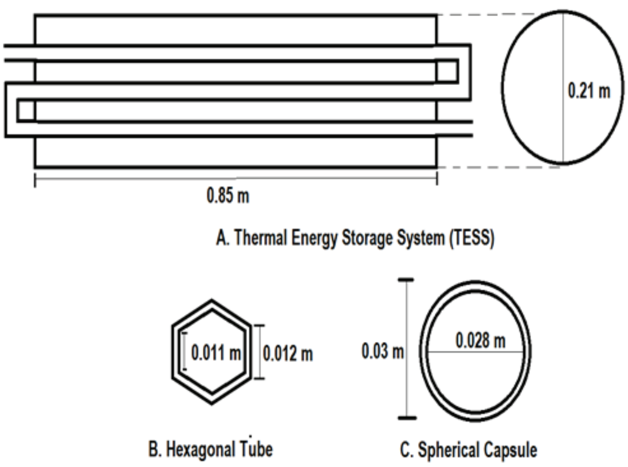

Figure 2. Modelled dimensions with 5.5 kg of cloth load for drying using the proposed TESS. A - shell, B - copper hexagonal tube and C - copper spherical capsules in TESS.

Table 1. Component dimensions for the proposed TESS

Sr No.	Dimension	Charging	Discharging	Final Dimensions
1	PCM_1	Paraffin wax	Paraffin wax	Paraffin wax
2	PCM_2	Beeswax	Beeswax	Beeswax
3	Heat required	7300kJ	7300kJ	7300kJ
4	S_o	0.012m	0.012m	0.012m
5	S_i	0.011m	0.011m	0.011m
6	L_t	0.85m	0.85m	0.85m
7	N_t	3	3	3
8	D_i	0.211	0.194m	0.21m
9	H_c	0.85m	0.85m	0.85m
10	R_{so}	0.015m	0.015m	0.015m
11	R_{si}	0.014m	0.014m	0.014m
12	Volume for PCMs	29L	24.44L	29L

of 5.5 kg was used for modelling the proposed TESS. After washing of cloths, the clothes contain approximately 55% of moisture [23]. To eliminate this moisture from the mass of clothes of 5.5 kg, the moisture weight is approximately 3 kg (55%) [23]. Using sensible and latent heat that the proposed TESS can provide, this moisture is removed.

The heat (Q_s) required to increase the temperature of dried moist cloths to 70°C is:

$$Q_s = SH_w * M_w = 168\ \text{kJ/kg} * 3 = 504\ \text{kJ} \qquad (1)$$

The heat (Q_L) required to evaporate moisture is:

$$Q_L = LH_W * M_W = 2257\ \text{kJ/kg} * 3 = 6771\ \text{kJ} \qquad (2)$$

Therefore the total heat (Q) required to dry 5.5 kg cloths is:

$$Q = Q_L + Q_s = 7275\ \text{kJ} \cong 7300\ \text{kJ} \qquad (3)$$

In Eqn. (1), the sensible heat of water (SH_w) per kg for temperature rise from 30°C to 70° C is the total heat (Q_s). Here c_p of water was considered as 4.185.5 kJ/Kg-K. In Eqn. (2), the heat to evaporate moisture is obtained from the steams tables at 100 °C as 2257 kJ/Kg. A total heat of 7300 kJ from hot fluid (for example, using solar power) is provided using hexagonal tubes for charging or discharging the proposed TESS. Hexagonal tubes are employed to improve heat transfer rates, to lower the charging or discharging cycle time the proposed TESS design. It can be mathematically derived that considering volume of cold PCM, V_C is equal to the volume of hot PCM, V_H respectively, the surface area of the hexagonal tubes, $A_{SH} = (6 \times s \times H)$ is increased by 5% over surface of the circular tube, $A_{SC} = (\pi \times D \times H)$ for same diameter. Secondly, the volume of PCM_1 is the difference between shell volume and tube volume in TESS. Thus, for the same amount of heating source provided (7300 kJ), there is a increase in volume of PCM_1 in the cylindrical shell of TESS. That is, it can be shown that, $V_H = 0.92 * V_C$ from $A_{SH} = A_{SC}$. Various physical dimensions arrived at are as shown in Figure 2 and the dimensions of components are as in Table 1.

