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Finned double-tube PCM system as a waste heat storage

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Abstract. In this work, focus is taken on developing a waste heat recovery system for capturing potential of exhaust heat from an air conditioner unit to be reused later. This system has the ability to store heat in phase change material (PCM) and then release it to a discharge water system when required. To achieve this goal, a system of Finned, Water-PCM, Double tube (FWD) has been developed and tested. Different profiles of fins attached to the (FWD) system have been investigated for increasing the thermal conductivity of the PCM. These include using Circular Finned, Water-PCM, Double tube (CFWD) system; Longitudinal Finned, Water-PCM, Double tube (LFWD) system; Spiral Finned, Water-PCM, Double tube (SFWD) system; as well as; Without Fins, Water-PCM, Double tube (WFWD) system. An experimental test rig that attached to an air-conditioner unit has been built to include 32- tubes of the FWD systems for both vertical and horizontal layouts during charging and water discharging processes. Results show a significant performance improvement when using spiral and circular fins during charging process at vertical position. However, longitudinal and without fins showed better performance in horizontal position. Overall, the developed SFWD system in vertical position has been found to exhibit the most effective type due to the fastest PCM melting and solidification. As compared to the WFWD system, the FWD systems have been found to increase the PCM temperature gain of about 15.3% for SFWD system; 8.2% for CFWD; and 4.3% for LFWD system.

1. Introduction

Heat recovery and energy storage systems are used for storing energy during the time when extra energy is available in order to be used afterward. In other words, they are used to correct the disparity between energy supply and energy demand; which results in saving capital cost. Furthermore, this can affect the environmental by reducing pollution. Phase Change Materials (PCM) can be used to store waste heat resulting from industry, furnace, air conditioner, etc.. In spite of great potential of PCM, the practical feasibility of latent heat storage is still limited, mainly due to a rather low thermal conductivity. This low conductivity implies small heat transfer coefficients and, consequently, thermal cycles are slow and not suitable for most of the potential applications.

Medrano et al. 2009 [1] investigated experimentally the heat transfer process during melting and solidification of five small heat exchangers working as latent heat thermal storage systems. Results show that the double pipe heat exchanger with the PCM embedded in a graphite matrix is the one with higher thermal power values. *Joudi et al. 2012* [2] utilized Finite Difference Method for solving transient two-dimensional conduction heat transfer equations with phase change. Results showed that the PCMs in a cylindrical container melt and solidify quicker than the square container. *Lokapurel et*



al. 2012 [3] designed a heat recovery system for air conditioner. The air conditioner condenser was replaced by a special heat exchanger. Results showed not just condenser heat was recovered, but also COP of the air conditioner was enhanced. *Mat et al. 2013* [4] performed a numerical study to investigate the melting process in finned triplex-tube heat exchanger with phase-change material. A two-dimensional numerical model is developed using the Fluent 6.3.26 software program. Around 43.3% reduction in the melting time was achieved as opposed to non-finned tubes. However, no experimental investigation has been conducted in this study. *Chang Liu et al. 2014* [5] accomplished an experimental work to study the phase change heat transfer inside a cylindrical latent heat energy storage that designed with a central finned copper pipe running the length of the cylindrical container. Longitudinal fins were added to the copper pipe to enhance the heat transfer. It was observed that conduction is the dominant heat transfer mechanism during the initial stage of charging, also during the entire solidification process.

The main aim of this work is to design, manufacture and test a new Waste heat Recovery System (WRS) to capture and reuse energy of exhaust hot gas that dissipated from air conditioner condenser. This system consists from a group of PCM double-tubes that arranged in vertical and horizontal layouts with water as a heat transfer fluid for discharging energy.

2. Experimental Work

The test rig is designed and manufactured as shown in figure (1). An air conditioner with a capacity of 24000 BTU/hr, was used. The waste heat exhausted from the condenser was used to supply test section with hot air. Group of extra heaters (12kw) sited inside the duct were used to guarantee that the test section will be supplied with hot air of (70°C) temperature at all times. The water system, which is used to recover waste heat from PCM, consists from 35 W water pumps, PVC connecting pipes and two insulated water tanks with a capacity of 20 Liter each. The second tank is initially empty and drains the water from first tank after passing through the FWD system. Four groups of test tubes (32 tubes in each group) were tested. The effect of various fins shapes of longitudinal, circular, spiral and without fins were investigated for both tube arrangements of vertical and horizontal. The tests were done through condenser hot waste gas charging and water discharging processes. The insulated test section integrates into two parts the perforated duct and the double-tube system. The first part is a square duct which has been manufactured from iron frame enclosed by transparency plastic material (Perspex), of 120 cm length, 30 cm height, and 6 mm thickness. Two of the parallel sides of the duct are perforated; the holes are arranged in a pattern of 5, 4 holes in each line with a total of 32 holes that has a diameter of 10 mm as illustrated and photographed in figure (2). The holes are set evenly in accordance with results obtained in this work for selecting the best distance between the holes as will be explained later.

