EFFECT OF UNIFORM AND VARIABLE FIN HEIGHT ON CHARGING AND DISCHARGING OF PHASE CHANGE MATERIAL IN A HORIZONTAL CYLINDRICAL THERMAL STORAGE

by

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The effect of fin profile on melting of phase change material (PCM) is presented. The test section contains an acrylic tube of 50 mm outer diameter and a copper tube of 16 mm outer diameter and a length of 1000 mm each. Both tubes are kept coaxially. The heat transfer fluid (HTF) flows through the copper tube. The PCM is paraffin wax and filled in the annular region. The considered fin profiles are the uniform and variable fin heights of circular, triangular and elliptical profiles. Fins are fixed on the HTF tube and protruded into the PCM. The total fin surface area is maintained same among the fin profiles and the fin arrangements. The one-third of the storage is provided with increasing fin height of 2-3 mm to melt the settled solid PCM. The hot and cold water is used to charge and discharge the PCM, respectively. Experiments are performed by the hot and cold-water inlet temperatures of 70 °C and 28 °C at a flow rate of 0.5 kg per minute. A faster and effective heat transfer from HTF to PCM and vice-versa is investigated. The variable elliptical fins showed faster charging and discharging by 25% and 20%, respectively, than the variable circular fins. The variable elliptical fins showed faster charging and discharging by 11.8% and 11% than the variable triangular fins. The charging and discharging efficiency of 80% and 74% are observed for the elliptical fin profiles.

Key words: *cylindrical PCM storage, fin profile, melting of PCM, solidification of PCM*

Introduction

The utilization of solar energy for domestic hot water (DHW) production is an alternative and attractive option for the fossil fuels. Thermal energy storage (TES) improves the efficiency and reliability of such solar thermal systems. Thermal energy may be stored in the form of sensible and latent heat to reduce the gap between the demand and supply of solar energy. Latent heat storage has a high-energy storage capacity per unit volume when compared to sensible heat storage. A large number of suitable PCM have been reported for TES with a low thermal conductivity in the range of 0.1-0.7 W/mK. The enhancement of the heat transfer to and from the PCM using metallic fins on the heat transfer tube surfaces are carried out by several researchers [1]. The optimum performance of solar air heater depends on the PCM materials and the geometry. The recent designs are the integration of storage into the collector to reduce the cost and volume of the system [2, 3]. Sharifi *et al.* [4] reported the horizontal fins producing a rapid melting during the early stages of the phase change and resulted in a slow melting regime in a horizontal metal enclosure filled with PCM. The effect of fin length and thickness on melting were reported.

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Thermal characteristics of paraffin are proved as one of the effective PCM for DHW. The transition temperature range and the heat of fusion are in the range of 40-110 °C and 140-280 kJ/kg. Paraffin wax is cost-effective, commercially available, chemically stable, the low vapor pressure in the melting process and no significant phase change segregation. Thermo chemical properties like thermal conductivity, thermal and chemical stability are needed to improve the effectiveness of PCM in the real-time applications [5]. The consecutive and simultaneous charging and discharging of PCM in a cylindrical thermal storage were investigated by Robynne and Dominic [6, 7]. Xiao and Zhang [8, 9] studied the charging and discharging behavior of shell-tube thermal storage. The melting and solidification of PCM in a horizontal tube in shell thermal storage are studied by Yazici *et al.* [10, 11] by moving the HTF tube eccentrically below the center to melt the settled solid PCM. Hosseini *et al.* [12] studied the effect of fin height and Stefan number on the performance of a shell and tube PCM heat exchanger. The increase in Stefan number reduced the melting time. The increase in fin height improves the solidification at a reduced melting rate. The melting and solidification of PCM were investigated using internal and external fins, metal meshes, foam structures and PCM enclosures with different geometries/orientations [13, 14]. The eccentricity of HTF tube decreases the melting time of PCM.

