A PARAMETRIC STUDY USING THE E-NTU METHOD FOR A PHASE CHANGE THERMAL STORAGE UNIT FOR A NIGHT TIME COOLING SYSTEM

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Abstract

An investigation into characterising and optimising the useful latent energy that can be stored within a tube-in-tank phase change thermal energy storage system has been conducted, with particular reference to off peak thermal storage applications. This process involved considering the thermal resistance during charging and discharging as well as the amount of phase change material (PCM) that can be physically stored within a storage system with tubes in a storage tank for a night time cooling system using a cooling tower. The thermal resistance was investigated through the use of the heat exchange effectiveness of the PCM system which was studied using a validated ε-NTU model. An energy storage density coefficient of a PCM system was determined and the impact of the tube length and the mass flow rate supplied to the system was investigated. This storage coefficient was optimised delivering a true energy storage density of 62.9% and 82% of the latent energy density of the PCM. This parameter can be directly compared to sensible storage systems and it was found that coil-in-tank systems can achieve a useful storage density of more than 20 times that of sensible storage systems.

1. Introduction

Melting and freezing phase change material (PCM) is an effective way to store thermal energy in the form of solar energy, industrial waste heat and off-peak electricity. The main advantages of such storage system are the high storage capacity and recovery at almost constant temperature (Choi and Kim, 1995; Agyenim et al., 2010). A phase change thermal energy storage system not only minimises the disparity between supply and demand but also improves the performance and reliability of the energy system and plays a vital role in energy conservation (Sharma et al., 2009). Due to the high energy storage density and the smaller amount of weight and volume for a known amount of energy, a phase change thermal energy storage system is a particularly attractive system compared to sensible energy storage system (Agyenim et al., 2010). Another major advantage of using PCM in a thermal energy storage system is the ability to store energy in low temperature differences.

The main disadvantage of using PCM in a thermal energy storage system is its low thermal conductivity. These thermal properties will often leads to low charging and discharging rates, which will in turn decrease the overall effectiveness of the system (Agyenim et al., 2010). To overcome the low thermal conductivity of PCMs, heat transfer enhancement techniques are required for most thermal energy storage applications. Extensive research has been conducted to study heat transfer enhancement techniques in PCMs. These techniques are finned tubes of different configurations (Choi and Kim, 1995; Abdel-Wahed et al., 1979; Ermis et al., 2007; Ismail et al., 2001; Horbaniuc et al., 1999; Sparrow et al., 1981; Sasaguchi and Takeo, 1994; Zhang and Faghri, 1996; Velraj et al., 1997), bubble agitation (Velraj et al., 1997), insertion of a metal matrix into the PCM (Trelles and Dufly, 2003; Hoogendoorn and Bart, 1992), using PCM dispersed with high conductivity particles (Mettawee and Assassa, 2007), micro-encapsulation of the PCM (Griffiths and Eames, 2007; Hawlader et al., 2003) or shell and tube (multitubes) (Agyenim et al., 2010; Hendra et al., 2005). This paper will focus on tube-in-tank phase change thermal energy storage systems which are similar to shell and tube.

Models created using the effectiveness-number of transfer units (ε-NTU) methodology have been conducted by several researchers. Browne and Bansal (Browne and Bansal, 2001) presented a new steady-state model for vapour-compression liquid chillers. The principle of this model is on physical laws and heat transfer coefficients. In order to better predict the heat transfer, the heat exchanger is divided into elements by applying the elemental ε-NTU methodology. Mathew and Hegab (Mathew and Hegab, 2010) developed a thermal model of a parallel flow microchannel heat exchanger subjected to external heat transfer. In the laminar flow regime, the effectiveness of the fluids in parallel flow microchannel heat exchangers and the axial temperature can be predicted. When subjected to external heating for a specific NTU, the effectiveness of the hot fluid would decrease while the cold fluid increased. In the presence of external cooling, the effectiveness of the hot fluid was observed to improve while the cold fluid degraded.