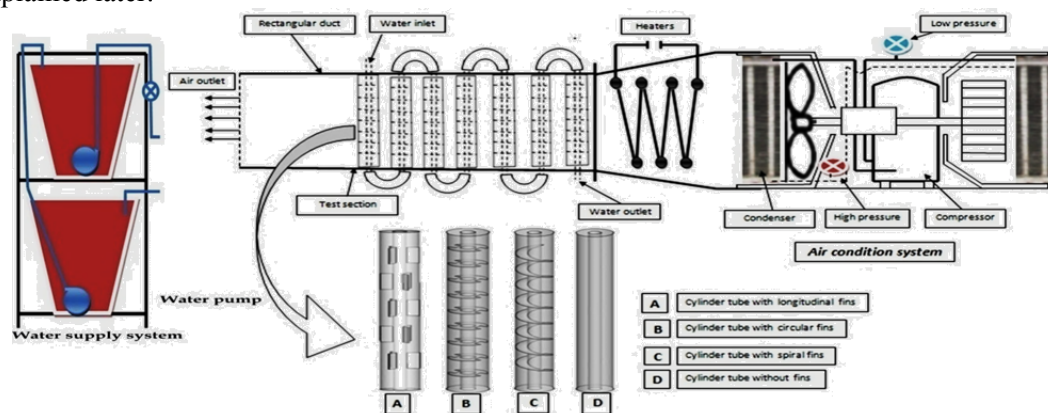


Figure 1. Experimental of the test rig.

The second part is the test tubes with a total number of 32 double-tubes that arranged along with the holes. Each test tube includes an outer glass tube with a diameter of 30 mm, thickness of 1.5 mm and length of 30 cm. The inner copper tube is positioned in the center of the glass tube with a length of 34 cm, inside diameter of 8 mm and thickness of 0.65 mm. The copper tube passes through the duct hole. The space between the glass and the copper tube is filled with PCM (paraffin wax). The outer glass tubes were used to capture waste energy of exhaust hot air from condenser during charging process, while the inner copper tubes were used for discharging process by using water flow. In order to raise the heat transfer process, three different shapes of fins with the same surface area have been welded around the copper tubes as shown in figure 3. All types of fins were made from copper with a thickness of 0.65 mm. To measure water, air, PCM and fins temperatures in the test section, 32 thermocouples of k-type with data logger have been installed in the FWD system. Figure 3 shows selected thermocouples positions of the test tubes

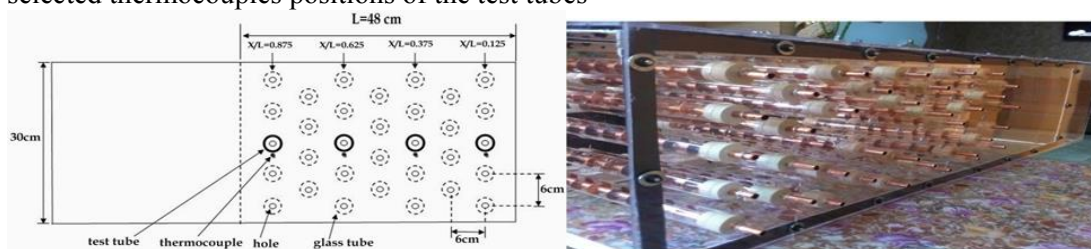


Figure 2. Double-tubes arrangement of the FWD system.

Pure wax produced by major Iraqi oil company (Al-Durra refinery) was selected as a PCM. The thermo-physical properties of the PCM have been measured experimentally and the results are shown in table (1). The thermal conductivity measurements of PCM were based on the ASTM standards. The transient test method is taken primarily from ASTM D5930 and ASTM D5334 standards. To check the reputability of the data, all experiments were performed at least twice (on different days). The error associated with experimental measurements of the temperature and mass flow rate of PCM, hot air; and water were done using the root sum square method. The estimated maximum values of uncertainties for temperature are 1.42% and for mass flow rate is 0.83%.

Table 1. Measured properties of PCM.