Walter *et al.* [15] investigated the effect of finned HTF tube in the vertical thermal storage. They demonstrated the obstruction reduced the melting and solidification velocity towards the outer shell. The radial conductive fins using circular, elliptical HTF tube in a horizontal cylinder were investigated by Rabienataj *et al.* [16]. They found the fins placed over the HTF tube suppressed the natural convection and improved the solidification process. The vertical elliptical tube enhanced the melting but not effective during the solidification process. A finned coil latent heat storage was investigated by and Chen *et al.* [17]. Hlimi *et al.* [18] investigate the constrained melting in a horizontal capsule. They observed the stable melting zone for low Rayleigh number due to dominant viscous effects. Rengarajan and Karunakaran [19] investigated the solidification rate using the triple concentric tubes by keeping the paraffin wax in the intermediate regions. The reduction of solidification is demonstrated. Xiong *et al.* [20] compared the HTF tube of single U-tube on the melting of PCM in a vertical cylindrical PCM container. They found the U-tube reduces the melting time by 25% when compared to the single tube. Antonio *et al.* [21] presented the effects of different parameters like thermostat temperature, capsule thickness, capsule conductivity and natural convection in the bath on the selection of materials or geometries of the PCM capsule.

Heat transfer from HTF to PCM in TES system is not effective due to buoyancy force and gravitation force, the melting of PCM is incomplete and solid PCM settlement is observed in the bottom of the acrylic container. The incomplete or prolonged melting of PCM implies the poor utilization of energy with reduced efficiency. During the charging process, the heat transfer from HTF to PCM is poor at the exit of the storage. Due to low thermal conductivity of PCM, it takes more time taken for complete charging and discharging of PCM. The solid PCM remains in the storage and consumes more time and input energy to melt completely. One of the cost-effective concepts is to optimize the geometry of shell and tube arrangement, thereby aiding natural convection and by improving the thermal conductivity of PCM. Fins are used in the thermal storage to reduce the melting duration of PCM. The heat transfer rate and phase change duration for charging and discharging are the main factors to be considered in the thermal storage systems. The recent research suggests the additives to the PCM to increase the heat transfer. However, there is a trade-off between the heat transfer and cost of additives. The effect of increasing fin height towards the cold end of the storage is not discussed in the literature. The effect of three fin profiles, namely circular, triangular and elliptical fins with two arrangements of uniform and variable fin height below the HTF tube axis are experimentally studied in this work. The fin profiles and arrangements are tested for the charging and discharging performance at a fixed HTF inlet temperature and HTF flow rate. The improved thermal performance is reported.

Experimental work

The experimental set-up consists of an electric heater (7 kW capacity) with thermostat-control, hot water supply tank, TES test section, circulating pump, flowmeter and flow control valves. The heater imitates the solar water heater. The TES test section consists of an acrylic tube of an outer diameter (OD) of 50 mm, the height of 1000 mm and 2.5 mm thickness. The copper tube has an OD of 16 mm and a length of 1000 mm. The PCM container and copper tube are kept concentric. The 90% volume of the test section is filled with 1.25 kg of paraffin wax (RT60). The PCM has a peak melting temperature, phase change enthalpy, specific heat and thermal conductivity of 60 °C (melting range is 58 °C and 61 °C), 160 J/g, 1.9 Jg/K (solid) and 2.1 Jg/K (liquid) and 0.2 Wm/K, respectively. The density of solid and liquid PCM at 15 °C and 80 °C is 880 kg/m^3 and 770 kg/m^3, respectively. The circular, elliptical and triangular fins are fixed on the HTF tube. The three fin profiles are shown in fig. 1. Fin surface area and the distance between the fins are same. Twenty fins are welded at a uniform interval on the HTF tube. The fin spacing is provided as 40 mm to assist the natural convection in the liquid PCM. Two fin arrangements are investigated in this work. One arrangement is with uniform fin height of 8 mm and another arrangement is with the six gradually increased fin heights (2-3 mm) near the exit. The uniform and variable fin heights are shown in fig. 2. The rear end fins provided 2-3 mm eccentricity below the axis of the HTF tube. Such fins have the additional length to diffuse the heat to the settled solid PCM. The total weight of variable fins is 13% more than the uniform fin profile.

