EXPERIMENTAL VALIDATION OF A CFD AND A E-NTU MODEL FOR TUBES IN A LARGE PCM TANK

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Abstract

An experimental validation for a computational fluid dynamics (CFD) and effectiveness-number of transfer unit (ε-NTU) model for tubes in a large phase change material (PCM) tank has been conducted. In previous work, experimental validation of a CFD and ε-NTU model was carried out on latent heat thermal storage systems having one, two and four coils of polyvinyl chloride tubes coiled inside a 290 mm diameter by 330 mm high cylindrical tank filled with PCM. The heat transfer fluid (HTF) passes through the tube during the charging and discharging processes. Salt hydrate PCM with phase change temperature of -27 °C was used for all the three tube configurations while water was used in the four tubes tank experiment. Further experimental validations of a CFD and ε-NTU model were carried out on a large PCM tank, having eight coils of copper tubes inside a 550 mm diameter by 830 mm high cylindrical tank filled with PCM. The inlet and outlet HTF temperatures as well as twelve temperature locations in the PCM tank were compared with the CFD results. The average effectiveness of the phase change process of each experimental point was also compared with results from the CFD as well as the ε-NTU technique. From this study, it was concluded that the CFD model and the ε-NTU technique developed can accurately predict the behaviour of the thermal storage system during the freezing process. There are however, discrepancies in the melting process due to the exclusion of the effect of natural convection in the models developed. The paper will give details of the CFD model of the phase change thermal storage system. Results from the CFD model, experiments and ε-NTU technique will also be presented.

Keywords: Phase change material, cold storage tank, tube in tank, computational fluid dynamics.

1. Introduction

Latent heat thermal energy storage has been proven to be an effective technology for energy storage because of its high-storage density and small temperature variation from storage to extraction. Cold storage is a practical method for storing energy in applications where cooling can be generated more efficiently or for less cost outside of the period of cooling demand. Thermal storage also makes it possible to use equipment with smaller cooling capacity.

It has been demonstrated that phase change materials (PCMs) are more energy dense than sensible energy storage when the temperature difference between heat source and sink are low. Research completed under the international energy agency (IEA) task 32 (Streicher, 2007), found that the storage density compared to water is strongly dependent on the temperature variation in the storage tank. For small temperature variations from 50 up to 70 °C and a PCM tank with immersed heat exchanger, the store can be sized about 1/3 of the volume compared to water. For the same PCM material but macro-encapsulated and for a temperature variation from 25 to 85°C or 20 to 70°C in solar combisystems, the PCM store will have the same size as a water store. Thus the application of PCM in hot water systems which require a large temperature variation achieved negligible benefit with respect to store size.

Numerous mathematical models of PCM in thermal storage units (TSU) have been developed over the years. These models have been used to determine the performance of the TSU for design and simulation purposes (Halawa et al., 2005). However, little attention has been placed on using these models to develop generic representations which can be readily used for the characterisation and ultimately the design and optimisation of a TSU with PCM. To quantify the impact of the thermal resistance of a PCM system, a one dimensional equation of the effectiveness of a TSU based on the effectiveness-number of transfer units (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.

Computational fluid dynamics (CFD) is a powerful tool for fluid dynamics and thermal design in industrial applications, as well as in academic research activities (Gan and Riffat, 1998; Riffat and Gan, 1998). Lacroix (1993a, 1993b), Hasan (1994), Dimaano and Watanabe (2002) as well as Sari and Kaygusuz (2001, 2002a, 2003) have experimentally investigated a shell-and-tube heat exchanger with PCM filling the shell side. All of them obtained similar PCM temperature profiles and specified governing mechanisms of heat transfer during the melting and the solidification processes. The heat transfer in this type of thermal energy storage system is typically a conjugate problem, involving the transient forced convective heat transfer between the heat transfer fluid (HTF) and the tube wall, heat conduction through the tube wall and solid-liquid phase change process of the PCM.

Trp (2005) conducted an experimental and numerical investigation of a shell-and-tube latent thermal energy storage unit during the melting and the solidification process with paraffin as the PCM. The HTF is circulating inside the tube and the PCM is contained in the shell side. The numerical method has been implemented with a self-written FORTRAN computer code. Numerical predictions for both the melting and the solidification processes agree well with the experimental data. After validating the computational model, Trp et al. (2006) performed the numerical analysis of the heat transfer during charging and discharging of the thermal energy storage system. Unsteady temperature distributions of the HTF, tube wall and the PCM have been obtained by various HTF operating conditions and various geometric parameters have been studied. It can be concluded that based on the heat transfer rate and the time in which the energy has to be stored, the operating conditions and dimensions geometric parameters can be selected. These results formed the design characterisation of the latent thermal energy storage system developed by Trp et al. (2005, 2006).

