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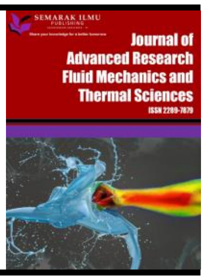

Investigative Study of Solidification and Melting of Stearic Acid in Triplex Pipe with Perforated Fin Surface

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ABSTRACT

The energy storage capacity of latent heat thermal energy storage systems is high therefore these systems are efficient among all other thermal heat storage. This study experimentally investigates the charging and solidification of stearic acid ($C_{18}H_{36}O_2$) in the finned triplex pipe heat exchanger with holes on the fin surface. The melting and discharging of stearic acid are carried out at steady inlet heat transfer fluid (HTF) i.e., water temperature. This study also investigates the result of the change in HTF flow rate on solidification and melting of phase change material. Finally, the study focuses on the comparison of average effectiveness for finned triplex tube heat exchanger and finned triplex tube with cylindrical holes on fin surface with rates of 0.33 and 0.43 Kg/s. The results showed that the average effectiveness with a finned triplex tube with a perforated fin surface is 4% more than that of a finned triplex tube at 0.33 Kg/s whereas it is 5 % more at 0.43 Kg/s during the charging process. On the other side during discharging process average effectiveness is 14 % more at 0.33 Kg/s and 11 % at 0.43 Kg/s.

1. Introduction

The main drawbacks of the sensible heat storage system (SHSS) are less energy density, it requires a larger vessel for a specific necessity of thermal energy, and it stores energy by raising the temperature of a solid or liquid. The latent heat thermal storage system becomes popular among investors because of its higher heat storage density, compactness, and phase change that takes place at an almost constant temperature [1]. Many authors studied comprehensively a variety of heat transfer and thermal conductivity enhancement techniques to perk up heat exchange among heat transfer fluid and phase change material [2]. These techniques include extended surfaces, multiple PCM, heat pipes, an addition of nanomaterial to PCM, and encapsulation of PCM [3]. Several techniques were reported in the literature, which focus on the Thermal characteristics of PCM to increase the rate of charging and solidification in triple pipe heat exchangers [4,5]. The

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following section focuses on the work carried out by various authors to perk up the PCM melting and discharging by the use of a triplex tube heat exchanger (TTHX). Rebhi *et al.,* [6] reviewed the forced convection heat transfer in a heat exchanger. The authors concluded that the lesser thermal performance of the heat exchanger was found because of less convective heat transfer between the absorber to the air. Elfaghi *et al.,* [7] carried out a numerical simulation of forced convection heat transfer with Al_2O_3 with volume fractions of 0.5, 1.0, and 2.0 percent in a circular pipe. The result showed that Al_2O_3 nanofluid enhanced convective heat transfer more than that of basic fluid. Experimentation carried out by Abdulateef *et al.,* [8] uses freezing of PCM in TTHX at the rate of 16.2, 29.4, and 37.5 kg/min with longitudinal fins. The results obtained showed that the time of solidification increased by 14 %, 16 %, and 18% for the above said flow rates. On the other way, Al-Abidi *et al.,* [9] employed internal, and external fins on the TTHX storage system to investigate the melting, and solidification of PCM. The author kept working fluid flow rate at 4, 8 and 16 Kg/min tested and found that melting time reduced by 58% at 16 kg/min. With seven different geometries of TTHX for solidification time, a similar kind of work was carried out by Al-Abidi *et al.,* [10]. The author concluded that solidification time was reduced by 35% using eight fins with 1 mm thickness. The result of the simulation showed that melting time dropped by about 34.7 % with eight fines of 47.6 mm in length [11]. A similar type of numerical investigation was done by Mat *et al.,* [12] using a TTHX system with three different heat addition methods. The internal and external fins with 42 mm fin length showed better performance than TTHX without fins by a 43.3% drop in melting time. Oo *et al.,* [13] numerically and experimentally investigated the heat transfer performance of teardrop dimples and protrusions. Four different cases with the spacing of S=1.125, 1.25, 1.5, and 2D between dimple to dimple and protrusion to protrusion were studied. The results obtained showed that teardrop dimples have higher heat transfer performance than protrusions for both numerical and experimental cases. Patel *et al.,* [14] numerically examined the influence of longitudinal fins on the melting and discharging with the help of Ansys 2D model. The results showed that with four longitudinal fins, melting and discharging time reduced by 60% and 46.15%. NematpourKeshteli *et al.,* [15] numerically investigated the charging of PCM in a TTHX with three cases. In the first case, the metallic foam was inserted into PCM with a 5% volume fraction and obtained a 69.52% decrease in melting duration. In the second case, the metallic foam was inserted into multilayer PCM, and the reduction in melting time reaching to 83.39% whereas in the third case melting time decreased by 53.17% when metal foam with nanoparticles was inserted in finned TTHX. Yao and Huang [16] proposed novel triangular fins to investigate the discharge performance of PCM in a triplex pipe storage system and compared it with rectangular traditional fins. The obtained results showed that reduction in freezing time by 30.98% compared to rectangular fins. Alsadig *et al.,* [17] utilize a stream analysis model to simulate baffled shell and tube heat exchanger and compared results with industrial data. The authors concluded that the results obtained by the stream analysis model do not exceed more than 2%. Al-Mahmodi *et al.,* [18] investigated the thermal behavior of nanocomposite-based PCM. The results obtained showed that after 150 thermal cycles Cu/Paraffin nanocomposite shows thermal reliability. Also, results showed that with adding 2.5% of Cu nanoparticles; thermal conductivity, specific heat, and thermal diffusivity increased by 39 %, 16%, and 9 % respectively. Lee [19] investigated numerically heat transfer in domestic water heat exchanger with Copper (Cu) and alumina (Al_2O_3) nanoparticles with volume fraction of 0.5 %, 1.0 %, 1.5 %, 2.0 %, 2.5 %, and 3.0 %. The efficiency obtained when 1.5% Cu or Al_2O_3 is mixed into water-based HTF is optimum. Abdulateef *et al.,* [20] experimentally and numerically investigated finned surfaces with nanoparticles with RT82 paraffin PCM. The PCM with 10% nanoparticles showed that for longitudinal fin reduction in melting time was 12% whereas for triangular fins it was 22%. With help of the response surface method, melting performance based on multi-parameter optimization was assessed by Huang *et al.,* [21]. The results indicate that melting performance perks up by 23.87% with the optimized model when compared to the original TTHE system. They also showed that the influence of the length of fin on melting is not more than 11.47%. The author also studied the freezing performance of the system with help of numerical simulation [22]. The simulation result indicates that at multistage pipe diameter 4 mm freezing performance increases by 50.19%. Entezari *et al.,* [23] investigated melting with a new helical coil type triplex tube and compared it with the horizontal straight unit, vertical unit, and double pipe helical coil. The melting time obtained dropped by 16, 44.7, and 80.4% respectively for horizontal, vertical straight, and helical coil double tubes. Rahim *et al.,* [24] designed and tested a combined system of a heat pipe, solar Fresnel lens, and phase change materials. The results showed that during discharging, 120 KJ of heat was retained for seven hours. Cherifa *et al.,* [25] numerically investigated the effect of the governing parameters on natural convection heat transfer in the saturated nanofluid porous cavity. The results showed that in the homogenous porous medium variation of permeability affects convection and also reduces heat transfer.

