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Experimental Investigation of Sinusoidal Tube in Triplex-Tube Heat Exchanger during Charging and Discharging Processes Using Phase Change Materials

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ABSTRACT

In this experiment effect of two full and half width sinusoidal inner tubes in triplex-tube heat exchanger with phase change material (PCM) was investigated. Length and diameter of the tubes have been chosen such that the area of each tube to be the same. Charging and discharging processes were carried out by inner tube, outer tube and both. Results indicated, PCM melting and solidification time for the full width sinusoidal inner tube, in the processes of charging and discharging from the inner tube, outer tube and two sides were shorter than the half width sinusoidal inner tube. Comparing the charging and discharging processes of these tubes with a straight inner tube indicated significant improvement in the amount and reduction in time of PCM melting. The melting mode in the straight tube process was incomplete after about 32.5 hours, however in the case of full and half width sinusoidal inner tube, the melting times were 8 and 10 hours, respectively. Moreover, it was an improvement of 54% in melting time from the outer tube in the full width sinusoidal tube and 35.8% in the half width sinusoidal tube.

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1. INTRODUCTION

Population growth has led to an increase in the consumption of energy, which is major challenge of today's researchers. This issue has become very important because of maintenance of worthy resources of the earth and the management method of their consumption. Meanwhile, the surplus increase in fossil fuel consumption is one of the most concerning issues that have always been discussed. Since this unnecessary consumption leads to an increase in greenhouse gas emissions and global warming on the one hand, and on the other hand, it causes air pollution and its harmful effects on human health. Therefore, the method of managing fuel consumption and preventing energy loss reduces their destructive effects. For this reason, the storage of thermal energy is one of the most important topics that have been considered more and scientists are researching for more efficient ways to store. One of the most effective of these methods is the use of storage systems using the latent heat of phase change materials (PCMs). The ability to store high thermal energy due to its high latent heat capacity, various temperature ranges, many applications in industries, factories, aerospace, solar cooling, and heating systems, and even home appliances could be considered as its advantages. Meanwhile, one of the most important applications of PCMs is the use of these materials in the heat exchanger. Heat exchangers are highly efficient equipment for exchanging heat between two or more fluids. Due to their wide usage, they have become increasingly important to agriculture and industry, and due to the high capacity of heat exchangers using PCMs, many studies have been carried out on this subject. Use of PCMs has been reported by Telkes and Raymond [1], Morrison et al. [2] and Sparrow et al. [3]. Marshall and Dietsche [4] carried out extensive studies on various applications of these systems, such as solar thermal systems. The study on PCM systems continued especially in the field of fundamental designs, systems and optimization

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processes, the study of transient behavior as well as the performance of these systems. Ding et al. [5] simulated the performance of a double pipe exchanger with time-varying input boundary conditions. In their study, the temperature and mass flow rate of the input fluid were linearly changed with time and simulation performed using enthalpy method. The results indicated with increasing temperature and mass flow in each mode, the melting time was decreased and the amount of stored energy increased. Kibria et al. [6] studied the heat transfer in the thermal energy storage system of the shell and tube heat exchangers. They found that increase in the temperature of the heat transfer fluid is more effective than increase in the mass flow rate of the heat transfer fluid in the melting and solidification.

One of the techniques for improving heat transfer in heat exchangers is the design of heat exchanger chambers. The PCMs are typically stored in thin and long heat tubes, cylindrical, or rectangular chambers. The results indicated that both the rectangular and cylindrical chambers are more useful than other types. The most common application was related to shell and tube geometry, which is 70%. In this type of geometry, the PCMs are located in a concentric radial space that the heat transfer fluid flows in the inner tube. Mosafa et al. [7] investigated a two-dimensional model of shell and tube heat exchanger with radial fins containing a PCM. Their results indicated that the process of solidification in a column shell is faster than that in the rectangular shell. Spiral tube exchangers are a type of heat exchanger that in their structure spiral tubes were used instead of straight tubes. Due to the wider side's surface of these tubes comparing to straight tubes, they have higher temperature than straight tubes and therefore, in the industry, especially in the chemical, pharmaceutical, and thermal processing industries, are used mostly [8–10]. Using the wide applications of these tubes in the industry, many studies have also been carried out. Most studies generally address the variation of the Nusselt number on the inner surface of these tubes, and in the forced convection condition, and there were fewer number of studies conducted on the Nusselt number of the outer surface of these tubes under free convection conditions. Tarbell and Samuels [11] applied conservation of energy, momentum, and continuity for the spiral tubes and reported the heat transfer coefficient of the internal surfaces of these tubes under forced convection for steady state condition using numerical technique. Ali [12] preformed some experiments on horizontal spiral tubes in which the air was in laminar flow and the walls were under various heat fluxes. He stated that by increasing the number of spirals of used spiral tube, the average Nusselt number would be reduced. Further, studying the results, a relationship was presented for obtaining the Nusselt number of these tubes, which is independent of the thermal flux and is only a function of Rayleigh number .