2. Previous work

In previous work (Tay et al., 2011; Castell et al., 2011), experiments were carried out on latent heat thermal storage systems having one, two and four coils of tubes coiled inside a 290 mm diameter by 330 mm high cylindrical tank filled with PCM. The HTF passes through the Polyvinyl Chloride tube during the charging and discharging processes. Salt hydrate PCM with phase change temperature of -27 °C was used for all the three tube configurations. In addition, experiments were carried out using water as the PCM in the tank with four coils. Experiments were conducted on both freezing and melting processes. A mathematical model was developed using the ε-NTU technique. Comparing the average theoretical effectiveness calculated by the mathematical model with those from experiment, it was observed that the experimental graphs follow the same trend as the theoretical graphs and the predicted values are in agreement with those from experiment. A three-dimensional CFD model using Ansys code was also developed for the four coils tank experiment using water as the PCM. The average effectiveness of the phase change process of selected experimental points was compared with results from the CFD as well as the ε-NTU technique. It was found that the CFD model can accurately predict the average effectiveness of the thermal storage system.

In this paper, a three-dimensional CFD model using Ansys code was developed to analyse the transient heat transfer during the phase change process of the PCM in a large tank. The average effectiveness of the phase change process evaluated from the CFD model will be compared with the experimental as well as the ε-NTU technique developed by Tay et al. (2010). This work endeavours to investigate the effect of natural convection on a large tank with a larger average tube distances.

3. Experimental set-up

An experimental investigation has been performed for a thermal energy storage system with coils of tube inside a PCM filled cylindrical tank. This work involved eight 3.33 metres length of copper tubes coiled inside a 550 mm diameter by 830 mm high cylindrical tank (refer to Fig. 1). The tank contained 158.7 kg of water (referred to as PCM0) for the first experiment, and then this was replaced with 179.2 kg of salt hydrate PCM with a phase change temperature of -11 °C (referred to as PCM-11) for the second experiment. The PCM tank had a compactness factor (CF) of 98% and both charging and discharging was investigated. The CF is the ratio of the volume of PCM to the volume of the tank. It was observed for all freezing and melting tests that the outlet temperature increases or decreases rapidly initially, achieves a constant temperature for a long period of time and then begins to increase or decrease at the end of the process towards the inlet temperature. Fig. 2 shows the schematic of the experimental set-up. The experimental apparatus was composed of a tube-in-tank thermal energy storage system (referred to as PCM tank), a HTF tank where 540 litres of HTF are stored and cooled by a refrigeration unit, two pumps, two flow meters and ball valves for switching between the freezing and melting tests.

The mass flow rate was measured using an Actaris rotary piston flow meter with an error of +/- 2% calibrated on a volumetric basis. The PCM temperature distribution during charging and discharging of the PCM tank was experimentally determined in both radial and axial directions. Twelve T-type thermocouples with an error of +/- 1 °C were placed inside the PCM at various locations. They were placed at axial distances of 0.152 m, 0.416 m, 0.680 m from the top of the tank. At each axial distance, four thermocouples were placed at various radial distances as shown in Fig. 3. Two OneTemp 4 wire RTD with an error of +/- 0.1 °C were placed at the inlet and outlet of the HTF into the inside of the tube. All thermocouples and RTDs were connected to the data acquisition system. A commercial software was used to acquire data from the thermocouples and RTDs, and to record them in a database format on a personal computer, for further processing. Temperature data was recorded at time intervals of 10s.