The Nusselt number (Nu_C) if circular tube is used is given by:

$$Nu_C = \frac{h_H * D}{k} \qquad (4)$$

The Nusselt number (Nu_H)for hexagonal tube is given as:

$$Nu_H = \frac{\sqrt{3} * h_H * s}{4 * k} \qquad (5)$$

From Eqns. (4) and (5) for the same Nusselt number, we find:

$$h_H = 4.04 * h_C \qquad (6)$$

Eqn. (6) suggests that for same thermal conductivity of circular and hexagonal tube material, the convective heat transfer coefficient in hexagonal tube is approximately 4.04 times greater than that for a circular tube. That is:

$$h_H = 4.04 \times h_C \qquad (7)$$

Total Heat Required for Thermal Charging of Proposed Tess with Two PCMs

Thermal charging of TESS shell volume with PCM_1

For shell side PCM_1 during charging process:

$$Q_{pcm1} = (\alpha * q * m_1) + \int_{T_1}^{T_2} m_1 * C_p * dt \qquad (8)$$

If the melting temperature (T_m) is PCM_1 melting temperature then the temperature of PCM_1 will vary from its atmospheric temperature, T_1 (solid state) to T_m and then from T_m to T_2 (above melting temperature). Thus we have:

$$Q_{pcm1} = m_1 \left[(\propto * q) + \int_{T_1}^{T_m} C_p * dT + \int_{T_m}^{T_2} C_p * dT \right] \quad (9)$$

Or,

$$Q_{pcm1} = m_1 \left[(\propto * q) + \left(C_{p1m} * (T_m - T_1) \right) + \left(C_{pm2} * (T_2 - T_m) \right) \right] \quad (10)$$

Eqns. (9) and (10) were used to obtain the unknown m_1, the mass of PCM_1. To find m_1, various design parameters that needs to be assumed are as in Table 1.

A number of spherical capsules filled with PCM_2 (beeswax) are inserted inside the volume that is left after subtracting the volume occupied by the three hexagonal pipes or ducts used for charging/discharging of the TESS. The volume occupied by number of spherical capsules (N_s), each of volume, V_s is equated with the volume that is left in the cylindrical shell after subtracting the volume occupied by the three hexagonal pipes. That is:

$$V_s * N_s = (1 - \gamma) * (V_{CL} - (3 * V_t)) \quad (11)$$

For the assumed dimensions in Table 1 it was found using Eqn. (10) that N_S = 784. To formulate the mass m_1 of PCM_1 in the shell, we have:

$$V_{PCM1} = V_C - (3 * V_t) - (V_s * N_s) \quad (12)$$

From Eqns. (11) and (12) we get,

$$V_{pcm1} = \gamma * \left[\left(\frac{\pi * D^2 * H}{4} \right) - \left(\frac{9\sqrt{3} * S^2 * H}{2} \right) \right] \quad (13)$$

The mass m_1 for PCM_1 is $m_1 = \rho_{PCM1} * V_{PCM1}$ (14)

Using value of m_1 (Eqn.14) and Eqn. 10, we get the equation for charging of TESS as:

$$Q_{pcm1} = \rho_{pcm1} * \gamma * \left[\left(\frac{\pi * D^2 * H}{4} \right) - \left(\frac{9\sqrt{3} * S^2 * H}{2} \right) \right] * \left[(\propto * q) + \left(C_{p1m} * (T_m - T_1) \right) + \left(C_{pm2} * (T_2 - T_m) \right) \right] \quad (15)$$

Eqn. (15) models the amount of heat required to charging the proposed TESS with three hexagonal pipes placed at 120°, to charge PCM_1 (paraffin) in its shell.