The purpose of the study is to investigate the performance of a triple pipe heat exchanger using stearic acid as a phase transition material. This study examined the influence of HTF flow rate on the effectiveness of PCM charging and freezing with cylindrical holes on the finned surface.

2. Experimental Setup

The horizontal triple pipe heat exchange device was used as a storage medium for experimental analysis of stearic acid with internal external dimpled fins. The thermophysical properties of the stearic acid are shown in Table 1.

Table 1
Thermophysical properties of the stearic acid [26, 27]

Properties	Value
Chemical Formula	$C_{18}H_{36}O_2$
Melting Point of Stearic acid	69.3 °C
The boiling point of Stearic acid	361 °C
<u>Density</u>	
Solid	1.08 g/cm^3
Liquid	1.15 g/cm^3
Latent heat	186.50 kJ/kg
Thermal conductivity	0.18 W/m °C
<u>Specific heat</u>	
Solid	2.83 kJ/kg °C
Liquid	2.38 kJ/kg °C

The experimental setup of TTTESS is shown in Figure 1. The experimental apparatus consists of three main parts: LH storage unit, storage tank with heater, and other accessories like circulation pump, flow meter, valve, etc. The specifications of the Triplex tube heat exchanger are shown in Table 2.

Table 2
Specifications of Triplex Tube Heat Exchanger

Triples tube specifications	
Material	Mild Steel
Length	500 mm
Radius of inner pipe (R_i)	25.4 mm
Radius of middle pipe (R_m)	75 mm
Radius of the outer pipe (R_o)	100 mm
Thickness of inner pipe	1.2 mm
Thickness of middle pipe	2 mm
Thickness of outer pipe	2 mm
Fin Dimensions	
Total number of fins	8
Width	480 mm
Length	42 mm
Thickness	1 mm
Number of holes on the fin surface	24 on each row
Number of rows	2
Diameter of hole	10
Pitch	20 mm
Thermocouples	
Number of thermocouples used	11
Position of thermocouples	
Measurement of atmospheric temperature	
Measurement HTF inlet temperature	T1
Measurement HTF outlet temperature	T2
Position of thermocouples from entrance and exit (4 on each side)	T3
Position of 8 thermocouples in a radial direction	100 mm, 37.5 mm and at 90°