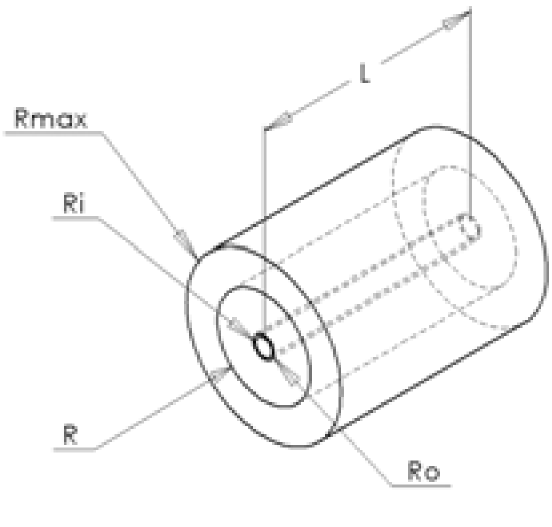
A major consideration with phase change storage systems is the thermal resistance to heat transfer between the heat transfer fluid (HTF) and the PCM (Belusko and Bruno, 2008). To reduce this resistance, PCM/graphite systems have been developed (Hamada and Fukai, 2005; Xia et al., 2010), as well as adding conductors within the PCM (Fan and Khodadadi, 2011) significantly enhance the heat transfer within the thermal storage system. To quantify the impact of the thermal resistance of a PCM system, a one dimensional equation of the effectiveness of a thermal storage unit (TSU) based on the ε-NTU approach has been formulated by Belusko and Bruno (2008). The effectiveness of one and two dimensional phase change within a PCM slab was defined in term of phase change fraction. Employment of phase change fraction characterizes the TSU into a single effectiveness parameter and thus developing a useful method for determining the size of the TSU, which defines the useful energy storage density for a specific application.

A simple mathematical model was developed by Tay et al. (2010) based on the ε-NTU technique for tubes in a phase change thermal energy storage system. Tubes are coiled inside a cylindrical tank filled with PCM. The HTF passes through the tube during the charging and discharging processes. The model assumes that the phase change of the PCM will be uniform with the tube. Experiments have been conducted to validate the numerical analysis. The results from the mathematical model and the experimental data revealed an agreement between the predicted and experimental values.

In this paper, a parametric study has been conducted on tubes in a phase change thermal energy storage system based on the ε-NTU technique developed by Tay et al. (2010). By varying the parameters of tubes in a phase change thermal energy system, it will enable a complete optimisation study and a comparison can be made to a sensible storage system.

2. Effectivessness-NTU Technique

A one dimensional mathematical representation of the heat flow between the HTF and the PCM at the phase change profile was then developed by Tay et al (2010). The NTU is determined from the thermal resistance to the heat flow within the HTF and the section of the PCM which has undergone phase change. One mathematical representation of the resistance in the PCM is defined. The phase change is assumed to occur in one dimensional from the internal surface of the tube to an external boundary in the PCM. The representation assumes the phase change occurs in a cylindrical pattern, defined by a round shape factor as shown in Fig. 1 (a). These assumptions are based on the internal temperature measurements within the PCM shown in Fig. 2. Fig. 1 (b) shows the thermal circuit for the models.



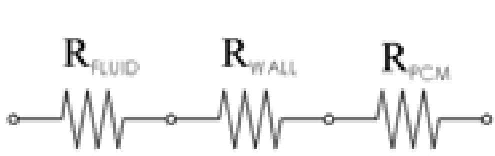


Fig. 1: Simplified model of the round shape factor (a) and thermal circuit (b) (Tay et. al., 2010)