Thermal charging of TESS spherical capsules volume with PCM_2

A similar mathematical modelling as per Eqns. (8) to (15) are followed to obtain the amount of heat required for charging of a number of spherical capsules (N_s) filled with PCM_2 (beeswax) phase change material for the proposed TESS. The results obtained are:

$$Q_{pcm2} = \rho_{pcm2} * (1 - \gamma) * \left[\left(\frac{\pi * D^2 * H}{4} \right) - \left(\frac{9\sqrt{3} * S^2 * H}{2} \right) \right] * \left[(\alpha' * q') + \left(C'_{p1m} * (T'_m - T_1) \right) + \left(C'_{pm2} * (T_2 - T'_m) \right) \right] \quad (16)$$

Thus the total heat required for charging of the proposed TESS is the summation of Eqn. (15) and (16). That is:

$$Q_C = Q_{pcm1} + Q_{pcm2} \quad (17)$$

Total Heat Required for Thermal Heat Discharging of Proposed TESS

Thermal heat discharging of TESS shell volume with PCM_1

The mathematical modelling methodology used in section 3.1.1 is used to formulate the heat released during the discharging of TESS Shell Volume with PCM_1 as:

$$Q_{pcm1} = \rho_{pcm1} * \gamma * \left[\left(\frac{\pi * D^2 * H}{4} \right) - \left(\frac{9\sqrt{3} * S^2 * H}{2} \right) \right] * \left[(\alpha' * q) + \left(C_{p2s} * (T_s - T_2) \right) + \left(C_{ps1} * (T_1 - T_s) \right) \right] \quad (18)$$

Heat recovered during discharging of TESS spherical capsules volume with PCM_2

The mathematical modelling methodology used in section 3.1.1 is used to formulate the heat recovered during the discharging of TESS Shell Volume with PCM_1 as:

$$Q_{pcm2} = \rho_{pcm2} * (1 - \gamma) * \left[\left(\frac{\pi * D^2 * H}{4} \right) - \left(\frac{9\sqrt{3} * S^2 * H}{2} \right) \right] * \left[(\alpha' * q') + \left(C'_{p2m} * (T'_s - T_2) \right) + \left(C'_{pm1} * (T_1 - T'_s) \right) \right] \quad (19)$$

Thus the total heat recovered during discharging of the proposed TESS is the summation of Eqn. (18) and (19). That is:

$$Q_d = Q_{pcm1} + Q_{pcm2} \quad (20)$$

Evaluation of the Proposed Mathematical Model with Published Results

Charging and discharging time for Paraffin A-53 only

Results from the proposed mathematical model in Eqns. (17) and (20) are compared with the findings reported in for charging and discharging cycle time of paraffin. They have published the time versus temperature variation during charging/discharging of four phase change materials (Paraffin grades A-40, A-44, A-46 & A-53) when charged/discharged individually. The results obtained using the proposed mathematical model are compared with those published in for charging or discharging of paraffin A-53 and

Table 2. Properties of Beeswax and Paraffin (Grade A-53)

Property (unit)	Beeswax	Paraffin wax
Phase change temperature (Melting Point) (°C)	62.4	60.8
Density when (kg/m^3)	970	760
Thermal conductivity (W/m·K) (Solid)	0.31	0.21
Thermal conductivity (W/m·K) (Liquid)	0.41	0.12
Specific heat (kJ/kg·K)	0.476	0.245
Latent Heat (kJ/kg)	242.81	171.87

their plots are as shown in Figs. 3 and 4 respectively. The characteristics of paraffin A-53 were used in the proposed modelled Eqns. (17) and (20) are as in Table 2. Paraffin grade A-53 (PCM_1) is used as compared to other grades of Paraffin grades A-40, A-43 and A-48 for its higher temperatures properties [24]. During validation it was assumed that both the starting time for charging and that for discharging is same and the proposed mathematical model.