Freezing experiments started at room temperature and the PCM was in a liquid state. Initial conditions were established when all thermocouples inside the PCM tank were recording the same temperature. The HTF at a temperature of -35 °C was circulated to the PCM tank until the PCM was fully frozen. The freezing experiments were stopped when all the thermocouples in the PCM tank were recording the same temperature, setting the initial condition for the melting tests. During the melting experiment, the HTF in the PCM tank was circulated to the fan coil unit in the cold room until all the PCM melted. The cold room acted as the cooling load for the melting process. The melting tests were stopped when all the thermocouples in the PCM tank were recording the same temperature. Fig. 4 is a typical temperature-time curve of a freezing process. The initial period represents the sensible cooling of the PCM as a liquid, the flat section represents the freezing process, and the final stage represents the sensible cooling of the PCM as a solid. These measurements were consistent with the internal temperature measurements taken throughout the PCM tank (Fig. 4). An inverse trend was also noticed in the melting test.

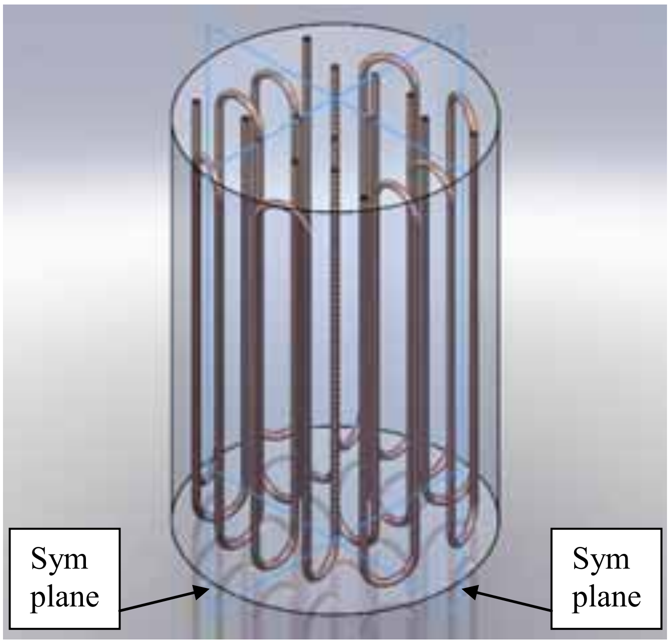

Fig. 1: Schematic of PCM tank with 8 copper tubes

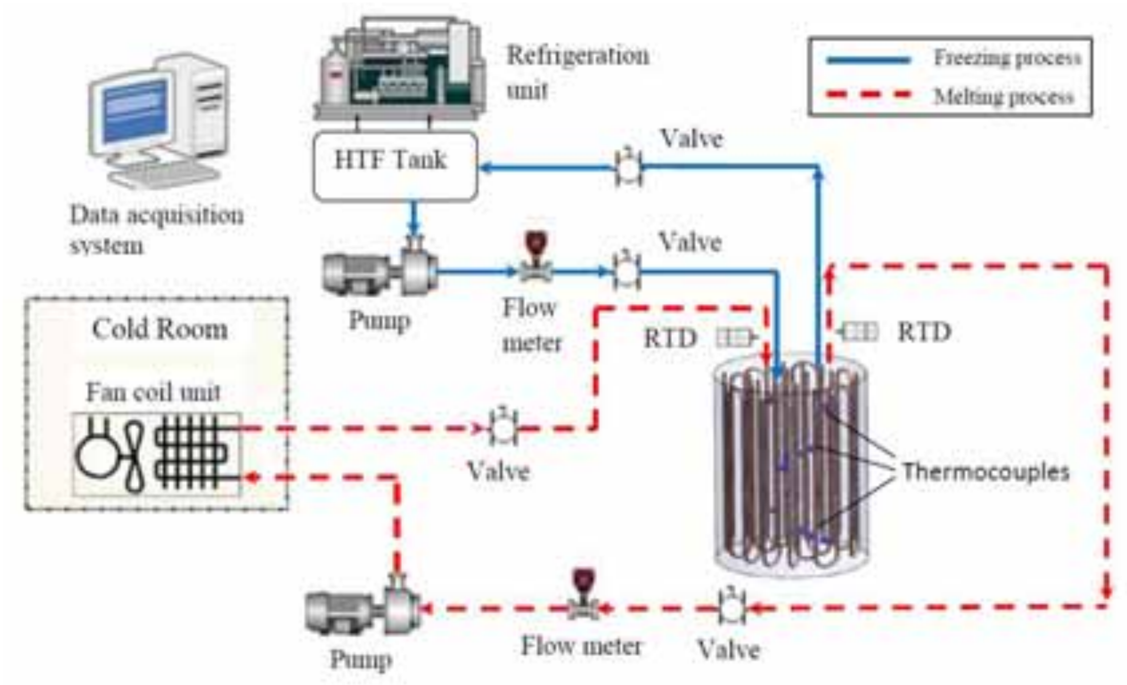

Fig. 2: Schematic of the experimental set-up