Use of several hot fluid carrier tubes is also another technique for improving heat transfer in heat exchangers. Agyenim et al. [13] studied experimentally a shell and a horizontal tube heat exchanger using PCM with an average temperature of 177.7 °C. They showed that application of multi-tubes inside the shell would improve the heat transfer rate in the charge and discharge process. Esapour et al. [14] examined the behavior of PCMs in multi-tube heat exchangers. In this study, water flows as a working fluid through the inner and outer tube/tubes, and the middle tube was filled with a phase change material of RT35. Some researchers have also studied the use of corrugated tubes as a technique for increasing heat transfer. In fact, these tubes increased the heat transfer rate in a double pipe exchanger by mixing the thermal boundary layer and creating turbulence. Vicenet et al. [15] examined the heat transfer and friction coefficient for a turbulent flow in Reynolds and Prandtl numbers range of 2000-90000 and 2.5-100, respectively. They observed that the friction coefficient and Nusselt number increase comparing to the straight tube by 300% and 250%, respectively. Petkhool et al. [16] examined the increase in heat transfer in an exchanger by a corrugated tube. They used a corrugated tube as an internal tube of double pipe heat exchangers. They indicated an increase in the Nusselt number and friction coefficient of 114% and 201%, respectively, compare to the straight tube. Laohalertdecha et al. [17] examined the evaporation heat transfer and the friction coefficient of the R134-refrigerant inside a horizontal corrugated tube. They provided relations for the Nusselt number and the friction coefficient as a function of the Reynolds number, wave step and depth, and tube diameter. Chen et al. [18] examined numerically and experimentally the system of energy storage with a spiral tube by using paraffin and compact graphite. They indicated that temperature difference of heat transfer had important effect on their storage system and Reynolds number had minor effect particularly when it is more than 8700.

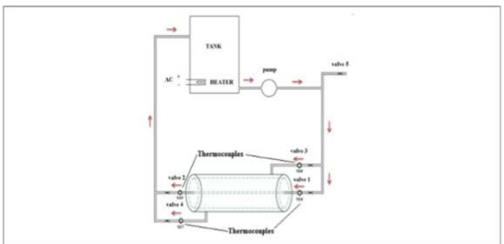
Various studies have been carried out on the use of PCMs in heat exchanger. The low thermal conductivity coefficient of PCMs has been a challenge to energy exchange. Of course, various studies have been done to resolve this problem. However, no study has been performed on the use of a sinusoidal inner tube in triplex-tube exchanger with phase change materials while simultaneously charged and discharged from the inner tube and the outer tube. On the other hand, comparison has not been made among the changes in the shape of the middle tube at the same surface area. For this purpose, a triplex-tube exchanger with two sinusoidal inner tubes was designed with half width and full width. The effect of shape of the inner tube on the process of melting and solidification of PCM were sought. Optimal changes in the charge rate, and its time were studied using full and half width sinusoidal inner tube. Results were also compared with the straight inner tube.

2. EXPERIMENT SETUP

Two steel tubes with a diameter of 4 and 6 inches, and a length of 1.2 meters were used. In some studies for manufacturing these systems, the radial distance between the tubes was set between 3 and 4 cm to improve the effective heat conductivity of these systems [19]. Both tubes were covered with an anti-rust layer. The inner tubes were placed in the concentric form, and the tips and the ends of both were covered with metal rings, which enclosed the space of the two tubes. For the internal tube, copper metal tube was used. Two inner tubes with the same surface area with different geometries, which located inside the heat exchanger as an internal tube, were used.

It should be noted that in this text the 4 inches width sinusoidal inner tube is called “full width sinusoidal inner tube” and the 2 inches width sinusoidal inner tube is called “half width sinusoidal inner tube”. Schematics of the system is shown in Figure 1. Figure 2 shows the heat exchanger with the installed location of the thermocouples, and the picture of setup.

Type K-thermocouples with an accuracy of ± 0.1°C were used in the inlet and outlet of the water of the heat exchanger numbered S14-17 as shown in Figure 1. Heat exchanger was designed with two types of inner tubes with the same surface area of different dimensions. Sinusoidal inner tubes were designed and used shown in Figures 2-A and B. The thermocouples were installed in the radial and angular position within the range of the first turning point of sinusoidal tube at the tube inlet in order to display the temperature of the PCM inside the heat exchanger. The location of thermocouples S1-S13 is shown in Figure 2C. Knowing the measuring accuracy of thermocouple and the data logger, the uncertainty was 0.06°C. Type Grundfos 60-25 UPS water pump was used. This linear water-circulating pump has a single-phase power as shown in Figure 2-D.



Process	Condition of valves			
	Valve 1	Valve 2	Valve 3	Valve 4
Charge and discharge from the inner tube	Open	Open	Close	Close
Charge and discharge from the outer tube	Close	Close	Open	Open
Charge and discharge from the both sides	Open	Open	Open	Open
Valve 5 used only for the input of working fluid into the system and closed during the process				

Figure 1.Schematic of experimental setup (S14, S15, S16, and S17 stand for thermocouples)

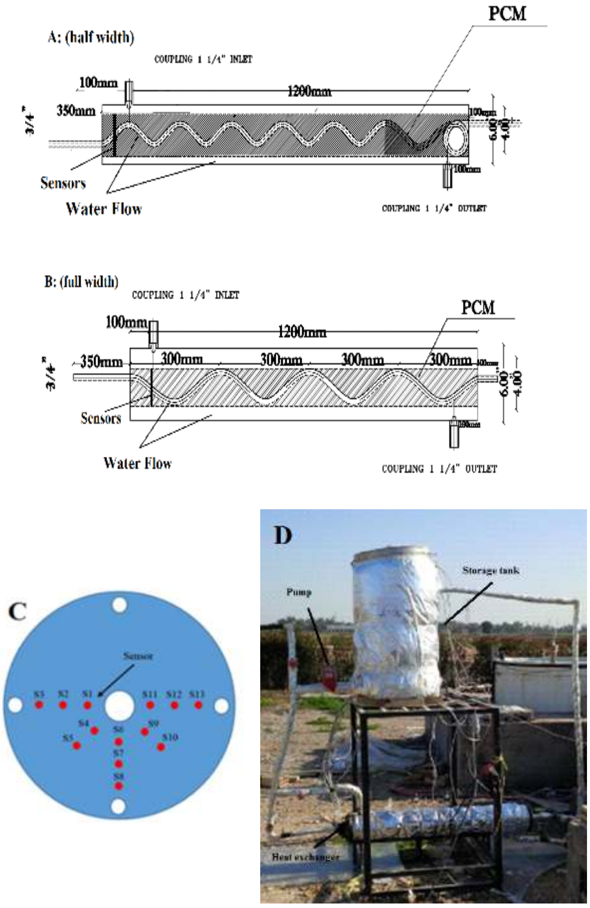


Figure 2. A, B) Schematic of heat exchanger, C) location of thermocouples and D) experimental setup picture