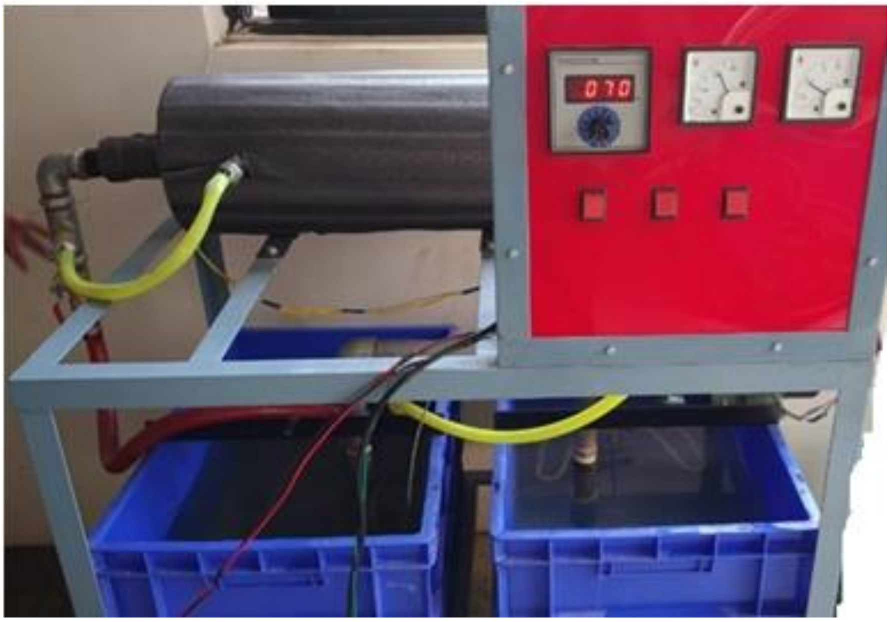
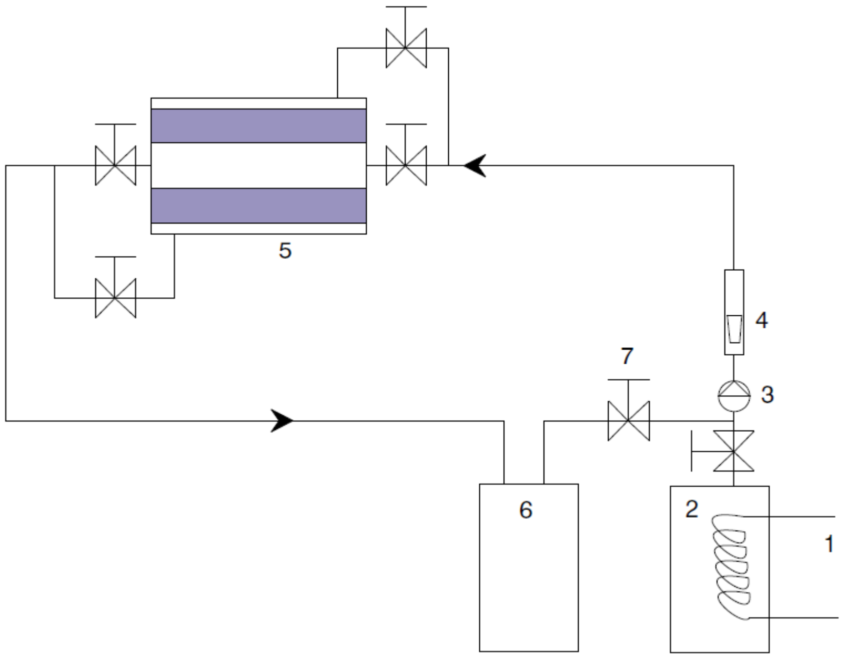