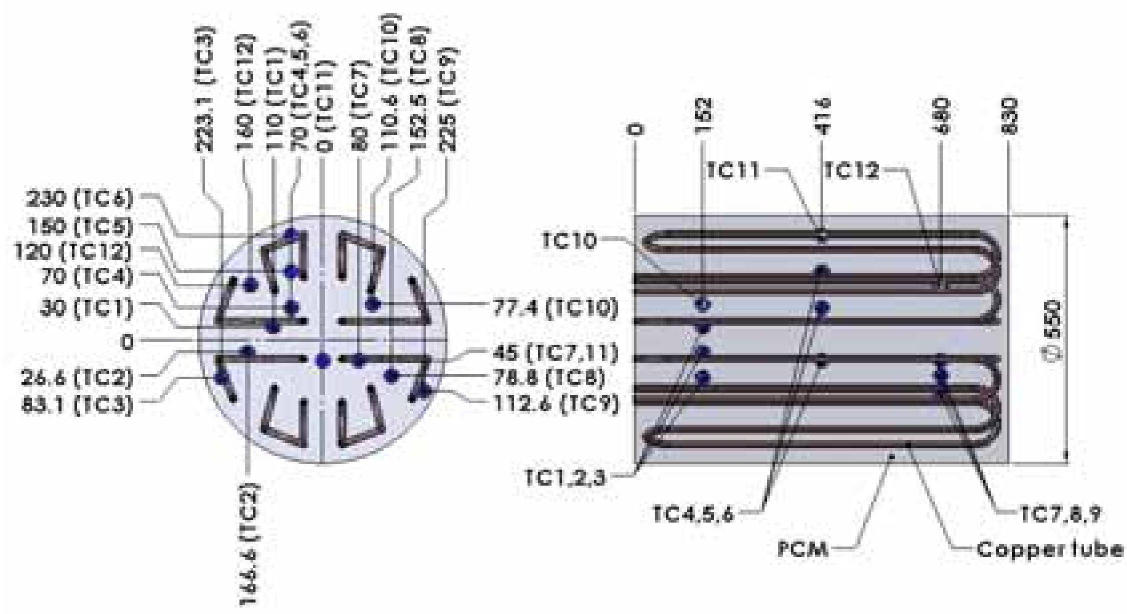

Fig. 3: Schematic of PCM tank design with thermocouple (TC) locations

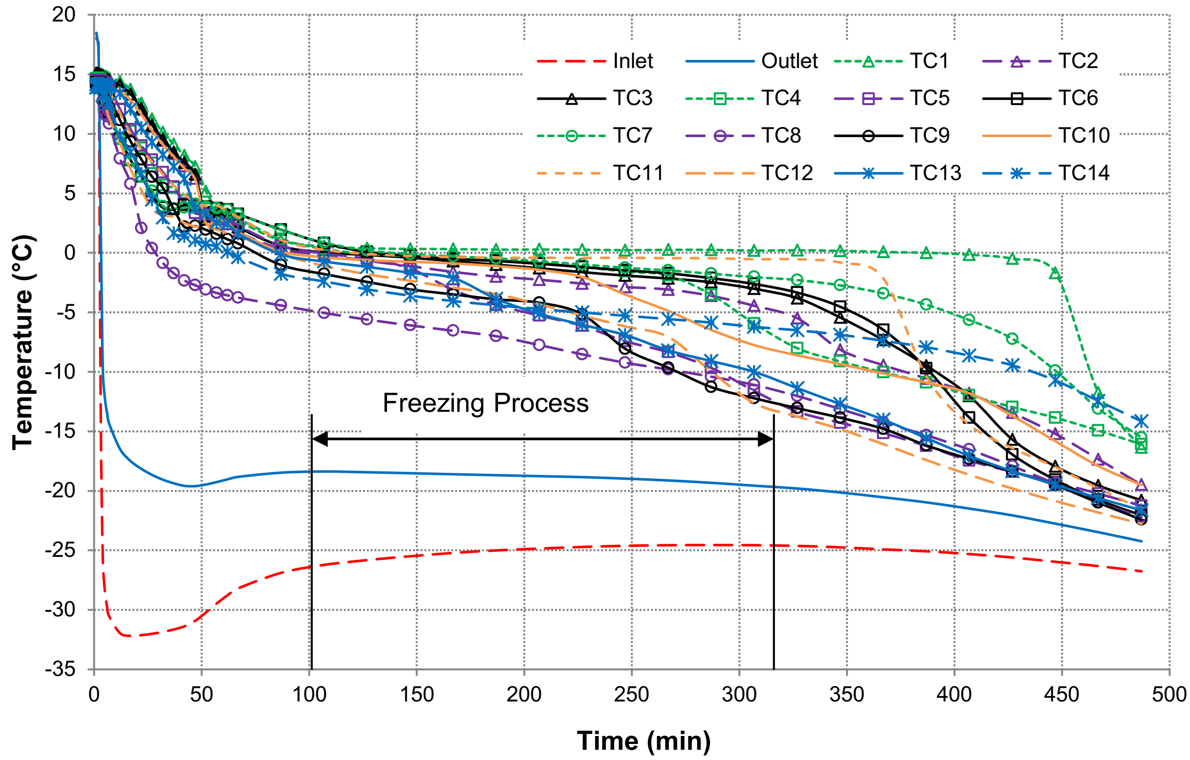

Fig. 4: Freezing process for the PCM Tank using PCM0 with mass flow rates of 0.184 kg/s with an average effectiveness of 0.25

The effectiveness is described as the ratio of the actual heat discharged over the theoretical maximum heat that can be discharged. In using a PCM subject to a small temperature variation during freezing and melting processes, the sensible energy storage is small and is therefore ignored (Sari and Kaygusuz, 2002b). Eq. 1 represents the local effectiveness at any point in time over the phase change period. As mentioned by Belusko and Bruno (2008), a PCM storage system can be analysed as a heat exchanger where the HTF exchanges heat with the PCM at the phase change temperature. Therefore, the effectiveness of the PCM storage system can be defined as that of a heat exchanger. The maximum effectiveness of the system arises when the outlet temperature of the HTF is the same as the phase change temperature. The process is a transient process and therefore the heat exchanger effectiveness is bounded between 0 and 1. The average effectiveness over the phase change process can be determined by the average inlet and outlet temperature over the phase change process. The average effectiveness gives an indication of the performance of the thermal storage unit.