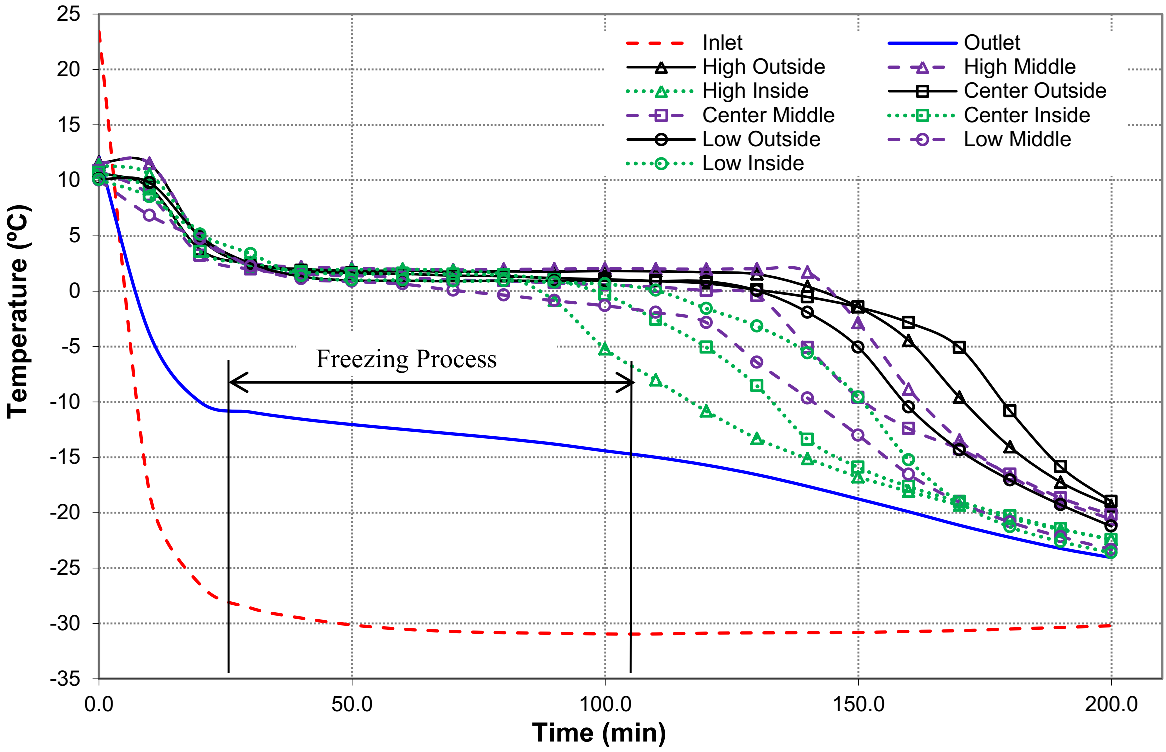


Fig. 2: Typical Freezing process for the Four Coils Tank with mass flow rates of 0.019 kg/s for PCM0 with an average effectiveness of 0.56 [26] (Tay et al., 2011)

In this work, the ε-NTU technique is validated for the freezing process using water (Tay et al., 2010). As for the melting process, it was found that the accuracy of the ε-NTU technique is dependent on the ratio of the average thermal resistance within the PCM to the total thermal resistance. When the resistance of the PCM is found to be high, the effect of natural convection will be significant, thus causing a large error between the ε-NTU analysis and the measured results. Therefore, the ε-NTU technique on the melting process will be validated when the ratio of the average thermal resistance within the PCM to the total thermal resistance is not too big, thus relying on the resistance of the HTF which is more consistent.

3. Characterisation of tube-in-tank PCM system

The PCM storage system consists of several tubes coiled inside a cylindrical tank filled with PCM. The HTF passes through the tubes during the charging and discharging processes as shown in Fig. 3. Heat transfer to the surroundings is ignored. When operating as an off-peak storage system, energy is stored in the PCM during the solidification or charging of the PCM and released from the PCM during melting or discharging process.