3. METHODOLOGY

The reservoir, water with volume of 100 liter was considered and the height required for this volume was calculated as being 60 cm from the bottom of the tank. Therefore, the height of reservoir was considered 85 cm. Temperature of the thermostat was set to 90°C, which produced temperature of about 80 to 85°C. Filling time to supply the flow rate by pump for one liter was measured three times every 1 minute. Then, the supplied average of flow rate was 11.465 lit/min. Paraffin wax as phase change material (PCM) was used with the physical properties as stated in Table 1. The space between the inner tube and the middle tube was filled with 10 kg of PCM. In charging tests, water flows inside the heat exchanger and time spending, temperature differences in both charge, and discharge process was obtained by measuring the amount of melted PCM and time required to complete the melting process. The heat exchanger performance criterion for these tests is set to recharge it completely at a shorter time. The experiments were carried out three times at each stage. After completing the charging process, in order to perform discharge test,

TABLE 1. Thermo physical properties of paraffin wax [20, 21]

Properties	Values
Thermal conductivity (Solid)	0.21 W/m K
Density (Solid)	930 kg/m^3
Density (Liquid)	830 kg/m^3
Specific Heat capacity	2.1 kJ/kg K
Latent heat of fusion	189 kJ/kg
Melting point	66-68 °C

water of reservoir was discharged and filled with the same amount of water at the ambient temperature, which is between 13-20°C. The governing equations of heat and power transfer rate are introduced in the Appendix.

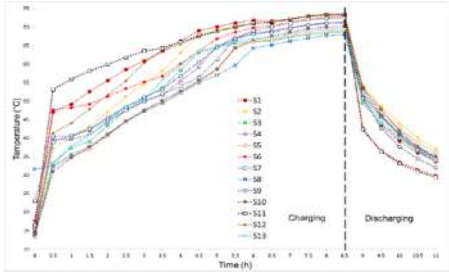
In the discharging tests, looking to which one of the tubes could accelerate the solidification process and how much of heat could be absorbed by the PCM in the charging process. For these tests, following assumptions were made; the mass flow rate of input fluid is stable, the temperature of input fluid is in constant range, the effect of the volume changes on phase change of the solid-liquid is negligible, and the end of the discharging process takes place when the temperature of PCM reaches to around 40°C.

4. RESULTS AND DISCUSSION

4. 1. Analysis of Charge and Discharge from the Inner Tube

Figure 3-a shows the full width sinusoidal tube at the test of charging from the inner tube. Except two thermocouples, all of the thermocouples show the PCM temperature variation of 13-20°C. The charging process began with entering the hot water at 83°C into the full width sinusoidal inner tube. The approximate PCM melting times of thermocouples from the start of the charging process are shown in Table 2.

It can be noticed that the time to reach full charge in this case is 8.5 hours. It can be concluded that the relative extremum points of the full width sinusoidal inner tube acted as a fin, which led to heat up the heat exchanger, therefore, this issue caused to increase the heat flux and accelerate the PCM melting process. After full charge of the heat exchanger, discharging process started by the flow of water at ambient temperature of 15°C. Figure 3-b indicates the average S1-S13 temperature of PCM and their deviation, inlet, outlet from inner tube. It can be noticed that the highest thermal loss occurs in the first time step of the discharging. Since, temperature different between cold water with PCM was higher. Therefore, the average temperature of all thermocouples within the PCM reached below 65°C at 8.5 hours from the start of process. Continuing the discharging process, the temperature drop is very slow due to the solid layer



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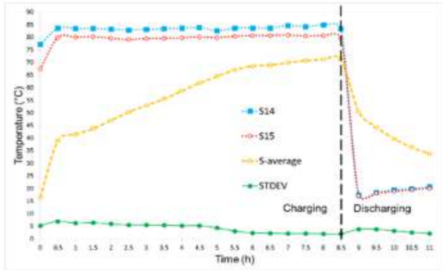

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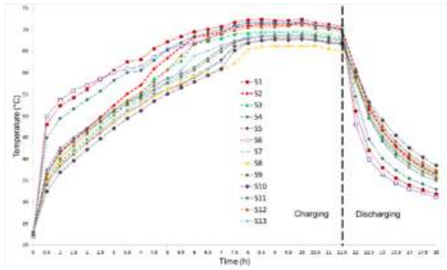
Figure 3. a) Temperature profile in process of charge and discharge of full width sinusoidal inner tube and b) their average, inlet, outlet, and deviation from average temperature

formation around the inner tube. This solid layer acts like thermal resistance and thus prevents heat transfer. It was observed that the PCM average temperature eventually reaches below 35°C. This process ended after 2.5 hours with a 4.6°C increase in temperature of the working fluid. As shown in the figure, the deviation of temperature of all thermocouples (S1-S13) from the average value is 4.09°C.