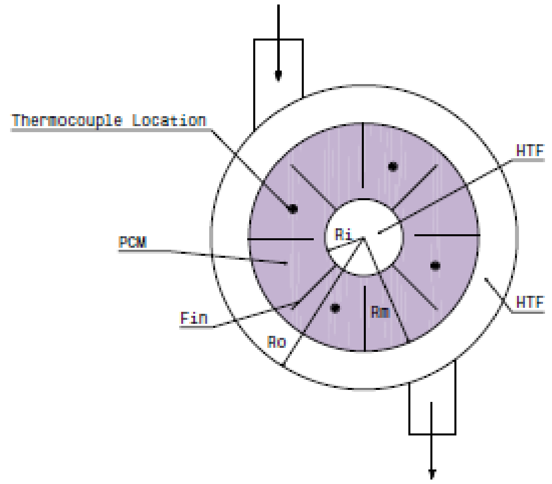
Fig. 1. Experimental setup

The physical arrangement of the TTHX has three horizontal concentric pipes of 500 mm in length. The heat exchanger is made up of Mild Steel. The inner pipe radius (R_i) and thickness are 25.4 mm & 1.2 mm respectively, the radius of the middle pipe is 75 mm (R_m) and the outer pipe is 100 mm (R_o) and the middle & outer pipe is 2 mm thick. The stearic acid (7 Kg) acts as phase transition material filled in the annular gap between the inside & outer tube whereas working fluid (water) flows through the inside and outside a pipe. The 480 mm wide, 42 mm long, and 1 mm thick fins (8 fins) with holes on their surface extended from the outer surface of the inside pipe and an internal surface of the middle tube. On each fin surface, a total of 48 drills with 10 mm diameter and 20 mm center-to-center distance were drilled in two rows i.e 24 holes in each row. The properties of stearic acid considered as; density = 1.08 kg/m^3, thermal conductivity = 1.18 W/mK, specific heat =2.83 KJ/kgK [26, 27]. At a distance of 100 mm from the entrance and exit of TTHX, eight thermocouples were inserted to measure the temperature of stearic acid. Out of eight thermocouples, four were installed on the right side (T4-T7) and the remaining four on the left side (T8-T11) with 0.5% accuracy at a 37.5 mm radius with a 90˚ angle. To measure HTF inlet (T2) and exit (T3) temperature two thermocouples were fixed. The flow diagram, the position of thermocouples, and a detailed view of the inner and middle pipe are shown in Figure 2(a), Figure 2(b), and Figure 2(c) respectively.

Insulation was provided to TTTESS with asbestos to reduce losses. The heat released by the heater starts the charging of stearic acid. The feed pump activates its operation when the temperature of the charging storage space reached to melting temperature of stearic acid and discharges hot water through the flow meter to the PCM in the latent heat storage unit. The thermostat is used to control the temperature of water in the storage tank. The charging process stops as all the thermocouples (T4 to T11) show the same temperature and the entire PCM liquefied. As soon as stearic acid liquefied the solidification, the process started and the direction of the flow of cold water reversed. The cold HTF then flows through the LH storage unit until stearic acid solidifies. The discharging process stops as soon as all thermocouples record the same temperatures.



1. Electric heater, 2. Charging storage tank, 3. Pump, 4. Rotameter, 5. Triplex tube heat storage system, 6. discharging storage tank, 7. Valves
(a)



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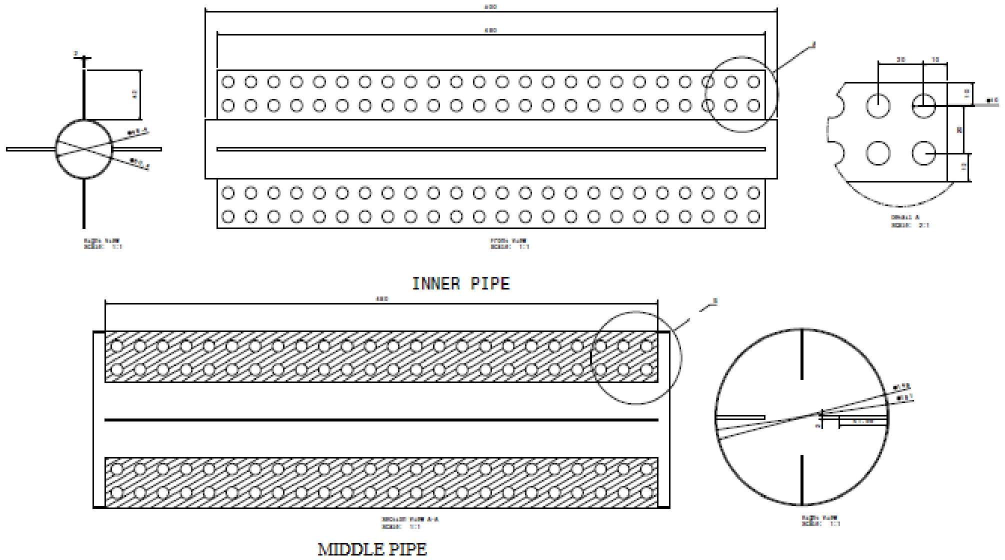

(c)

Fig. 2. (a) Flow diagram of set up, (b) Position of Thermocouples, (c) Detailed view of inner and middle pipe

3. Experimental Results

3.1 Heat Exchanger Effectiveness

During the phase change process very small variation in the PCM temperature, hence sensible heat is neglected. The effectiveness of LHTESS is considered as the effectiveness of heat exchanger as TTHX is used as LHTESS here [28]. As we know during the charging and freezing of PCM triplex pipe heat exchanger effectiveness is an important parameter [29]. During experimentation, it's assumed that the rate of flow of water is equally separated into the inside tube and annular space. The mean effectiveness at some stage in the time of phase change at any point is given by

$$\varepsilon = \frac{T_{inlet} - T_{outlet}}{T_{inlet} - T_{mean}} \tag{1}$$

where, T_{mean} = average temperature of PCM

3.1.1 Effectiveness of finned surface

Figure 3 shows the effectiveness of the heat exchanger with fins on the outside surface of the inner tube and inside surface of the middle pipe during charging at a rate of 0.33 and 0.43Kg/s of HTF. Figure 4 compares the effectiveness of the heat exchanger during solidification for HTF mass flow of 0.33 and 0.43 Kg/s. it was observed from Figure 3 and Figure 4, that at a flow rate of 0.43 Kg/s; the mean effectiveness of TTHX was slightly greater during charging as well as discharging. The effectiveness is much higher during charging than that during the discharging process due to the influence of free convection.