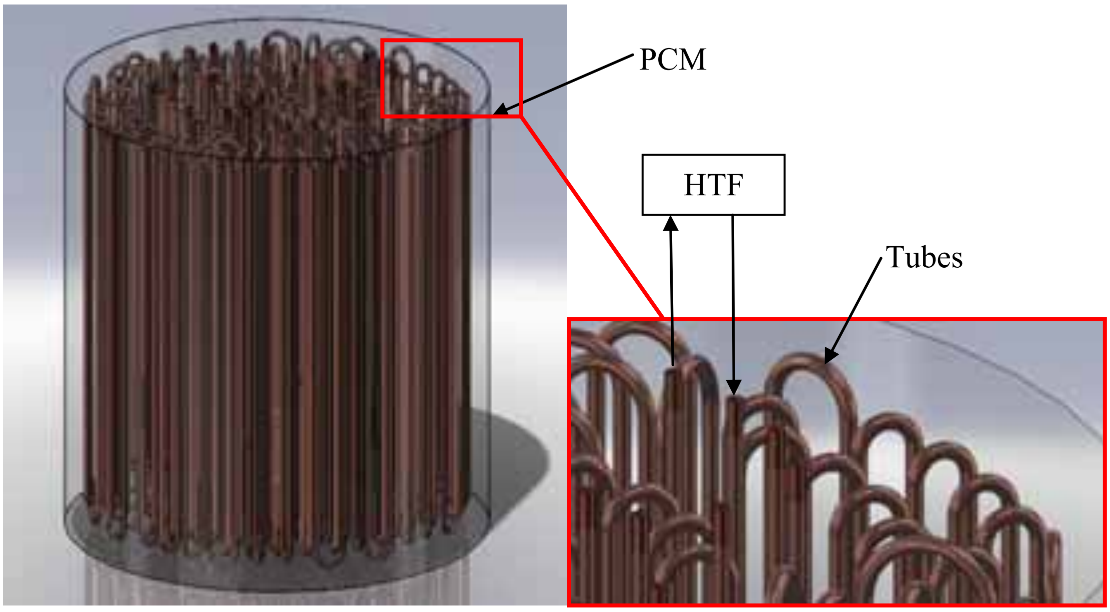


Fig. 3: Tube-in-tank PCM energy storage system

During the phase change process, heat is exchanged between the heat transfer fluid and the phase change interface within the PCM, at the phase change temperature. This heat transfer is a function of the thermal resistance in the heat transfer fluid and in the PCM proportion which has already changed phase. Therefore the outlet fluid temperature is determined by the thermal resistance in the system and limited by the phase change temperature. Maximum heat transfer is achieved when the outlet temperature equates to the phase change temperature.

In order to achieve energy efficient storage the inlet temperature of the heat transfer fluid during charging should be the maximum possible temperature to maximise the coefficient of performance of the refrigeration system. The maximum possible temperature is determined by the required rate of heat removal from the PCM during the charge period, which is determined by the thermal resistance to heat transfer. To maximise the charge fluid temperature, the outlet fluid temperature should equate to the PCM phase change temperature, while providing adequate heat transfer.

The thermal resistance also affects the discharge temperatures which are achieved from a PCM storage system. Discharge temperatures are specified by the cooling requirements of the load. Ideally, the discharge temperature should equate to the phase change temperature of the PCM. However, due to the thermal resistance, the discharge temperature will be above this temperature, and therefore a lower temperature PCM is required. As a result, charging this PCM is more energy intensive. Consequently, energy efficient storage is dependent on minimising the thermal resistance to heat transfer in the PCM storage system, effectively minimising the temperature difference between the heat sink and the heat source. This approach minimises any sensible storage in the PCM which is defined by the change in temperature of the material, and as a result, sensible energy storage is ignored.

The outlet temperature from the PCM system determines the heat transferred between the heat transfer fluid and the PCM and consequently, thermal performance can be expressed in terms of heat exchange effectiveness. This effectiveness directly relates to the thermal resistance in the PCM storage system as explained by Belusko and Bruno (2008). If the heat transfer rate does not vary with time, the effectiveness of a PCM storage system is defined by eq. 1, where Q_{act} is the actual energy stored, Q_{max} is the max energy stored, T_{in} is the inlet temperature of the HTF, T_{out} is the outlet temperature of the HTF and T_{pcm} is the temperature of the PCM. Therefore, over the period of phase change, the actual energy stored and released is defined by this effectiveness, which directly affects the useful energy that is stored. Therefore the actual useful energy which is stored is the product of the effectiveness of freezing and melting.

$$\varepsilon = \frac{Q_{act}}{Q_{max}} = \frac{(T_{in} - T_{out})}{(T_{in} - T_{pcm})} \qquad \text{(eq. 1)}$$

The compactness factor, CF for PCM in a tube-in-tank thermal storage system is represented by eq. 2, and directly affects the volumetric energy density of a storage system. The CF is the ratio of the volume of PCM to the volume of the tank. Therefore the expected storage density of a PCM storage system can be defined by an energy storage density coefficient, γ, which can be directly applied to the volumetric latent heat of a PCM as in eq. 3, where ε_f is the freezing effectiveness and ε_m is the melting effectiveness. The resultant storage density represents the storage density achievable by the PCM system, and can be directly compared to a sensible energy storage system.

$$CF = \frac{R_{max}{}^2 - R_o{}^2}{R_{max}{}^2} \quad \text{(eq. 2)}$$

$$\gamma = \varepsilon_f . \varepsilon_m . CF \quad \text{(eq. 3)}$$

To consider pumping losses within the PCM storage system, a modified freezing and melting effectiveness value, ε_{f*} and ε_{m*} was determined using eq. 4. Total losses of the system, P_L are then calculated using eq. 5 where $\dot{V}$ is the volumetric flow rate.

$$\varepsilon_{f*,m*} = \varepsilon_{f,m} - \frac{P_L}{Q_{max}} \quad \text{(eq. 4)}$$

$$P_L = \frac{\Delta P.\dot{V}}{\eta_p.\eta_{p.s}} \quad \text{(eq. 5)}$$

Pump efficiency, η_p and power station efficiency, $\eta_{p.s}$ were fixed at 50% and 35%, respectively. As the heat transfer fluid moves through the tubes, the pressure drop can be evaluated by eq. 6 where f is the friction factor; d is the inner tube diameter and u_m is the velocity of the HTF in the tube. The entrance and exit losses are ignored as these exist in any sensible storage system.