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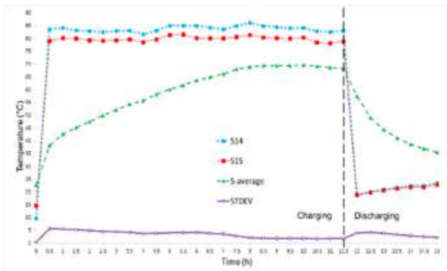

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Figure 4. The PCM average, inlet, outlet temperature, and deviation from average temperature for a) full width sinusoidal b) half width sinusoidal for charge and charging

In the half width sinusoidal inner tube, as shown in Figure 4-a, the PCM temperature varied in the range of 22-23°C from the start of the charging process. Further, the approximate PCM melting times of thermocouples from the start of the charging process are also shown in Table 2. Heat exchanger was fully charged after approximately 10 hours. Considering the thermocouples melting process in this case, the melting layer was created around the inner tube through conduction heat transfer and then, the growth of molten layer through the convection heat transfer. It should be noted that thermocouple S8 was found around the melting point 10 hours after the start of the charging process. This can be attributed to the reduction of the ambient temperature and thermal loss of the outer tube. At the end of charging process, the discharging started. After 30 minutes from the start of discharging, all of the thermocouples near the inner tube had the highest temperature drop compared to the thermocouples farther from the inner tube due to the conduction heat transfer. Figure 4-b indicates the average temperature S1-S13 and their deviation of PCM, inlet, and outlet from the inner tube. It can be noticed that the highest thermal loss occurs in the first time step of the discharging of PCM. Therefore, the average temperature of all thermocouples within the PCM reached below 65°C at around of 10 hours from the start of process. It was observed that the PCM average temperature eventually reaches below 35°C. This process ended after more than 5 hours with an increase in temperature of the working fluid by 6°C. Moreover, figure shows deviation of temperature of all thermocouples (S1-S13) from the average value is 3.32°C.

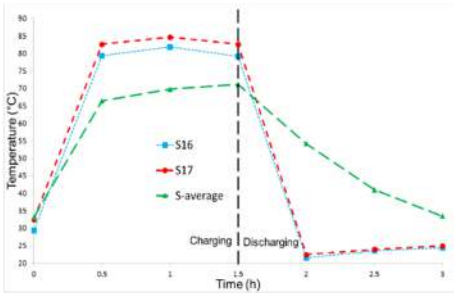
TABLE 2. Melting point time from the start of the charging inner tube process

Thermocouple	Time (Hours)	
	Full	Half
S1	4	4.5
S2	4.5	5.5
S3	5.5	6
S4	5	7
S5	6	7.5
S6	5	5
S7	5.5	7.5
S8	6.5	8
S9	5.5	7
S10	6	7.5
S11	4	5
S12	4	6
S13	5.5	6.5

Further, Table 2 compares full and half width sinusoidal inner tube. It is clear that melting time in full width condition in all zones is less than half width condition. These differences in outer thermocouples are more than inner thermocouples, e.g. melting time spending in S5 and S7 are 1.5 and 2 hours, respectively. In addition, comparing temperature average of both systems in their maximum can be concluded that temperature average of full width situation has improved 2.4% to half width.

4. 2. Analysis of Charge and Discharge from the Outer Tube As shown in Figure 5-a, when the hot water flow into the outer tube of the heat exchanger where the full width sinusoidal inner tube is located, the PCM temperature varied in the range of 32-33 °C before the start of the charging process from the outer tube. As shown in Figure 1, it should be noted since the water at 80°C passes through the outer tube in this case; the S16 and S17 thermocouples indicate the inlet and outlet temperatures. After 30 min from the start of charging, system was affected by the conduction heat transfer mechanism. Then the PCM melting started and by increasing the rate of molten PCM, after one hour from the beginning of the charging process, the last thermocouple recorded the melting of PCM.

In the process of discharging from the outer tube, according to the figure, data shows that the heat exchanger was completely discharged after 90 min from the start of flowing cold water inside the outer tube at



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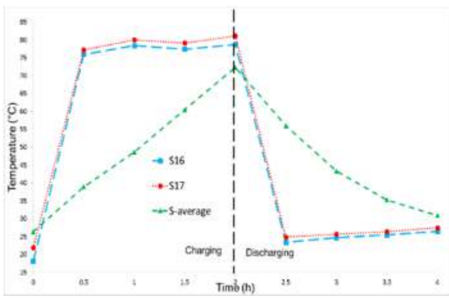

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Figure 5. The PCM average, inlet, and outlet temperature for a) full width sinusoidal b) half width sinusoidal for charging from the outer tube

15°C. Moreover, the temperature drop during the discharging process over the time intervals in this case was higher than the full width sinusoidal inner tube, which is due to the increase in heat transfer area and formation of more solid PCM layer. In addition, the figure illustrates the process of heating the water during the discharging process from the outer tube. Therefore, the discharging process from the outer tube lasted 90 min and increased the temperature of working fluid with ambient temperature by 4.5°C. The average temperature S1-S13 of all thermocouples within the PCM reached just under 70°C after 1.5 hours as started and reached 33°C at the end of process .

Based on Figure 5-b, the hot water flow into the outer tube of the heat exchanger where the half width sinusoidal inner tube is located, the PCM temperature varied in the range of 22-27°C at the start of the charging process. The charging process from the outer tube started with flowing hot water at 80°C through the outer tube of the heat exchanger. After 2 hours from the start of charging, all thermocouples inside the PCM indicated the melted PCM temperature. In this case, with starting the charging process, the solid PCM begins to melt and molten layer was formed in a ring around the middle tube. This molten layer became thicker by continuing the charging process. In addition, this figure illustrate that average of S1-S13 of all thermocouples in the PCM reached 72°C after 2 hours. Beside this working fluid indicated a rise of 5.1°C. It can be said that, at the beginning of the discharging process, a narrow thickness of solid layer under the conduction heat transfer mechanism formed over time, this layer became thicker. Therefore, after 2 hours from the start of the discharging process, the solid layer acts like thermal resistance and prevents the heat transfer and average temperature of PCM reached below 31°C at the end of the process.

Further, Table 3 compares full and half width sinusoidal inner tube at charging by outer tube versus time to reach the melting point. It is clear that such as inner tube, melting time in the full width in all zones is less than half width condition. Although the PCM in heat exchanger with full width could melt in less time than half width, by comparing with maximum temperature average of both systems, it can be concluded that average temperature of the full width situation has dropped 1.6% to the half width.