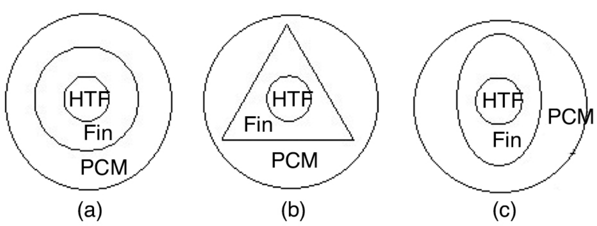

Figure 1. Fin profiles (a) circular, (b) triangular, and (c) elliptical fins

Both the arrangements of fins are tested with the same HTF, fluid inlet temperature and flow rate during the charging or discharging of PCM. Hot water is passed from the tank to the test section containing PCM and re-circulated by a circulating pump. The water-flow rate is controlled by the adjustable speed drive for single phase motor pump. The water tank temperature is adjusted and controlled by a thermal control unit. The heater section and TES are insulated using 50 mm thick glass wool material. The K-type thermocouples are located at the overhead tank, inlet and outlet of the copper pipe, respectively.

The variable fin height is considered to enhance the PCM melting in the cold section below the HTF tube. The bottom tip of the fin is used to enhance and ensure complete melting of

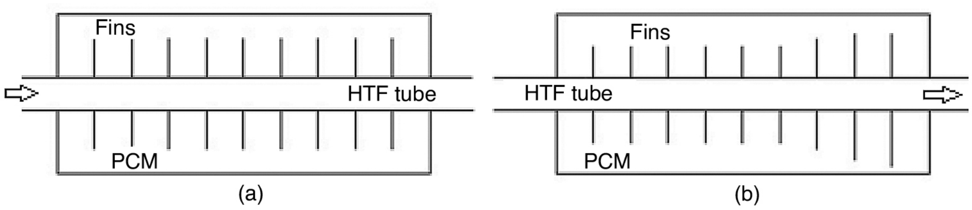

Figure 2. Schematic diagram of fin height; (a) uniform fin height; (b) variable fin height

PCM. The elliptical geometry with increased fin height increases the conduction heat transfer to the PCM. The incremental in fins height are provided based on HTF flow direction. At the inlet side, the fin height remains uniform height and at the outlet side the fins height increased to maximum to ensure the efficient heat transfer within the PCM. The same fin arrangement is studied for both charging and discharging periods. The HTF flow rate and inlet temperature are 0.5 kg per minute and 70 °C, respectively, during the charging of PCM. The HTF inlet temperature is 28 °C during the discharge processes at a flow rate of 0.5 kg per minute. The photographic view and schematic diagram of the experimental setup are shown in fig. 3.

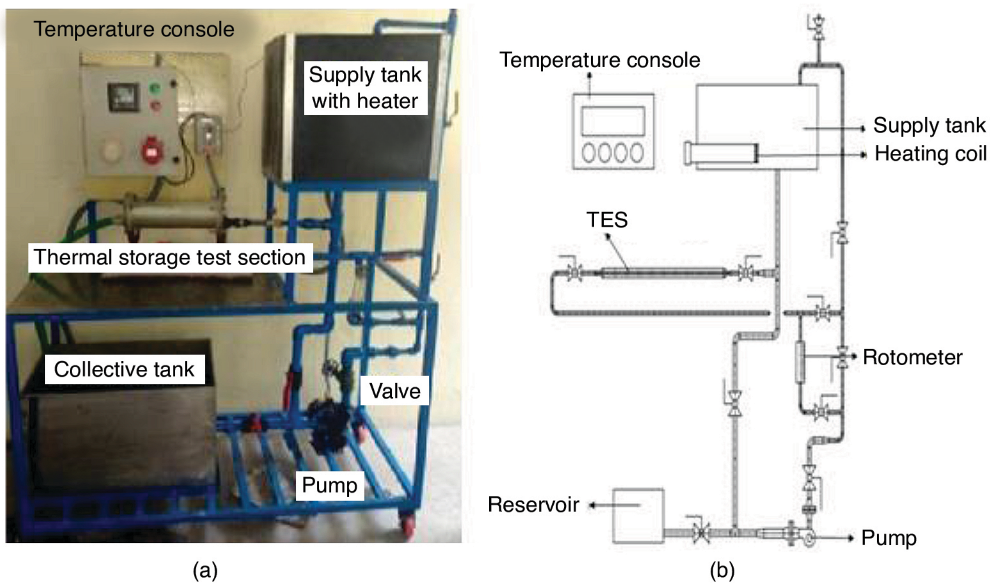

Figure 3. Experimental set-up; (a) photographic view without insulation (b) schematic diagram

Heat transfer by heat transfer fluid is given:

$$Q_u = mC_p\,(T_o - T_i) \tag{1}$$

where m [kgs^{-1}] is the HTF flow rate, C_p [Jg^{-1}K^{-1}]is the specific heat of HTF, and $(T_o - T_i)$ is the temperature difference of HTF at inlet and outlet of TES.