$$\Delta P = f.\frac{L}{d}.\rho.\frac{u_m{}^2}{2} \quad \text{(eq. 6)}$$

Therefore, the modified energy storage density coefficient of the system, γ* can be written as:

$$\gamma * = \varepsilon_{f*} . \varepsilon_{m*} . CF \quad \text{(eq. 7)}$$

4. Thermal storage optimisation

A parametric study of the energy storage density coefficient was conducted, investigating the impact of the length of the tube, tube diameter, number of tubes and the mass flow rate. The analysis is based on a night time cooling system using cooling towers as a heat sink for a typical multi-storey commercial building with a total floor area of 8000 m^2. The design load is 120 W/m^2 or 960 kW and a PCM with a phase change temperature of 17 °C is used for this analysis (Belusko, 2008). The material of the tube used is copper. Based on a night time operation of 9 hours, this equates to a total potential storage capacity of 8640 kWhrs which requires 93.6 m^3 of PCM volume. During the night time, water from the outlet of the cooling tower is used as the HTF to charge the thermal energy storage system. The storage system in turn discharges its energy to the chilled ceiling panels to cool the building during the day time. The properties of the PCM and the range of parameters investigated during the simulation are specified in Tab. 1.

Tab. 1: Properties of heat transfer fluid and PCM

	Temperature, °C	*Dynamic Viscosity, mPa.s*	*Thermal Conductivity, W/m.K*	*Specific Heat, kJ/kg.K*	*Density, kg/m³*
PCM17(Liquid)	Phase change at 17	-	0.43	1.9	1525
PCM17(Solid)	-	-	1.5	-	-
Water	15	1.139	0.6	4.186	1000

4.1 Optimal design

Fig. 4 shows the maximum energy density coefficients achieved for the optimum length of tube in the system, for the flow rates ranging from 5,000 kg/hr to 900,000 kg/hr for 12.7mm outside diamter of the tube and number of tubes in the system is fixed at 100. The range of this optimum storage density coefficient is 0.613 to 0.972. These values can be compared directly to a sensible energy storage system based on the heat transfer fluid used in this study. Based on 93.6 m^3 of PCM charging over 9 hours, assuming unity effectiveness, equates to a constant load of 960 kW, which will be the specified cooling load.

Tab. 2 shows the temperature difference which meets this load for the flow rates presented in Fig. 4, from which the sensible energy that is stored within the heat transfer fluid is determined during the charging process. The total sensible energy stored was determined based on the volume of the PCM storage facility which incorporates 93.6 m^3 of PCM, the total tube volume and the volume filled by the heat transfer fluid, as determined by inner volume of the tubes. The table also shows for each flow rate, the corresponding optimum length of tube which achieves a maximum storage density coefficient extracted from Fig. 4, and the subsequent total useful energy stored within the PCM system based on the storage coefficient.