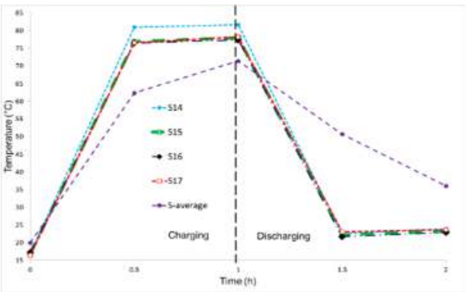
TABLE 3. Melting point time from the start of the charging from the outer tube

Thermocouple	Time (Hour)	
	Full	Half
S1	0.5	2
S2	0.5	1.5
S3	0.5	1.5
S4	1	2
S5	0.5	2
S6	1	2
S7	1	2
S8	1	2
S9	1	2
S10	0.5	2
S11	0.5	2
S12	0.5	2
S13	0.5	2

4. 3. Analysis of Charge and Discharge from Both Inner Tube and Outer Tube

As shown in Figure 6-a, for performing this test, hot water at 80°C was introduced into the full width sinusoidal inner tube and inside the heat exchanger outer tube, the temperature of PCM at the start of the charging process varied in the range of 15-20°C. As shown in Figure 1, it should be noted that since the water passes through the outer tube in this case, the S14, S15, S16, and S17 thermocouples indicate the inlet and outlet temperatures. After the start of the charging process approximately 30 min, the average temperature of PCM reached 62°C and after 60 min was 71°C. Since during the charging process, the thermal flux from the inner tube and outer tube, receptively, caused the PCM around the inner tube and the middle tube to be affected by the conduction heat transfer mechanism. Continuing the charging process, the molten volume was increased within the ring space of the inner and the middle tube, while the rest of the PCM reached the melting point of PCM through the convection heat transfer. The type of heat transfer in this condition is natural convection due to molten PCM in the middle shell. In the full width inner tube, the relative extremum points which was connected to the 4-inch inner tube acts as a fin and accelerate the melting process, as well. During the discharging process, it was observed that after an hour from the start of discharging, the average S1-S13of all thermocouples in the PCM shows 36°C. Moreover, the figure shows that during this time interval, the fluid temperature increased by 3°C.

In charging from half width sinusoidal inner tube in the outer tube, all thermocouples inside the PCM at the instant of the start of the charging process indicated temperature range of 30-35°C. Figure 6-b shows that after 90 min from the start of the charging, the average temperature S1-S13 of the PCM is 78°C. It can be noticed that the heat transfer was initially carried out through conduction heat transfer mechanism, and then followed by strong natural convection due to the flux of molten PCM. It should be mentioned that the close distance of the relative extremum points to the outer tube also increased heat transfer and accelerated the melting



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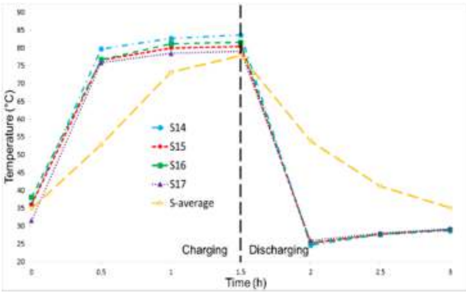

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Figure 6. Average PCM, inlet, and outlet temperature for a) full width sinusoidal inner tube and outer tube b) half width sinusoidal for charging from inner tube and outer tube

process. In addition, the final average temperature of PCM in discharging reached 35°C. Finally, this figure shows that the rate of heating water during the discharging process from both outer tube and inner tube side is 4.5°C.

Further, Table 4 compares the full and half width sinusoidal inner tube during charging outer tube and inner tube. It is seen that, except for S7 where the distance of this thermocouple to outer tube and inner tube is more than others, melting time in the full width in all zones are equal with the half width condition.

TABLE 4. Melting point time from the start of the charging inner tube-outer tube process

Thermocouple	Time (Hour)	
	Full	Half
S1	1	1
S2	1	1
S3	1	1
S4	1	1
S5	1	1
S6	1	1
S7	1	1.5
S8	1	1
S9	1	1
S10	1	1
S11	1	1
S12	1	1
S13	1	1

In addition, comparing the average temperature of both systems in their maximum can be concluded that the average temperature of the full width situation dropped 8.3% to the half width.

Comparison of temperature rise during discharging process is shown in Table 5. In the half width mode, the temperature rise in the fluid for all cases is more than the full width mode. In the case of discharges from the half width sinusoidal tube, the fluid experienced temperature increase of 6ºC, which shows an improvement by about 30.4% as compared to the full width tube, which has increase of 4.6°C.

In the cases of flowing fluid from the outer tube and from both sides, increase in temperature is 13.3 and 63.3%, respectively. This can be attributed to having more time for heat transfer between fluid and the PCM in the half width mode.

4. 4. Comparison with Straight Tube

Results of the process of charging and discharging from the inner tube, outer tube and both sides of the heat exchanger in the cases of using the full and the half width sinusoidal tube as the inner tube inside the heat exchanger were compared with the straight inner tube. It should be reminded that straight inner tube had the same area with both sinusoidal inner tubes. As shown in Table 6, there is a significant improvement in the melting rate as well as a significant reduction in the time of full melting of the PCM in the heat exchanger. Hence, the incomplete melting occurred after 32.5 hours when the straight inner tube was used, whilst the melting time was 8.5 hours by using the full width sinusoidal inner tube, and this time was 10 hours by using the half width sinusoidal inner tube. The results indicate more time for exchanging heat energy with PCM. This is because the sinusoidal tube is longer than the straight tube and it caused PCM to melt completely.