Heat stored in the PCM is given:

$$Q_{ch} = m_{PCM}\,[C_{p,PCM}\,(T_m - T_i) + H + C_{p,PCM}\,(T_f - T_m)] \tag{2}$$

where m_{PCM} [kg] is the mass, $C_{p,PCM}$ [kJkg^{-1}K^{-1}] is the specific heat, T_i, T_f, and T_m are the initial, final, and melting temperature of the PCM and H [Jg^{-1}] is the phase change enthalpy. The charging and discharging efficiency is calculated using the heat lost or gained by the HTF and the heat stored or released by the PCM. The heat stored by the heating of PCM is calculated using the eq. 2. The temperature of PCM are recorded at three locations in the PCM container at a distance of 0.3 m, 0.6 m, and 0.9 m from the HTF entry using K-type thermocouples (accuracy of ± 0.5 °C). Two thermocouples are kept at each thermocouple locations from 12.5 mm and 42.5 mm from the bottom inner surface of the PCM container. Six thermocouples are used inside the PCM container to observe the temperature distribution in the PCM. The thermocouple locations in the PCM are shown in fig. 4.

The flow rate is measured by a flowmeter (accuracy of ± 1 kg/h). The uncertainty of charging and discharging time is 1.58%. The measurements are found within the permissible errors of less than 5%.

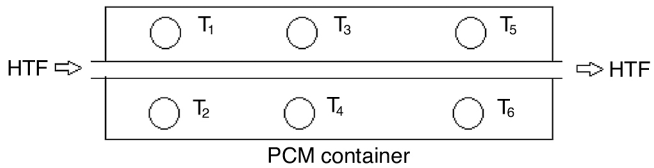

Figure 4. Thermocouple locations in the PCM

Results and discussion

Three fin profiles are tested to charge the PCM using hot water at a flow rate of 0.5 kg/min and a temperature of 70 ºC. Cold water at the same flow rate and a temperature of 28 ºC is used to discharge the heat of PCM. The ambient temperature is observed in the range of 30°C and 33 °C during the experimental work. The average temperature of PCM during the charging and discharging for the fins profiles and arrangements followed a similar trend over the time. The melting time, charging, and discharging efficiencies are determined. Figure 5 shows the temperature measured by the six thermocouples and the thermocouples near the entry (T1 and T2) showed the melting is earlier than the PCM at the exit (T5 and T6). Temperature at thermocouple – 6 reached the melting point of PCM after 20 minutes than the thermocouple – 1.

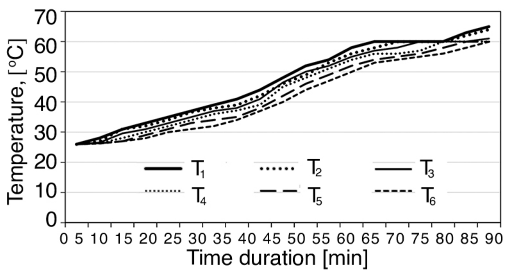

Figure 5. Temperature of PCM at six thermocouple locations for uniform circular fin profile

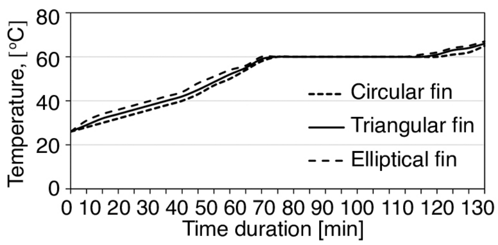

Figure 6. Charging behavior of PCM for the uniform fin height arrangement

Figures 6 and 7 show the time of charging the PCM for the uniform and variable fin height arrangements respectively. The average temperature of PCM is shown in the figs. 6-9 with respect to the uniform and variable height fins.