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

3. Effectiveness-NTU technique

The ε-NTU representation developed by Tay et al. (2010) has been used to calculate the average effectiveness of the phase change process for the thermal energy storage system investigated in this work. Calculated values are compared with the experimental results for the freezing and melting processes of the PCMs used.

4. Simulation model

A three-dimensional CFD model using Ansys code was developed to analyse the transient heat transfer during the phase change process of the PCM tank as shown in Fig. 1. Only a quarter of the tank needs to be modelled because two axes of symmetries are assumed. The model has been simplified by ignoring the two persplex tube holders. Fig. 5 shows a quarter of the PCM tank with the inlet tube extended.

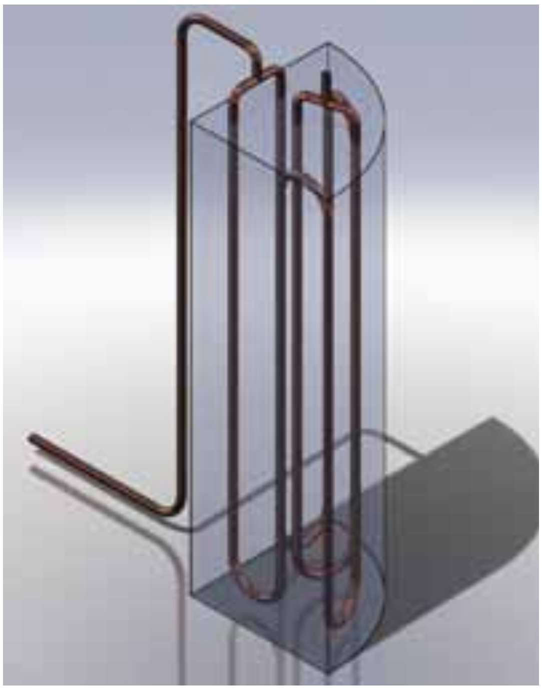

Fig. 5: Schematic of a quarter of the PCM tank

A model with 5,013,927 cells was created for this simulation. The CFX-PRE within version 12.1 of the academic research code ANSYS was utilised. Three domains were created; the HTF and PCM were created as fluid domains while the tube was created as a solid domain. In order for the CFX-PRE to be able to recognise the two different fluid materials used in the HTF and the PCM domains, beta features need to be enabled while constant domain physics need to be disabled.