Charging and discharging from the outer tube using the full width sinusoidal inner tube, as an inner tube inside the heat exchanger, is optimal in the melting rate and more effective while comparing to the outer tube when using the straight or half width sinusoidal inner tube. In the full width sinusoidal inner tube, the heat

TABLE 5. Temperature difference (°C) of the water during the discharge process

Type of experiment	Inner tube	Outer tube	Both sides
Full width sinusoidal tube	4.6	4.5	3
Half width sinusoidal tube	6	5.1	4.5
Percentage change compared to full width	30.4 %	13.3 %	50 %

TABLE 6. Comparison with straight inner tube

Type of experiment	Charging		Discharging	
	Duration	Percentage change compared to straight tube	Duration	Percentage change compared to straight tube
full width sinusoidal tube				
Inner tube	8.5 h	N.A	2.5 h	44.4%
Outer tube	90 min	54%	90 min	0
Both sides	60 min	35%	60 min	0
Half width sinusoidal tube				
Inner tube	10 h	N.A	3.5 h	22.2%
Outer tube	120 min	38.5%	120 min	-0.33%
Both sides	90 min	2.2%	90 min	-50%
Straight tube				
Inner tube	Incomplete charge	-	4.5 h	-
Outer tube	195 min	-	90 min	-
Both sides	92 min	-	60 min	-

transfer occurs through its thermal bridges as conduction heat transfer from the middle tube to the full width sinusoidal tube. It causes to heat up the full width sinusoidal inner tube. In the process of charging and discharging, the full width sinusoidal inner tube acts as a fin, which increases the heat transfer rate. It can also be noticed that in the melting from both sides, use of the sinusoidal inner tube reduced the time of full melting.

Further, the results indicate 54% improvement in the melting from the outer tube in the sinusoidal inner tube and 35.8% improvement in the melting from the outer tube in the half width sinusoidal inner tube. In addition, it can be seen that not only the melting process occurs in less than time comparing to using a straight inner tube, but also the discharge process is carried out in less time. Therefore, there is significant improvement in time reduction due to the increase in the heat transfer area.

5. CONCLUSION

In this study, the effect of using the sinusoidal tube as an inner tube inside a triplex-tube heat exchanger on the process of melting and solidification of PCM was investigated. A triplex-tube heat exchanger with paraffin between its inner tube and the middle tube and two internal sinusoidal tubes were used. Two tubes were designed and fabricated one in the form of half width and the other in the form of full width. Experiments were carried out through three ways depending on the pathway of water flow, charging from the inner tube, charging from the outer tube and charging from both inner tube and outer tube. The discharge tests were performed similar to the charge process, with the exception that in the discharging process, the reservoir water was filled at ambient temperature. Then, the results of this mode were compared with that of using the straight inner tube. The following results were obtained:

- Use of full width as compared to the half width sinusoidal tube, reduces the time required for complete melting. A 15% improvement was obtained in the case of charging from the tube, 25% from the outer tube, and 33.3% from both inner tube and outer tubes.
- Comparing the charging processes using straight inner tube as inner tube revealed that the use of a full width sinusoidal inner tube improves the performance in terms of the rate of melting of paraffin as well as reducing the time needed for the maximum melting in the exchanger. Therefore, in the charging process from the inner tube, the exchanger was not completely charged after 32.5 hours for the straight inner tube, while the use of the sinusoidal inner tube in both modes caused the complete melting of the paraffin in less than one third of the time. Moreover, in charging from the outer tube and from both sides, the full width sinusoidal inner tube improved melting rate by 54% and 35%, respectively, compared to the straight inner tube.
- Comparing results in discharging mode indicated that the full width sinusoidal inner tube reduces the time require for full discharging. Hence, it showed better performance by 29% in the discharging process from the inner tube, 25% from the outer tube, and 33.3% from both sides.
- In the full width sinusoidal inner tube, the relative extremum points connected to the middle tube of the heat exchanger act as fins. As a result, the heat is transmitted to the middle tube of the heat exchanger through the conduction heat transfer mechanism and consequently increases the thermal flux. The placement of full width sinusoidal tube as an inner tube inside the heat exchanger reduces the charging and discharging processes as compare to the straight inner tube or half width sinusoidal inner tube.
- Charging from both sides when the full width sinusoidal inner tube used inside the heat exchangers, is more efficient as compared to charging from both sides when the half width sinusoidal inner tube or straight inner tube.

6. REFERENCES

1. Telkes, M. and Raymond, E., "Storing solar heat in chemicals –

a report on the Dover house", ***Heat Vent.***, Vol. 46, No. 11, (1949), 80–86.