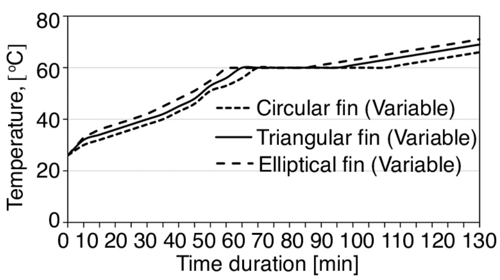

Figure 7. Charging behavior of PCM for the variable fin height arrangement

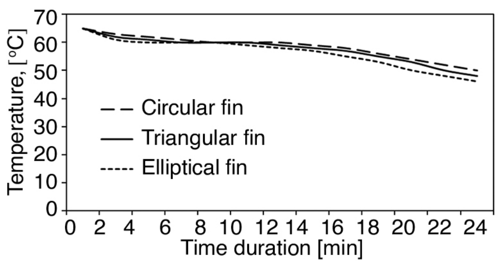

Figure 8. Discharging behavior of PCM for the uniform fin height arrangement

Figures 8 and 9 show the time of discharging the PCM for the uniform and variable fin arrangements. The variable length of fins at the rear end of the storage is observed effective in the complete melting and solidification of the PCM. Variable fin height is provided only after one-third length of the storage where the PCM melting is slow due to the drop in temperature of the HTF. Testing of the same length of fins throughout the storage and the variable fin length *i.e.*, incremental fin length near the outlet is also tested with the same HTF inlet conditions. The melting of PCM or solidification of PCM near the entry is completing at a faster rate than the end of the storage. The drop in the temperature of the HTF lacks the thermal energy to melt or solidify the PCM at the rear end.

The increased fin increases the heat conduction and assists the phase change process. There is an increase of the charging efficiency of 4% for the same operating inlet temperature for the elliptical fins. From fig. 10, the time required for charging of PCM from room conditions to 50 °C is observed with 115 minute, 110 minute, and 105 minute for the uniform fin profiles and 100 min, 85 minute and 75 minute for variable fin heights of circular, triangular and elliptical fins, respectively. The reduction of charging time by uniform elliptical fins are 8.7% and 4.5% when compared to circular and triangular fins respectively. The reduction of charging time by the variable height of elliptical fins are 25% and 11.8% when compared to circular and triangular fins, respectively.

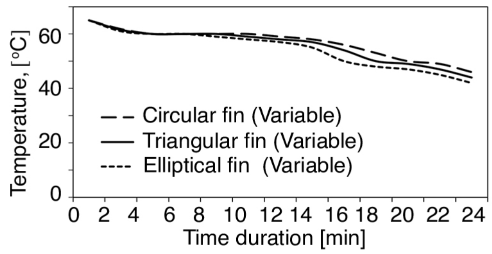

Figure 9. Discharging behavior of PCM for the variable fin height arrangement

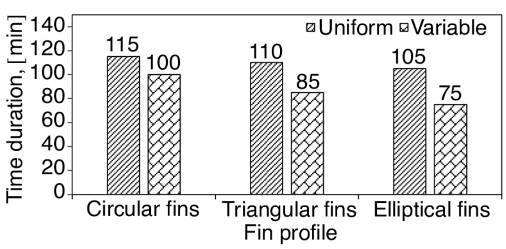

Figure 10. Charging time of PCM using uniform and variable fin arrangements

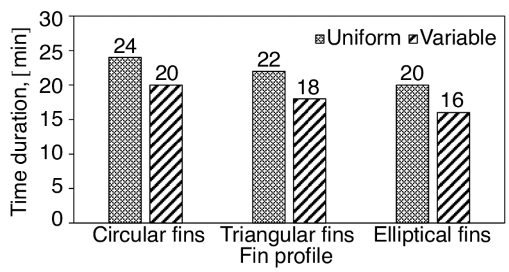

Figure 11. Discharging time of PCM using uniform and variable fin arrangements

The discharging experiments are carried out on the PCM storage at the HTF flow rate of 0.5 kg per minute to extract the stored heat of the PCM. The HTF inlet temperature is 28 °C for all tests. From fig. 11, the time required for discharging of PCM from melting point to 50 °C is observed with 24 minute, 22 minute, and 20 minute for the uniform fin profiles and 20 minute, 18 minute, and 16 minute for variable fin heights of circular, triangular and elliptical fins respectively. The thermocouple readings are used to observe the complete melting of PCM. The reduction of discharging time by uniform elliptical fins are 33% and 9% when compared to circular and traingular fins respectively. The reduction of discharging time by the variable height of elliptical fins are 20% and 11% when compared to circular and triangular fins, respectively.