Since this is a transient problem, a transient analysis type was selected. In order to reduce the computation time, buoyancy in the PCM was ignored, therefore, a larger time step was possible. The time step for the freezing process was set to 1 min. In order to satisfy convergence criteria of 1E-04, the number of iterations for every time step was between 50 and 200 during the initial sensible cooling. The number of iterations reduced to between 20 and 50 at the beginning phase change and less than 10 during the second half of the phase change process. The time step for the melting process was set to 1 min. In order to satisfy convergence criteria of 1E-04, the number of iterations for every time step was between 100 and 200 during the initial sensible heating. The number of iterations reduced to less than 20 at the beginning phase change and less than 10 during the second half of the phase change process.

The inlet of the HTF has been set as the inlet boundary with static temperature and mass flow rate based on the experimental data. The outlet of the HTF has been set as the outlet boundary while the rest of the surfaces of the HTF have been set to have a fluid and solid interface with the inner surfaces of the tube. The outer surfaces of the tube that are submerged in the PCM have been set to have a solid and fluid interface with the PCM. The rest of the outer tube surfaces that are outside the PCM have been set as the wall boundaries with adiabatic heat transfer. The two cutting surfaces of the PCM have been set as symmetry boundaries since this model is a quarter of the full model. The rest of the outer surfaces of the PCM have been set as wall boundaries with adiabatic heat transfer. At time t=0, the PCM is taken to be a motionless solid or liquid that is maintained at a constant temperature based on the experimental data.

5. Results and Discussion

The freezing and melting processes in the PCM tank were conducted and the results were analyzed. Five experimental points for each experiment were selected for validation. The average effectiveness of the phase change process of each experimental point was also compared with results from the CFD as well as the ε-NTU technique.

Figs. 6 and 7 show the comparison between the ε-NTU technique, CFD model and the experimental values of the average effectiveness against the ratio of the mass flow rate to area, during the charging and discharging processes for the PCM tank using PCM0. It can be observed in Fig. 6 that the charging process revealed an agreement between the predicted and experimental values. The experimental effectiveness was found to be slightly higher than the calculated effectiveness using the ε-NTU technique and this is due to the three-dimensional conduction occurring during the experiment which enhances heat transfer. Since CFD model simulates using three dimensional heat transfer, it can be seen from Fig. 6 that the experimental effectiveness agrees well with the CFD effectiveness. The experimental values for the discharging process as shown in Fig. 7 are higher than the values generated by the ε-NTU technique and the CFD model. This is due to the effect of natural convection during the melting process. The predicted values determined by the ε-NTU technique and the CFD model however, agreed well since both models ignored the effect of natural convection.