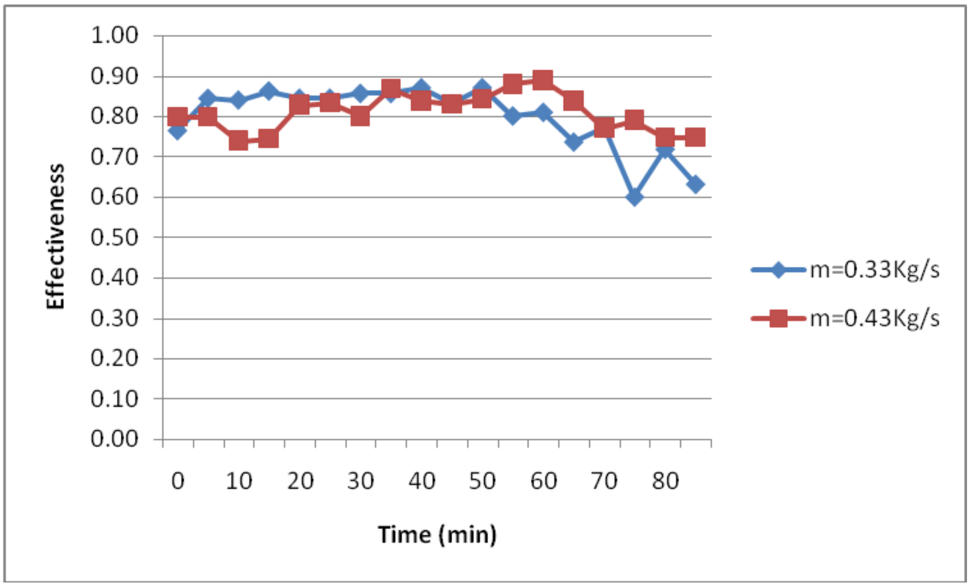

Fig. 3. Effectiveness of heat exchanger during charging

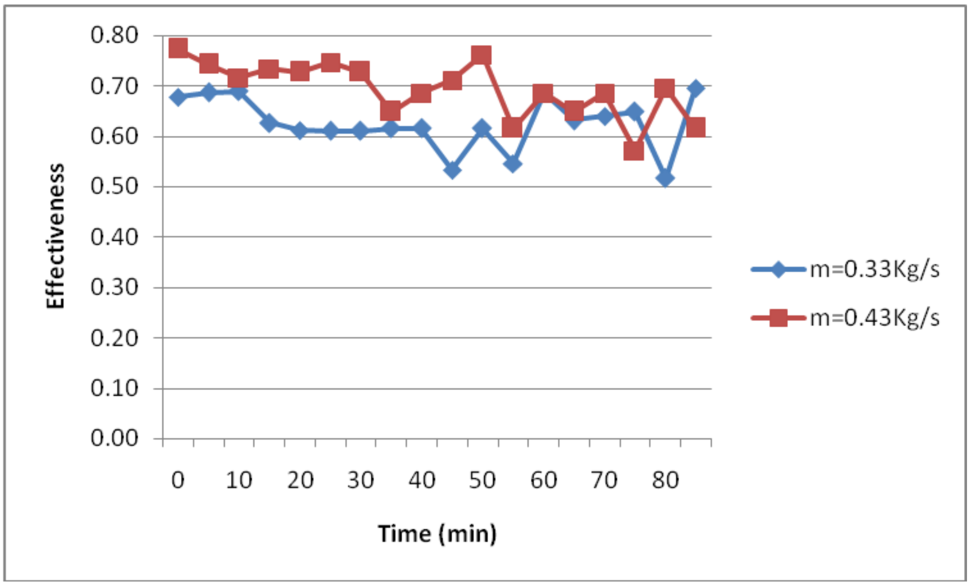

Fig. 4. Effectiveness of heat exchanger during discharging

3.1.2 Effectiveness of perforated finned surface

Figure 5 shows the effectiveness of the Heat exchanger versus melting time for 0.33Kg/s and 0.43Kg/s HTF mass flow rates. At 0.43 Kg/s mass flow rate effectiveness is slightly higher than that of 0.33 Kg/s. Figure 6 gives detailed insights into the effectiveness of a finned heat exchanger with holes on the surface at 0.33 and 0.43 Kg/s flow rate during solidification. The effectiveness obtained from results showed it is higher during the charging than discharging process because of the natural convection effect.