2. Morrison, D.J. and Abdel-Khalik, S.I., "Effects of phase-change energy storage on the performance of air-based and liquid-based solar heating systems", ***Solar Energy***, Vol. 20, No. 1, (1978), 57–67.
3. Sparrow, E.M., Larson, E.D., and Ramsey, J.W., "Freezing on a finned tube for either conduction-controlled or natural-convection-controlled heat transfer", ***International Journal of Heat and Mass Transfer***, Vol. 24, No. 2, (1981), 273–284.
4. Marshall, R. and Dietsche, C., "Comparisons of paraffin wax storage subsystem models using liquid heat transfer media", ***Solar Energy***, Vol. 29, No. 6, (1982), 503–511.
5. Ding, W.K., Fan, J.F., He, Y.L., Tao, W.Q., Zheng, Y.X., Gao, Y.F., and Song, J., "A general simulation model for performance prediction of plate fin-and-tube heat exchanger with complex circuit configuration", ***Applied Thermal Engineering***, Vol. 31, No. 16, (2011), 3106–3116.
6. Kibria, M.A., Anisur, M.R., Mahfuz, M.H., Saidur, R., and Metselaar, I.H.S.C., "Numerical and experimental investigation of heat transfer in a shell and tube thermal energy storage system", ***International Communications in Heat and Mass Transfer***, Vol. 53, (2014), 71–78.
7. Mosaffa, A.H., Talati, F., Tabrizi, H.B., and Rosen, M.A., "Analytical modeling of PCM solidification in a shell and tube finned thermal storage for air conditioning systems", ***Energy and Buildings***, Vol. 49, (2012), 356–361.
8. Xin, R.C., Awwad, A., Dong, Z.F., Ebadian, M.A., and Soliman, H. M., "An investigation and comparative study of the pressure drop in air-water two-phase flow in vertical helicoidal pipes", ***International journal of heat and mass transfer***, Vol. 39, No. 4, (1996), 735–743.
9. Abdalla, M.A., "A four-region, moving-boundary model of a once-through, helical-coil steam generator", ***Annals of Nuclear Energy***, Vol. 21, No. 9, (1994), 541–562.
10. Kozo, F. and Yoshiyuki, A., "Laminar heat transfer in a helically coiled tube", ***International Journal of Heat and Mass Transfer***, Vol. 31, No. 2, (1988), 387–396.
11. Tarbell, J.M. and Samuels, M.R., "Momentum and heat transfer in helical coils", ***The Chemical Engineering Journal***, Vol. 5, No. 2, (1973), 117–127.
12. Ali, M.E., "Laminar natural convection from constant heat flux helical coiled tubes", ***International Journal of Heat and Mass Transfer***, Vol. 41, No. 14, (1998), 2175–2182.
13. Agyenim, F., Eames, P., and Smyth, M., "A comparison of heat transfer enhancement in a medium temperature thermal energy storage heat exchanger using fins", ***Solar Energy***, Vol. 83, No. 9, (2009), 1509–1520.
14. Esapour, M., Hosseini, M.J., Ranjbar, A.A., Pahamli, Y., and Bahrampoury, R., "Phase change in multi-tube heat exchangers", ***Renewable Energy***, Vol. 85, (2016), 1017–1025.
15. Vicente, P.G., Garcıa, A., and Viedma, A., "Experimental investigation on heat transfer and frictional characteristics of spirally corrugated tubes in turbulent flow at different Prandtl numbers", ***International Journal of Heat and Mass Transfer***, Vol. 47, No. 4, (2004), 671–681.
16. Pethkool, S., Eiamsa-Ard, S., Kwankaomeng, S., and Promvonge, P., "Turbulent heat transfer enhancement in a heat exchanger using helically corrugated tube", ***International Communications in Heat and Mass Transfer***, Vol. 38, No. 3, (2011), 340–347.
17. Laohalertdecha, S., Dalkilic, A.S., and Wongwises, S., "Correlations for evaporation heat transfer coefficient and two-phase friction factor for R-134a flowing through horizontal corrugated tubes", ***International Communications in Heat and Mass Transfer***, Vol. 38, No. 10, (2011), 1406–1413.
18. Chen, C., Zhang, H., Gao, X., Xu, T., Fang, Y., and Zhang, Z., "Numerical and experimental investigation on latent thermal energy storage system with spiral coil tube and paraffin/expanded graphite composite PCM", ***Energy conversion and management***, Vol. 126, (2016), 889–897.
19. Buddhi, D., "Thermal performance of a shell and tube PCM storage heat exchanger for industrial waste heat recovery", In Proceedings ISES Solar World Congress, (1997).
20. Khan, Z., Khan, Z., and Ghafoor, A., "A review of performance enhancement of PCM based latent heat storage system within the context of materials, thermal stability and compatibility", ***Energy conversion and management***, Vol. 115, (2016), 132–158.
21. Abhat, A., "Low temperature latent heat thermal energy storage: heat storage materials", ***Solar energy***, Vol. 30, No. 4, (1983), 313–332.
22. Peiró, G., Gasia, J., Miró, L., and Cabeza, L. F., "Experimental evaluation at pilot plant scale of multiple PCMs (cascaded) vs. single PCM configuration for thermal energy storage", ***Renewable energy***, Vol. 83, (2015), 729–736.
23. Harald, M. and F., C.L., Heat And Cold Storage With PCM: An Up To Date Introduction Into Basics And Applications, Springer, Berlin, (2008).

APPENDIX

Governing Equations of Heat and Power Transfer Rate

One of the most important issues in the study of heat exchangers are the calculation of the amount of stored heat transfer and the production power. The heat transfer rate ($\dot{Q}$) obtain from the Equation (1) [22, 23]:

$$\dot{Q} = AU.\Delta T_{lm} \quad (1)$$

On the other hand, the Transmission energy can obtained from the Equation (2):

$$P = \frac{dQ}{dt} = \dot{Q} = C_P.\frac{dV}{dt}.(T_{out} - T_{in}) \quad (2)$$

In these relationships, A is the heat transfer area, U is the overall heat transfer coefficient, CP is the specific heat, dV/dt is the transferred fluid flow, and ΔTlm is the logarithmic average temperature difference. ΔTlm obtain using Equation (3).

$$\Delta T_{lm} = \frac{\Delta T_{in} - \Delta T_{out}}{ln\frac{\Delta T_{in}}{\Delta T_{out}}} \quad (3)$$

Since the heat transfer in the system occurs between PCM and the working fluid, the logarithmic average temperature difference is then obtained according to Equation (4).

$$\Delta T_{lm} = \frac{(T_{PCM} - T_{in}) - (T_{PCM} - T_{out})}{ln\frac{T_{PCM} - T_{in}}{T_{PCM} - T_{out}}} \quad (4)$$

By inserting into Equation (1), the heat transfer coefficient and the overall heat transfer coefficient can be obtained using Equations (5) and (6).

$$U = \dot{Q}.\frac{ln\left[\left(T_{PCM} - T_{in}\right)/\left(T_{PCM} - T_{out}\right)\right]}{\pi\, d_{out}.L.\left(T_{out} - T_{in}\right)} \tag{5}$$

$$\dot{Q} = C_P.\frac{dV}{dt}.\left(T_{out} - T_{in}\right) = AU.\frac{T_{out} - T_{in}}{ln\frac{T_{PCM} - T_{in}}{T_{PCM} - T_{out}}} \tag{6}$$