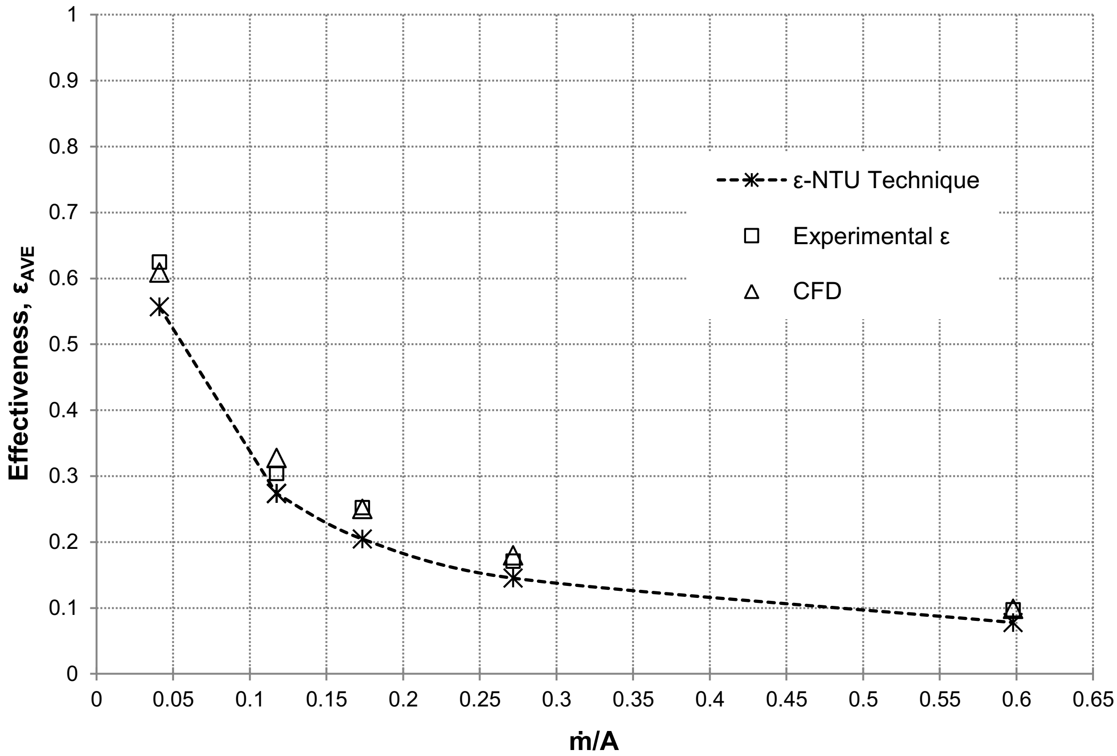

Fig. 6: Comparison of Effectiveness over the ratio of ṁ/A for Experimental and Theoretical Freezing Results for the PCM Tank using PCM0

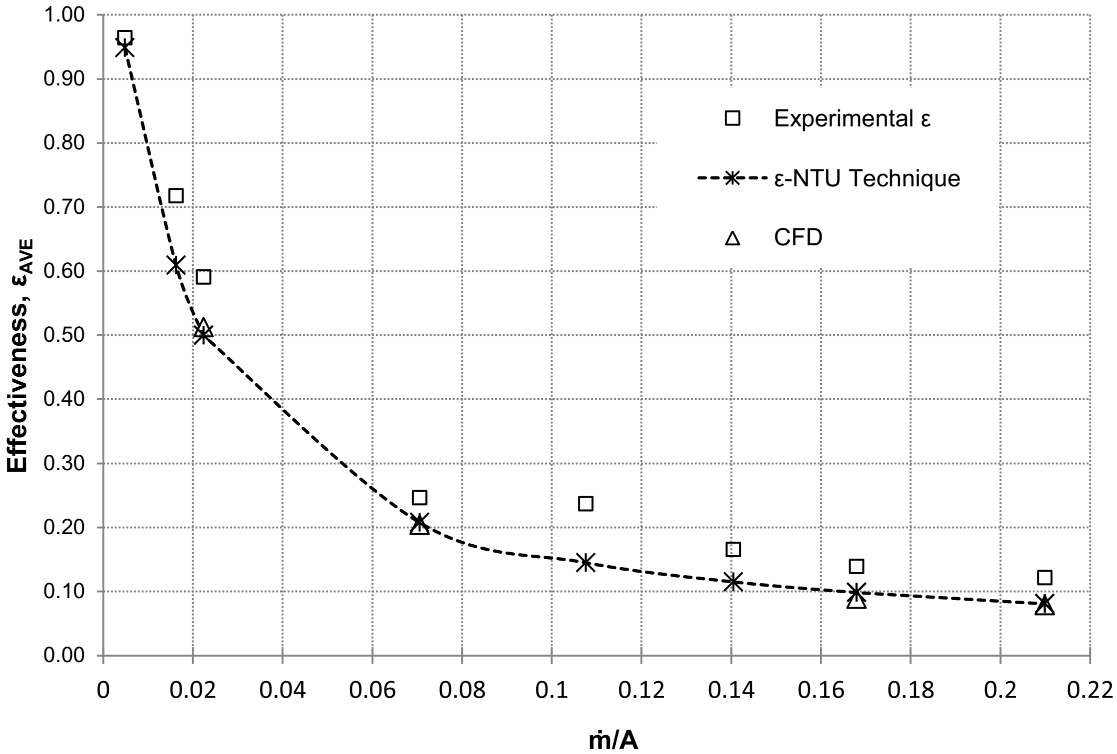

Fig. 7: Comparison of Effectiveness over the ratio of ṁ/A for Experimental and Theoretical Melting Results for the PCM Tank using PCM0