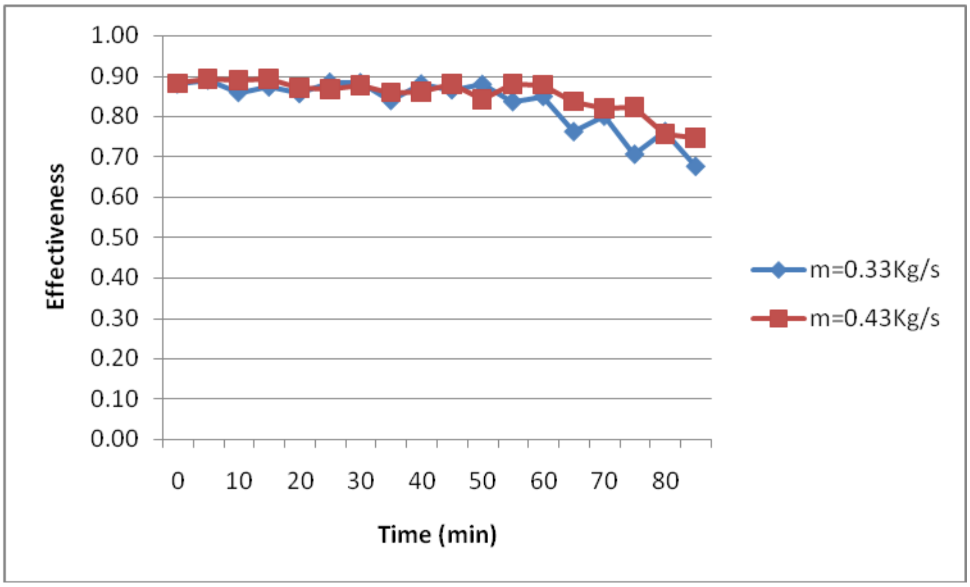

Fig. 5. Effectiveness of heat exchanger with holes during charging

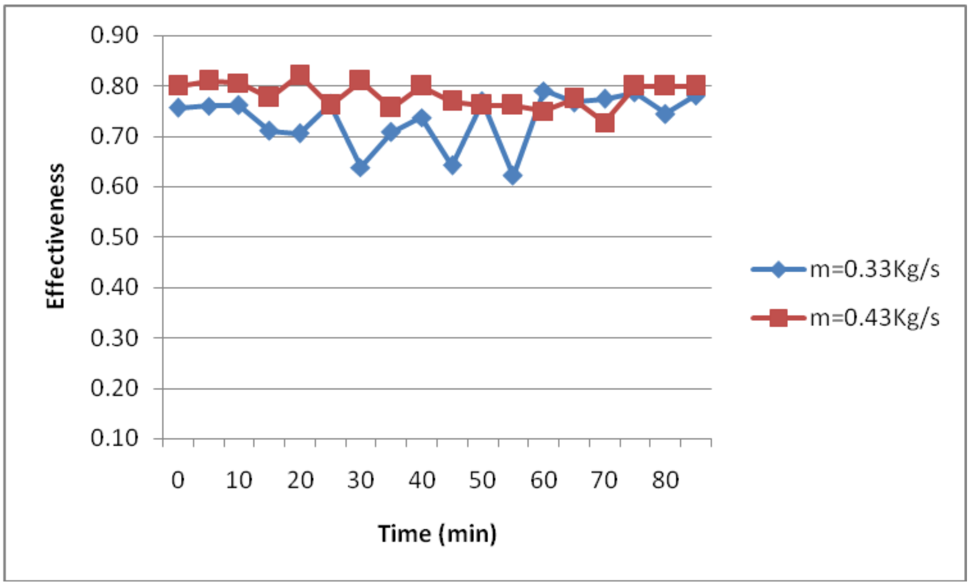

Fig. 6. Effectiveness of heat exchanger with holes during discharging

3.2 Comparison of Effectiveness

The effectiveness obtained by fins with perforated surface and fins without holes during charging and discharging at 0.33 and 0.43 Kg/s mass flow of water compared in the following sections.

3.2.1 Charging

Figure 7 shows the comparison of the effectiveness of finned heat exchanger with & without holes on fin surface during charging at 0.33 Kg/s and Figure 8 shows a Comparison of the effectiveness of finned heat exchanger with & without holes on fin surface during charging at 0.33 Kg/s. As shown in Figure 7 and Figure 8, at both flow rates effectiveness of TTHX with holes on the fin surface is much better than that of fins without holes on it during the melting process. The effectiveness obtained with holes on the fin surface is 0.83 and without holes is 0.80 at 0.33 Kg/s whereas it is 0.85 and 0.81 at 0.43 Kg/s respectively.