The heat lost by the water across the TES is used to determine the cumulative heat input over the time duration. The heat stored in the PCM is determined through the initial and final temperature of PCM in the test duration. The charging efficiency is the ratio of heat stored in the PCM to the heat input by the hot water. The charging efficiency varies from 76.6 to 79.8% for the uniform fin height and 78.2 to 82.6% for the variable length fins in fig. 12.

The discharging efficiency varies from 70.6 to 73.7% for the uniform fin height whereas 72.5 to 75.7% for the variable length fins at the end from fig. 13. The complete discharge occurs faster and it will be useful to meet the thermal needs with a faster response time. The charging and discharging efficiency of 80% and 74% are observed for the variable length elliptical fins.

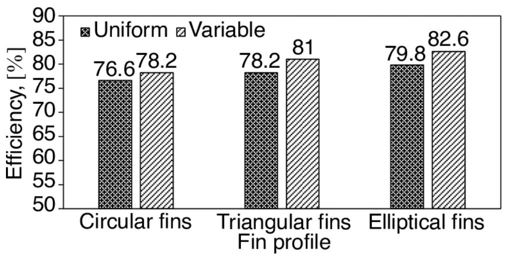

Figure 12. Charging efficiency of TES using uniform and variable fin arrangements

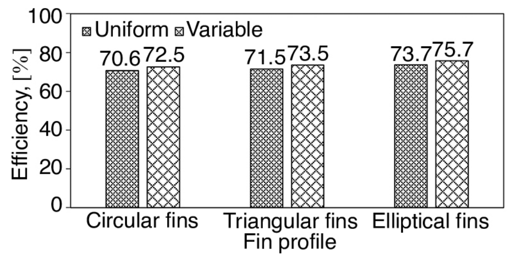

Figure 13. Discharging efficiency of TES using uniform and variable fin arrangements

The fins with more height in the cold end of the storage further improves the thermal performance of the storage. The gradually increasing fin height towards the farther end of the storage makes the complete melting of PCM. Elliptical fins with incremental length have the maximum heat transfer rate at the selected HTF flow rates and inlet temperature. The elliptical fins are observed with more heat transfer rate in elliptical fin geometry than circular fin geometry. The elliptical fins are more efficient than the other fin types. Also with the incremental length of the elliptical fins are effective to melt the settled solid PCM at the bottom of the shell. The melting time is reduced by 25% by changing the fins from variable circular to variable elliptical fins. The elliptical fins are observed with faster heat addition as well as heat retrieval between the PCM and the HTF when compared to circular and triangular fins. The elliptical fins diffuse the heat into the PCM and aid the melting process by heat conduction. The selection of an elliptic fin is beneficial for the maximum heat transfer at a particular fin volume and the fixed mass of PCM.

Conclusions

The elliptical fin profile is found to be effective when compared to circular and triangular fins by melting the settled solid PCM in the bottom of the storage. The quick charging process makes the maximum storage of energy in the stipulated operational hour of the solar collector. The complete discharge occurs faster and it will be useful to meet the DHW with less time. The charging and discharging efficiency are observed as 80% and 74% for the variable elliptical fin arrangements. The variable fin height of 2-3 mm reduces the melting time and solidification time compared to the uniform fin arrangements. The elliptical fins with variable fin height are charging the PCM faster by 25% and 11.8% than the variable circular and triangular fins, respectively. The elliptical fins with variable fin height are discharging the PCM faster by 20% and 11.8% than the variable circular and triangular fins respectively. Elliptical fin profiles with gradually increasing the fin height from the hot end to cold end are suitable for effective charging of TES for the DHW applications. This concept is not only applicable to a small thermal storage alone but also to the large scale thermal storage designs.

Nomenclature

C_p – specific heat of HTF, [$Jg^{-1}K^{-1}$]
H – phase change enthalpy, [Jg^{-1}]
m_{PCM} – mass of PCM, [kg]
$\dot{m}$ – mass-flow rate of HTF, [kgs^{-1}]
Q_u – heat transfer rate, [W]
T_m – melting temperature of PCM, [K]
T_f – final temperature, [K]
T_i – initial temperature, [K]
T_o – outlet temperature, [K]

Acromyms

DHW – domestic hot water
HTF – heat transfer fluid
OD – outer diameter
PCM – phase change material
TES – thermal energy storage

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