The charging process for the ε-NTU technique and CFD model have been validated. Therefore, it is not necessary to revalidate the charging process for PCM-11. It is however necessary to show the behaviour of the discharging process since the discharging process for PCM0 has shown that the effect of natural convection are significant in larger tank. Fig. 8 shows the comparison between the ε-NTU technique, CFD model and the experimental values of the average effectiveness against the ratio of the mass flow rate to area, during the discharging process for the PCM tank using PCM-11. Similar to PCM0, the experimental values are found to be higher than the values generated by the ε-NTU technique and the CFD model due to the effect of natural convection. It was also observed that the effect of natural convection for PCM-11 is higher than PCM0.

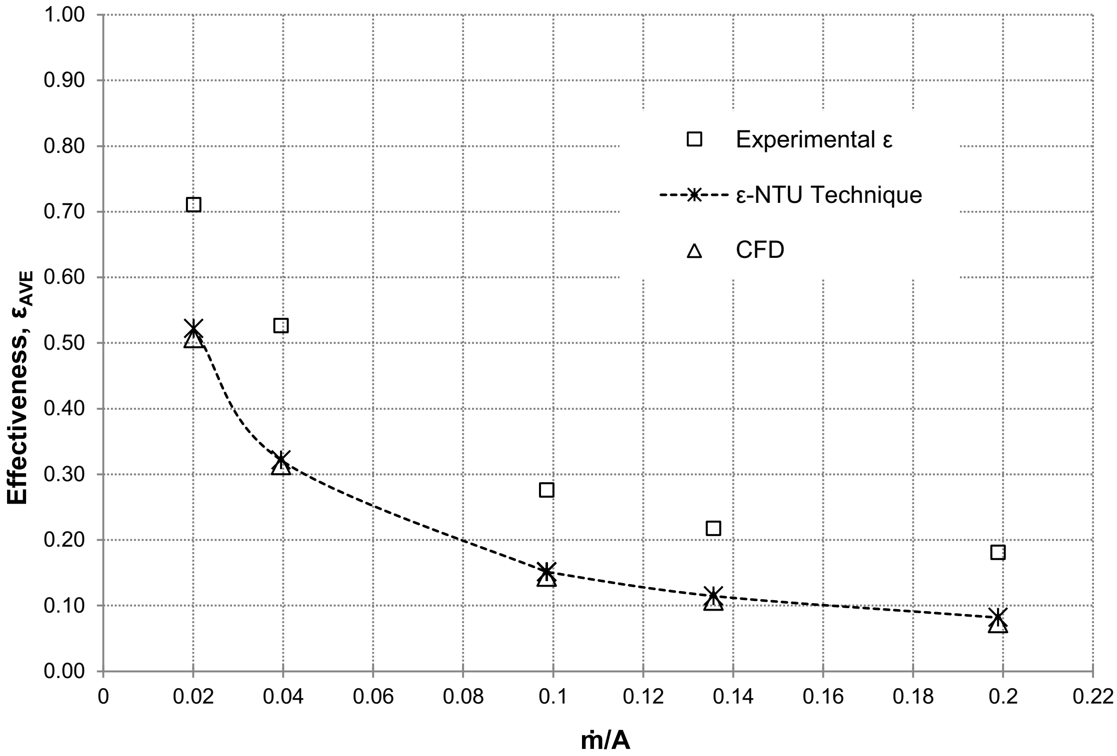

Fig. 8: Comparison of Effectiveness over the ratio of ṁ/A for Experimental and Theoretical Melting Results for the PCM Tank using PCM-11

6. Conclusion

An experimental validation of a CFD model and a ε-NTU technique were conducted for a thermal energy storage system with eight coils of tube inside a PCM filled cylindrical tank. The CFD model has been created ignoring the effect of natural convection. As this validation was conducted on a PCM tank where the average tube distances was large (100 mm), natural convection is significant during the melting process and cannot be ignored. Therefore the experimental results are found to be higher than the CFD model and the ε-NTU techinique. However, the experimental results for the freezing process agrees well with the ε-NTU techinique and the CFD model. It was also found that the effect of natural convection was insignificant for thermal storage systems with high surface area. Furthermore, the three dimensional CFD analysis can be replaced by the one dimensional ε-NTU techinique to design and characterise thermal energy storage system.

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