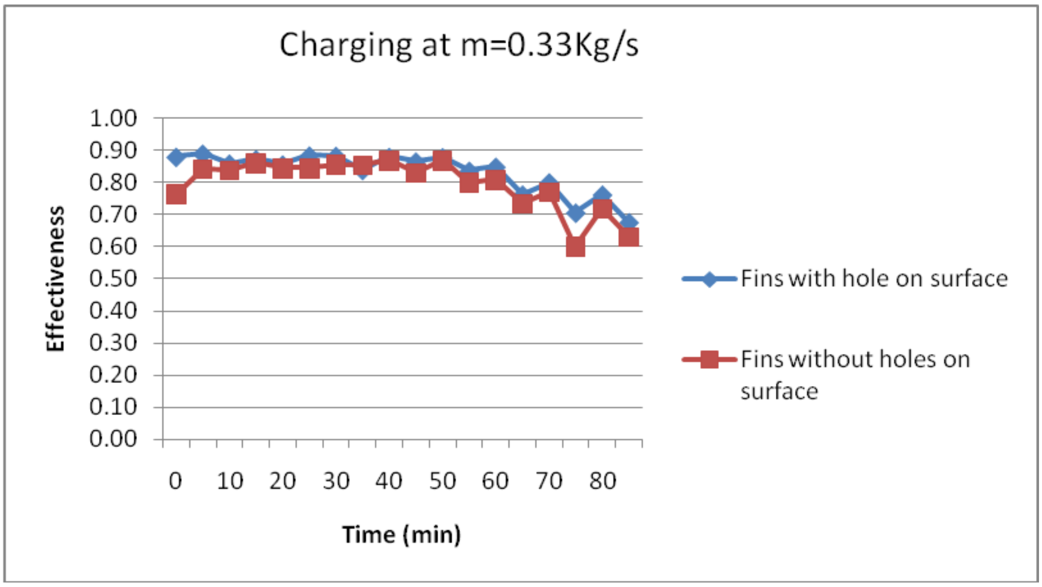

Fig. 7. Comparison of the effectiveness of finned heat exchanger with & without holes on fin surface during charging at 0.33 Kg/s

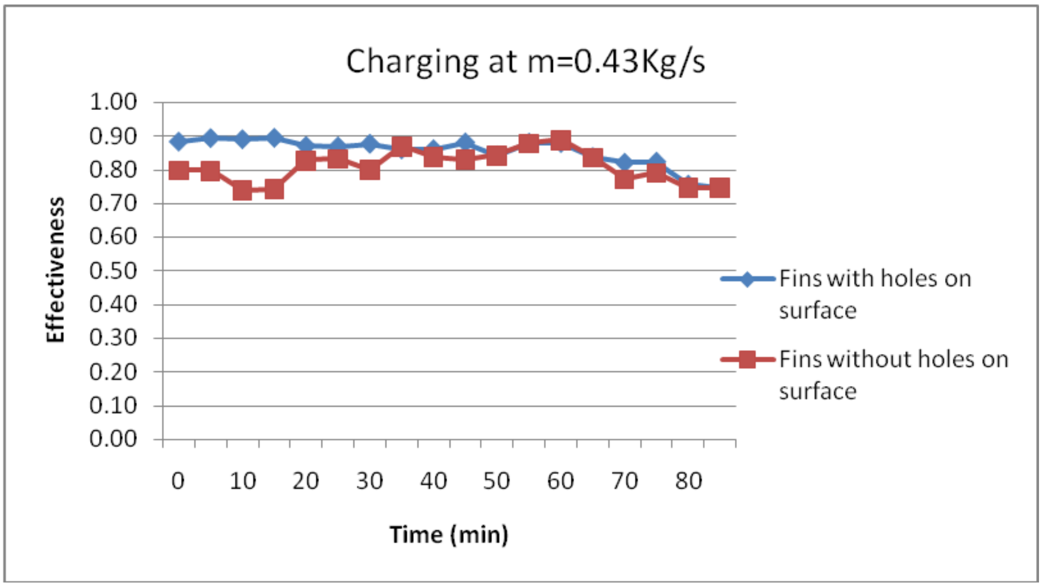

Fig. 8. Comparison of the effectiveness of finned heat exchanger with & without holes on fin surface during charging at 0.43 Kg/s

3.2.2 Discharging

As shown in Figure 9 and Figure 10, at 0.33 Kg/s and 0.43 Kg/s; the effectiveness of TTHX with holes on the fin surface is greater than without holes on it during the solidification process. At 0.33 kg/s, effectiveness obtained is 0.73 with holes on the fin surface and 0.63 without holes whereas, at 0.43 Kg/s, effectiveness is 0.78 and 0.69 with holes on the fin surface and without holes respectively.