It was observed in Figure 3 that, as the temperature was varied for the proposed mathematical model, charging time shows a close behaviour in the beginning. As the temperature rises above 51°C the curve is linearly rising. This is because only sensible heating is absorbed up to 51°C, after which, latent heating consume more time to change the phase from solid state to liquid state for Paraffin A-53. The physical significance is that during solid phase for Paraffin A-53 heat transfer is due to conduction mode only but during its liquid phase heat is transferred by conduction and convection modes. An 8.39% differential error was observed in data by the proposed mathematical model as compared with the published data.

Figure 4 shows plots of discharging time versus temperature for the proposed mathematical mode and experimentation published results. It was observed that during discharging of heat using Paraffin A-53, there was a higher temperature drop for small time interval in the beginning of the process. Below 51°C temperature, the variation of temperature with time is almost linearly downward. As discussed earlier, during discharging, heat is discharged by conduction plus convection mode when Paraffin A-53 changes from liquid to solid (up to 51°C) and only by conduction mode after 51°C as it turn to a solid state. A 9.7% differential error was observed in data by mathematical model compared to published data. This error was observed on the higher side and the model will be subsequently

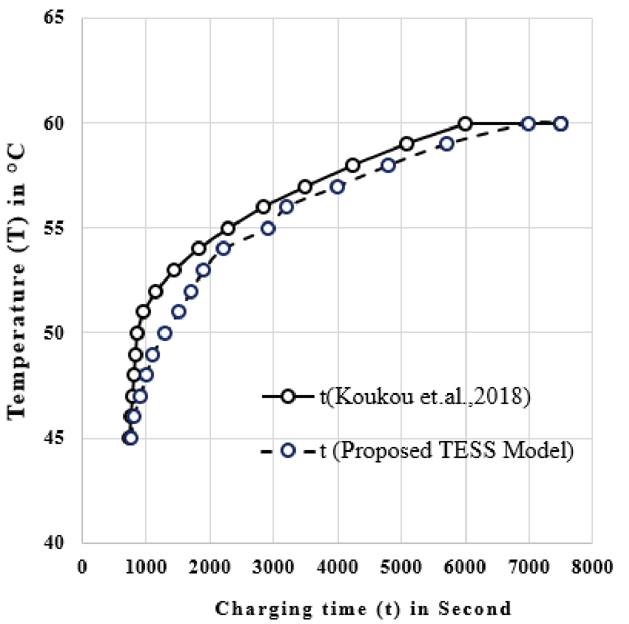

Figure 3. Charging time v/s Temperature. Comparison of results from the proposed mathematical model with published data from for Paraffin.

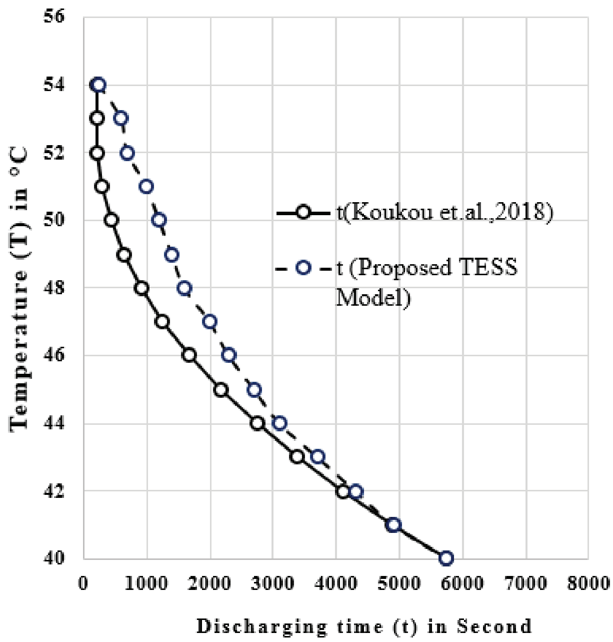

Figure 4. Discharging time v/s Temperature. Comparison of results from the proposed mathematical model with published data from [6] for Paraffin A-53.

modified as the conductivity and heat storage capacity varies with temperature.