The power of the system is obtained through Equation (9) by simplifying the calculations and using Equations (7) and (8).

$$ln\frac{T_{PCM} - T_{in}}{T_{PCM} - T_{out}} = \frac{AU}{C_P.\frac{dV}{dt}} \tag{7}$$

$$T_{out} - T_{in} = \left(T_{PCM} - T_{in}\right).\left(T_{PCM} - T_{in}\right).\left[1 - exp\left(-\frac{AU}{C_P.\frac{dV}{dt}}\right)\right] \tag{8}$$

$$P = \dot{Q} = C_P.\frac{dV}{dt}.\left(T_{PCM} - T_{in}\right).\left[1 - exp\left(-\frac{AU}{C_P.\frac{dV}{dt}}\right)\right] \tag{9}$$

However, it is necessary to obtain the flow rate and overall heat transfer coefficient to find the melting power that in this system has a constant flow rate with a certain value.

To find the overall heat transfer coefficient, Equation (10) must be used. In this equation, R is thermal resistance which is obtained according to Equation (11) considering the heat transfer between the working fluid and PCM.

$$R_t = \frac{1}{kA} \tag{10}$$

$$R_t = R_p + R_{HTF} + R_{PCM} \tag{11}$$

The thermal resistance of the tube, Rp, is obtained using Equation (12).

$$R_p = \frac{1}{2\pi.L.k_p}.ln\left(\frac{D_{ext}}{D_{int}}\right) \tag{12}$$

Moreover, for the cylindrical shape, the thermal resistance of PCM, Rpcm, can be obtained from Equation (13) below:

$$R_{PCM} = \frac{1}{2.\pi.L.k_{pcm}}.ln\left(\frac{D_{ext,PCM}}{D_{int,PCM}}\right) \tag{13}$$

To find the thermal resistance of the heat exchanger, RHTF, Equation (14) can be used.

$$R_{HTF} = \frac{1}{\alpha_{HTF}.A_{int}} = \frac{1}{\frac{Nu.k_{HTF}}{D_{int}}.\pi.D_{int}.L} \tag{14}$$

In this equation, α is the convection heat transfer coefficient and Nu is Nusselt number. Considering the laminar or turbulent fluid flow in the tube, Equations (15) or (16) can be used:

$$Nu_{Re\le 2300} = Re^{1/3}.Pr^{1/3}.\left(\frac{\mu_b}{\mu_w}\right)^{0.14}.\left(\frac{D_{int}}{L}\right)^{1/3} \tag{15}$$

$$Nu_{Re\ge 2300} = \frac{\left(Re - 1000\right).Pr.\left(\frac{f}{8}\right)}{1 + 12.7.\left(Pr^{\frac{2}{3}} - 1\right).\left(\frac{f}{8}\right)^{1/2}} \tag{16}$$

Here, Re is the Reynolds number, Pr Prandtl number, f the friction factor, and μ the fluid viscosity. In the case of a completely turbulent flow, the approximate value of f can be obtained by using the relationship developed by Petukhov, namely, Equation (17).

$$f = \frac{1}{\left(0.79.ln\left(Re\right) - 1.64\right)^2} \tag{17}$$

Using the stated equations and according to the studies carried out in this research, the results indicate that with constant value of area, the transferred flow and the specific heat, the full width sinusoidal tube increased the K term. This increased the exponential term number in Equation (9) and, considering the negative sign of the exponential term, the increase in the numerator of the fraction reduces its value, therefore the Transmission energy of the exchanger in full width mode is more than half width mode. For example, now consider the inlet temperature of the tube, and the melting temperature of PCM, 25oC and 68 °C, respectively; therefore, the Transmission energy of the heat exchanger for the full width sinusoidal tube and half width sinusoidal tube were obtained as 1820.4, 1396.66 W, respectively.

Experimental Investigation of Sinusoidal Tube in Triplex-Tube Heat Exchanger during Charging and Discharging Processes Using Phase Change Materials

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چکیده

در این آزمایش اثر لوله‌های تمام‌دامنه و نیم–دامنه‌ی سینوسی به عنوان لوله‌ی داخلی در مبادله‌کن حرارتی سه‌لوله‌ای با استفاده از ماده‌ی تغییرفازدهنده (PCM) بررسی شده. طول و قطر لوله‌ها به‌گونه‌ای انتخاب شده‌اند که مساحت هر دو لوله یکسان باشد. فرایندهای شارژ و دشارژ کردن به‌وسیله‌ی لوله‌ی داخلی، لوله‌ی بیرونی و هر دو لوله‌ی درونی و بیرونی انجام شد. نتایج نشان داد که زمان ذوب و انجماد PCM برای لوله‌ی داخلی سینوسی تمام‌دامنه، در فرآیندهای شارژ و دشارژ از لوله‌ی داخلی، لوله‌ی بیرونی و دو طرف، از لوله‌ی سینوسی نیم‌دامنه در زمان کوتاه‌تراست. مقایسه فرایندهای شارژ و دشارژ این لوله‌ها با یک لوله‌ی داخلی مستقیم نشان دهنده‌ی بهبود چشم‌گیر در کاهش زمان ذوب PCM است. فرایند ذوب در حالت لوله‌ی مستقیم بعد از حدود ۳۲/۵ ساعت ناقص بود و این در مورد لوله‌ی داخلی سینوسی تمام‌دامنه و نیم‌دامنه به‌ترتیب ۸ و ۱۰ ساعت بود. همچنین، در حالت ذوب از لوله‌ی بیرونی، ٥٤ درصد در لوله‌ی سینوسی تمام‌دامنه و ۸ درصد در حالت لوله‌ی سینوسی نیم‌دامنه بهبود در زمان ذوب را نشان می‌دهد.

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