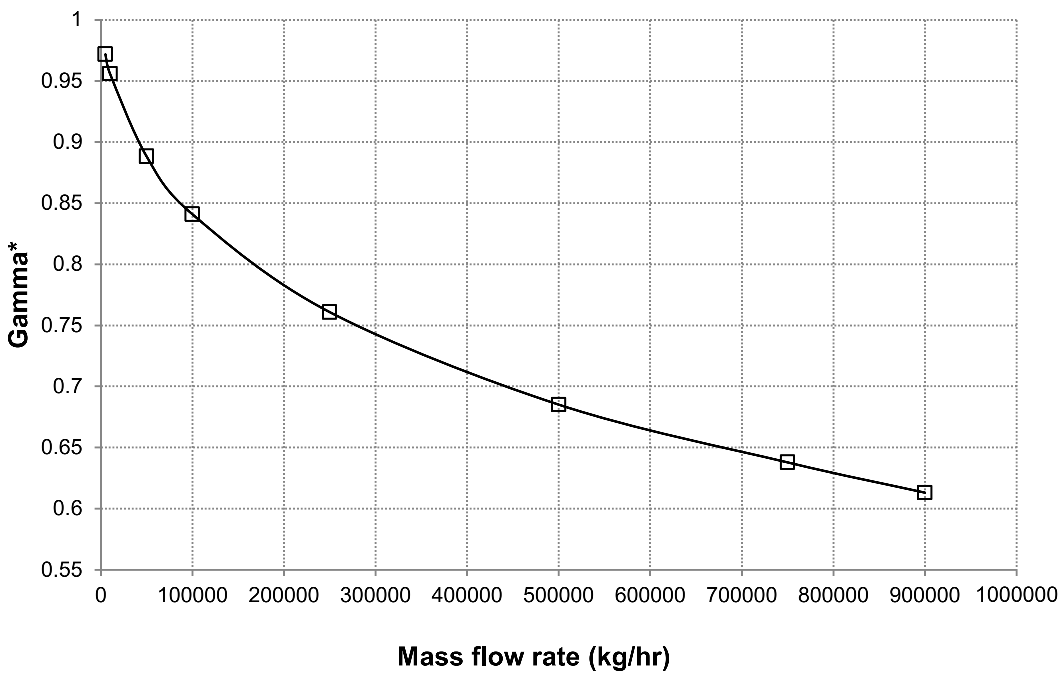


Fig. 4: Chart of Gamma* against the mass flow rate

Tab. 2: Energy stored within a PCM and sensible energy storage system

ṁ, kg/hr	*Length of tube, m*	*ΔT needed to achieve 960kW*	*γ**	*Useful energy extracted from PCM system, MJ*	*Total storage volume, m^3*	*Sensible energy storage in HTF, MJ*	*Latent / Sensible ratio*
5000	19200	165.2	0.972	30223.47	96.03	66377.45	0.46
10000	28800	82.6	0.956	29732.10	97.25	33609.01	0.88
50000	76800	16.5	0.888	27625.60	103.33	7142.09	3.87
100000	110000	8.3	0.841	26155.42	111.97	3869.62	6.77
250000	187000	3.3	0.761	23663.91	124.83	1725.59	13.71
500000	264000	1.7	0.685	21310.91	137.68	951.67	22.39
750000	319000	1.1	0.638	19840.98	134.01	617.52	32.13
900000	348000	0.9	0.613	19070.57	137.68	528.70	36.07

The calculated useful stored energy can be directly compared to the sensible energy stored within the heat transfer fluid. The data shows that at lower flow rates the sensible energy storage can store more useful energy then an optimised PCM system, as the temperature differences needed to meet the cooling load are large. However at higher flow rates and lower temperature differences of less than or equal to 16.5 °C, the useful energy stored is a factor of at least 3 more than the sensible energy stored. This confirms the capability of PCM systems as an energy storage system when considering low temperature differences. At low temperature differences of less than 2 °C, the energy storage density coefficient is less than 70%; however the overall storage density of a PCM system is at least 20 times greater than the sensible energy density that can be achieved within the heat transfer fluid. With increasing flow rates, the ratio of the latent to sensible energy that can be stored consistently increases. However at the maximum flow rate investigated this ratio reduces and reflects the impact of low heat exchange effectiveness that is achieved at this high flow rate.

5. Conclusion

The useful energy storage density of PCM thermal storage systems is significantly affected by the thermal resistance to heat transfer in the PCM system and the compactness factor. An energy storage density coefficient has been presented for a tube-in-tank PCM thermal energy storage system, which incorporates the impact of the thermal resistance during the charging and discharging phase, through the use of heat exchange effectiveness and the compactness factor of the system.

Using a validated ε-NTU numerical model of a tube-in-tank PCM thermal energy storage system, a parametric study has identified that with increasing mass flow rate, the storage density coefficient decreases. The study also identified that for a given tube diameter and number of tubes in the storage system, an optimum length of tube exists for each mass flow rate which maximises the storage density coefficient. Using this coefficient the useful energy storage within a PCM system can be directly compared to a sensible storage system. It was determined that the useful energy stored relative to a sensible storage system increases significantly at low temperature differences between the fluid and the phase change temperature. At lower temperature differences the required mass flow rates are high impacting on the effectiveness, however due to the design of the PCM arrangement, heat exchange effectiveness is still sufficiently high that adequate cooling can still be achieved. The effectiveness parameter was also determined to be an important design parameter to ensure that the PCM system is able to meet temperature specifications during discharging.

Overall, PCM systems which deliver a high energy storage density require a design which can achieve reasonable effectiveness as high mass flow rates. Tube-in-tank PCM thermal energy storage systems achieve this outcome.

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