Fraction of Paraffin in Total Paraffin Plus Beeswax Mixture in the Proposed TESS

To find the best fraction of paraffin (PCM_1) to beeswax (PCM_2) in the TESS, two characteristics (thermal conductivity (K) and heat storage capacity (Q)) of PCMs are considered. PCM_1 is varied from 70% to 95% in the mixture of (PCM_1 + PCM_2) and K in (W/mK) and Q in (kJ). Thermal conductivity for TESS with different PCM percentage was calculated by using formula for TESS with capsules.

$$K_{1,2} = 0.23 + \left[\frac{0.04 \times \rho \times Ns}{Hc \times Nt} \times \cosh^{-1}\left(\frac{(1.818 \times S) + D - (4 \times Z^2)}{3.64 \times D \times S}\right)\right] \quad (21)$$

In Eqn. (21), N_s is the number of spherical balls and N_t is the number of tubes. H_c is the height of the cylinder shell, ρ is the density of paraffin or beeswax. S is the hexagonal pipe side dimension, D is the diameter of cylinder shell, Z is the distance between the outer shells inside to spherical ball. Figure 5 is the plot of PCM1, PCM2 and a combination of PCM1 and PCM2 percentages. It can be observed that a combination outputs maximum thermal conductivity. The reason behind the drastic increase in thermal conductivity is due to use of n number of capsules. These capsules provide parallel electrical analogy for resistance which will provide series thermal conductivity arrangement in TESS. So whenever there is series arrangement of thermal conductivity there is summation of all thermal conductivity and the system will achieve maximum value.

Figure 5 is the plot of the fraction of PCM_1 in (PCM_1+PCM_2) versus K and Q of the mixture. This analysis was performed so that to obtain an optimal thermal storage capacity (Q) and thermal conductivity (K) of the fraction of PCM_1 and PCM_2 in the proposed TESS.

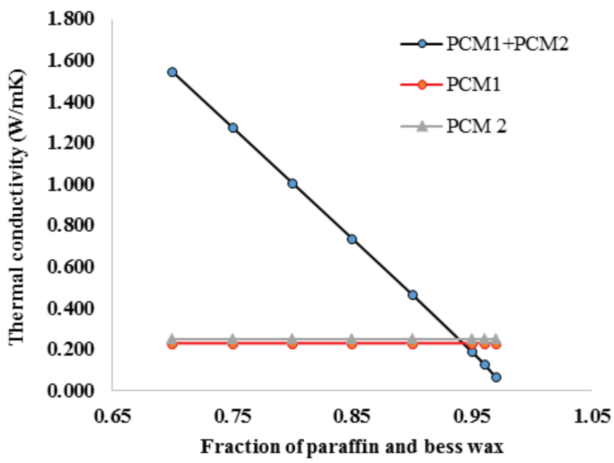

Figure 5. Thermal conductivity of paraffin wax, beeswax and its different percentage combinations.

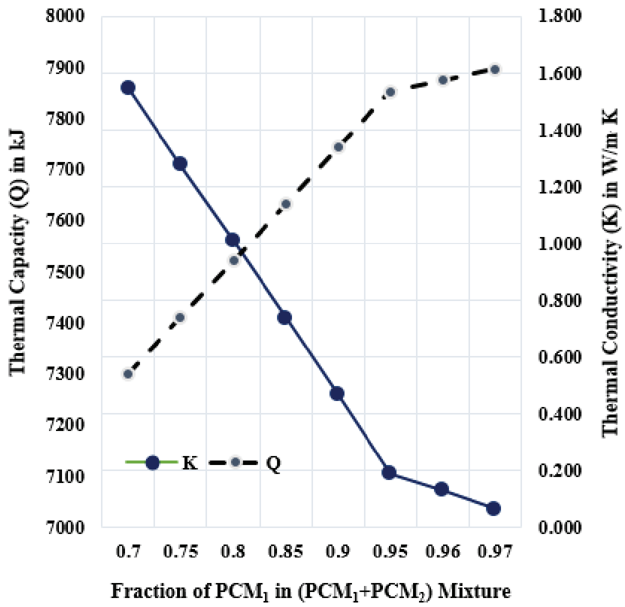

Figure 6. Fraction of paraffin (PCM_1) in total mixture of (PCM_1 + PCM_2) by volume versus Thermal Conductivity (K) and Heat Capacity (Q) of the mixture.