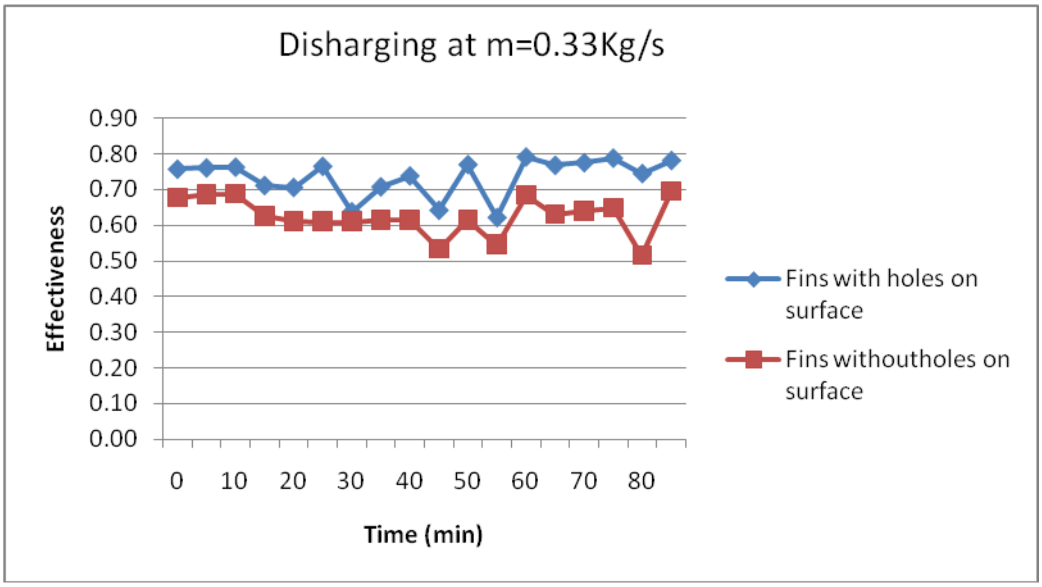

Fig. 9. Comparison of the effectiveness of finned heat exchanger with & without holes on fin surface during discharging at 0.33 Kg/s

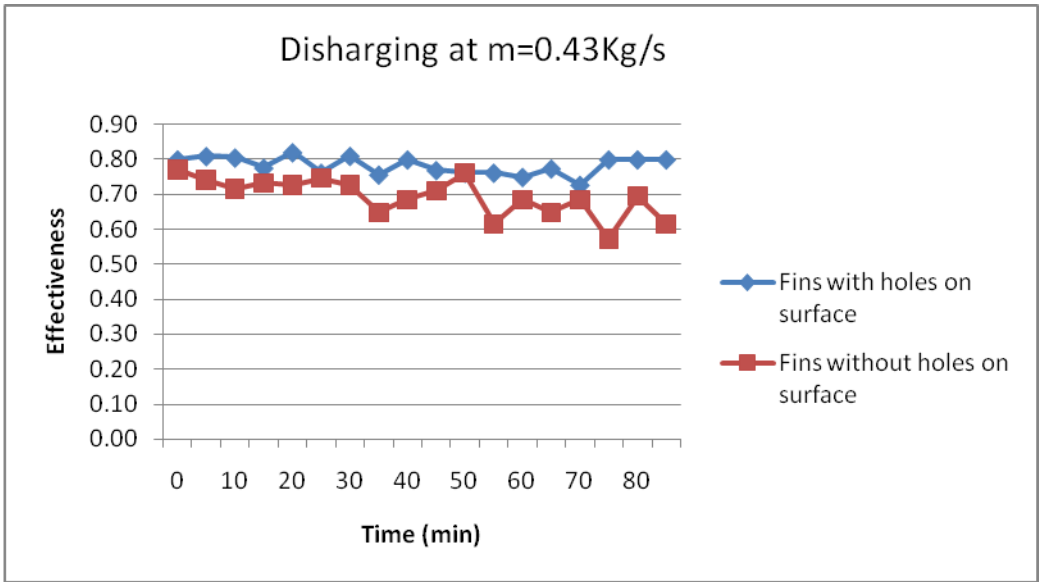

Fig. 10. Comparison of the effectiveness of finned heat exchanger with & without holes on fin surface during discharging at 0.43 Kg/s

4. Conclusion

The triple pipe heat exchanger as a latent energy thermal heat storage system has been experimentally investigated using stearic acid as phase transition material with longitudinal fins with and without holes on the fin surface. The experiments were conducted for heat transfer fluid flow of 0.33 and 0.43 Kg/s during the charging and discharging processes. The average effectiveness of HX was investigated for melting and solidification. The results showed that the average effectiveness with the finned triplex tube with holes on the fin surface is 4% more than the finned triplex tube at 0.33 Kg/s whereas it is 5 % more at 0.43 Kg/s during the charging process. On the other hand, during discharging process average effectiveness is 14 % more at 0.33 Kg/s and 11 % at 0.43 Kg/s.

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