In Figure 6, it was observed that the thermal conductivity (K) decreased as the percentage of paraffin increased in the mixture of (PCM_1 and PCM_2). The decrease in K is due to two reasons, namely, a smaller thermal conductivity of paraffin and due to smaller fraction of PCM_2 in the mixture (PCM_1 and PCM_2). Consequently, when the percentage of paraffin increased in the mixture (PCM_1 and PCM_2) the amount of heat stored (Q) in TESS increased. The increase in Q is attributed to paraffin properties like high heat capacity, high latent heat and greater volume of paraffin in the shell. Figure 6 suggests that the PCM_1 and PCM_2 combinations in the proposed TESS display high thermal conductivity at a lower PCM_1 amount, but if the PCM_1 lower than 70% in the mixture of (PCM_1 + PCM_2) , the number of spherical capsules with PCM_2 in the shell of proposed TESS cannot be accommodated. Therefore the performance of the proposed TESS is investigated for a ratio of 70% paraffin (PCM_1) in shell and 30% beeswax (PCM_2) in copper spherical capsules floating in paraffin in shell.

Performance Analysis of Proposed TESS

Heat storage capacity of TESS with and without capsules

Eqns. (15), (16) and (22) were used in the performance analysis for 70% paraffin (PCM_1) in shell and 30% beeswax (PCM_2) in spherical capsules floating in PCM_1 in shell.

$$Q_{70pbw} = \left[\frac{\pi * D^2 * H}{4} - \frac{9\sqrt{3} * S^2 * H}{2}\right] * \left[\left[\rho_{pcm1} * 0.7 * ((\alpha * q) * (C_{p1m} * (T_m - T_1)) + (C_{pm2} * (T_2 T_m)))\right] + \left[\rho_{pcm2} * (1 - 0.7) * ((\alpha' * q') + (C'_{p1m} * (T'_m - T_1)) + (C'_{pm2} * (T_2 - T'_m)))\right]\right] \quad (22)$$

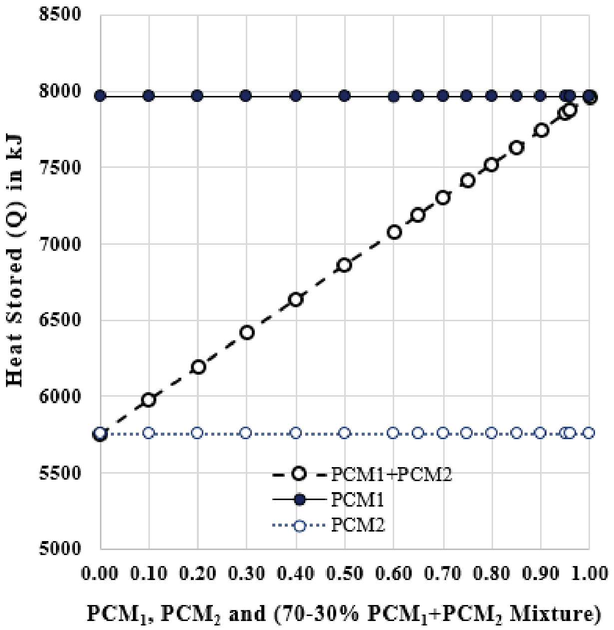

Figure 7. Heat storage capacity (Q) in kJ versus percent of PCM_1, PCM2 and the 70-30% combination of Paraffin (PCM_1) and Beeswax (PCM_2) in the proposed TESS.

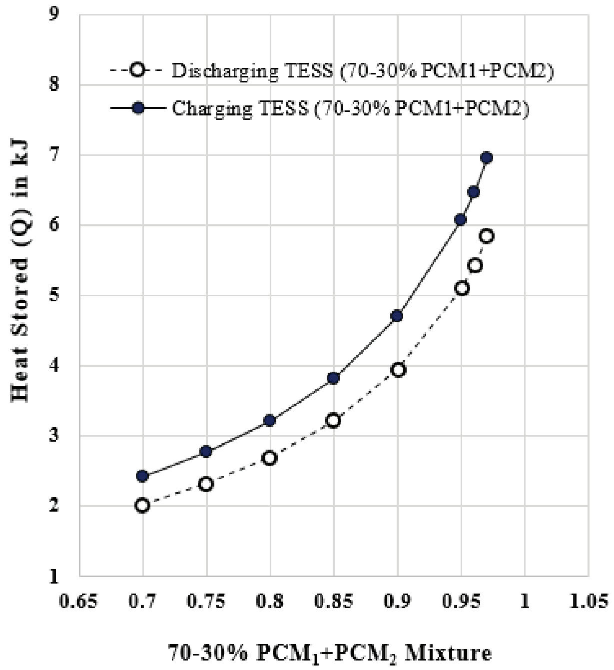

Figure 8. Charging and heat recovery time for the 70-30% paraffin (PCM_1) and beeswax (PCM_2) respectively in the proposed TESS.

Figure 7 is the plot of heat storage capacity in kJ versus the only PCM_1, only PCM_2, and the 70-30% mixture of (PCM_1 + PCM_2) respectively. It was observed that a 70-30% combination of paraffin in shell and beeswax in spherical capsules show combined properties for the two PCMs in the proposed TESS. 70-30% combination of the two PCMs shows a 21.5% greater heat storage capacity if beeswax was used alone and shows an 8.4% reduction in storage capacity if paraffin was used alone in the TESS.

Charging and discharging time for Paraffin in shell and beeswax in capsules for the proposed TESS

The charging or heat recovery time for the proposed TESS with 70% volume PCM_1 (paraffin in shell) and 30% volume PCM_2 (beeswax in spherical capsules) was analysed using Eqns. (23) and (24) respectively. Eqns. (23) and (24) are derived by equating the quantity of heat required during charging/ discharging for PCMs per unit time by convection against the total amount of heat stored or extracted from the proposed TES system. Matlab® was us ed to simulate the results are as shown in Figure 8.

$$t_c = \frac{Q_c * SF_{S-C}^2 * SF_S^2 * K_1 * K_2 * h_1 * h_2}{\Delta T * [((SF_{S-C} * K_1) + (SF_S * K_2)) + ((SF_{S-C} * h_1) + (SF_S * h_2))]} \quad (23)$$

$$t_d = \frac{Q_d * SF_{S-C}^2 * SF_S^2 * K_1 * K_2 * h_1 * h_2}{\Delta T * [((SF_{S-C} * K_1) + (SF_S * K_2)) + ((SF_{S-C} * h_1) + (SF_S * h_2))]} \quad (24)$$

The charging and heat recovery time increased due to reduction in thermal conductivity of PCMs combination and discharging time is greater than charging time. This is due to the more amount of energy required for solidification is higher than liquefaction. Hence by using 70-30% of paraffin and beeswax provided a better option for storage of heat energy and also reduced charging time then discharging time for the proposed TESS. It was obtained using the mathematical model the charging and discharging time of 2 hours 41 minutes and 3 hours 12 minutes for the proposed TESS respectively. With the proposed combination of secondary heat storage with primary storage the charging time and discharging time reduced by approximately a factor of 2.5.

CONCLUSION

A mathematical model with two phase change materials in a single thermal energy storage device shell was proposed and compared for an assumed cloth dryer capacity (7300 kJ) with published experimental data. The proposed TESS used 70% paraffin as the primary heat storage phase change material in the cylindrical shell and 30% beeswax filled in a number of copper spherical capsules (floating in 70% paraffin) as the secondary heat storage phase change material. A copper hexagon three tube arrangement was modelled for heat transfer fluid flow and placed at 120° which showed increased heat transfer surface area during charging and discharging cycle of TESS. The results indicate that with the use of hexagonal tubes, the average heat transfer coefficient increased by approximately 32% relative to the use of circular tubes for the proposed TESS.

In the proposed 70-30% paraffin-beeswax TESS (heat storage capacity 7330 kJ) an increase in the heat storage capacity of approximately 21.5% was obtained over using only beeswax or only paraffin as PCM in the TESS. The heat charging period and heat discharge period were further affected for the proposed TESS A 70-30% combination of the two PCMs shows a 21.5% greater heat storage capacity if beeswax was used alone and shows an 8.4% reduction in storage capacity if paraffin was used alone in the TESS. The model predicts charging and discharging time of approximately 2.6 and 3.2 hours for heat storage of 7300 kJ respectively.

NOMENCLATURE

TESS	Thermal energy storage system
PCM	Phase change material
PCM_1	paraffin
PCM_2	beeswax
LMTD	Log mean temperature difference
LH_W	Latent heat of wet steam
SH_w	sensible heat of water
Q_{pcm1}	Paraffin heat
Q_{pcm2}	Beeswax heat
Q_{pcm}	combine Paraffin and Beeswax heat
Q_c	Heat during charging process
Q_d	Heat during discharging process
Q_{70pbw}	Heat in 70% paraffin and 30% beeswax phase change material
T_1	Initial temperature
T_2	Final Temperature
T_m	Paraffin melting temperature in charging process
T'_m	Beeswax melting temperature in charging process
T_s	Paraffin wax solidification temperature in discharging process
T_s	Beeswax solidification temperature in discharging process
m_1	Mass of PCM_1
m	Mass flow rate of heat transfer fluid
V_S	Volume of sphere capsules
V_{CL}	Volume of cylinder shell
V_t	Volume of tubes
V_H	Volume of hexagonal tube
V_C	Volume of circular tube
V_{pcm1}	Volume of paraffin
ρ_{pcm1}	Density of paraffin
ρ_{pcm2}	Density of beeswax
C_{pm1}	Specific heat capacity of paraffin in liquid phase during charging
C'_{pm2}	Specific heat capacity of beeswax in liquid phase during charging
C_{p1m}	Specific heat capacity of paraffin in solid phase during charging
C'_{p1m}	Specific heat capacity of beeswax in solid phase during charging
C_{p2s}	Specific heat capacity of paraffin in liquid phase during discharging
C'_{p2s}	Specific heat capacity of beeswax in liquid phase during discharging
C_{ps1}	Specific heat capacity of paraffin in solid phase during discharging
C'_{ps1}	Specific heat capacity of bees wax in solid phase during discharging
h_H	Convective heat transfer coefficient of hexagonal tube
h_C	Convective heat transfer coefficient in circular tube
h_1	Convective heat transfer coefficient of paraffin
h_2	Convective heat transfer coefficient of beeswax
K_1	Thermal conductivity of paraffin
K_2	Thermal conductivity of beeswax
K	Thermal conductivity
U_{CT}	Overall heat transfer coefficient in hexagonal tube
U_{HT}	Overall heat transfer coefficient in circular tube
SF_{S-C}	Shape factor of paraffin
SF_S	Shape factor of beeswax
t_c	Charging time
t_d	Discharging time
α	Fraction of mass melted
α'	Fraction of mass solidify
q	Latent heat per unit mass during melting
q'	Latent heat per unit mass during solidification
H	Height
L_t	Length of tubes
H_C	Height of shell cylinder
D	Diameter of Shell cylinder
d	Diameter of spherical capsules
R_{si}	Spherical capsule internal radius
R_{so}	Spherical capsule outer radius
D_i	Cylindrical shell internal diameter
S_i	Internal side of hexagonal tube
S_o	Outer side of hexagonal tube
N_s	Number of spherical capsules
N_t	Number of tubes
ϒ	Fraction of paraffin phase change material

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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