Melting point (C)	63.7
Solid Density(kg/m ³)	796
Liquid Density(kg/m ³)	766.5
Viscosity (kg/m.sec)	0.0127

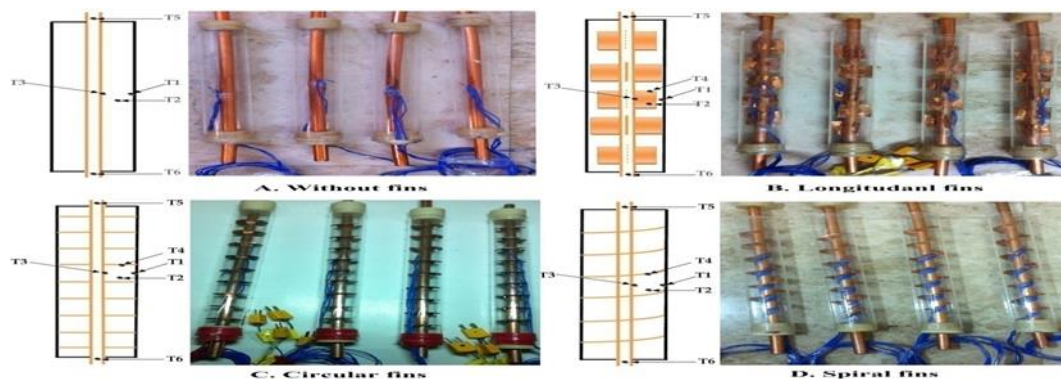


Figure 3. Thermocouples positions of the test tubes.

3. Results

Figure 4 demonstrates comparison between gained temperature in both vertical and horizontal states. It was found that spiral and circular fins had more significant enhancement during charging process at vertical position. However, longitudinal and without fins showed better performance in horizontal position. It is found that about 8.2%, 2.6%, 1.6%, and 1.3% enhancement of gained temperature in vertical state as opposed to the horizontal state for SFWD, CFWD, LFWD, and WFWD respectively.

Figure 5 demonstrate the difference between the temperatures of PCM for each type of WD recovery system. From figure it is seen that PCM temperature is the highest when using spiral fins. As compared to no-fins geometry; the rate of gained temperature increase has been found to be (15.3%, 8.2% and 4.3%) with the use of spiral, circular and longitudinal fins respectively. Overall, spiral geometry fins has been found to exhibit the most effective type due to the fastest the PCM melting and the fastest solidification.

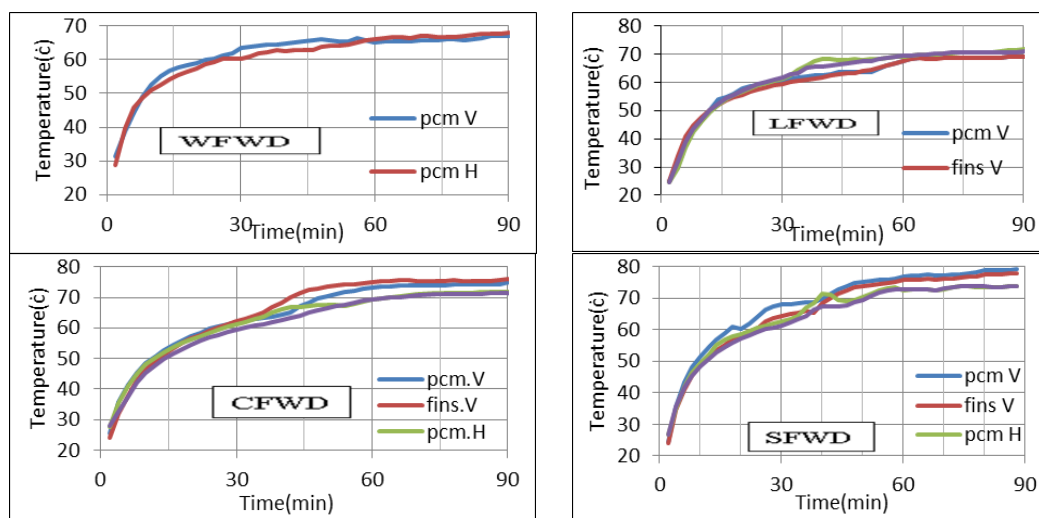


Figure 4. Comparison between vertical and horizontal position thermal response inside WD recovery system.

Figures 6 shows the transient radial temperature distributions during charging process from hot waste gas of the A/C unit through vertical and horizontal CFWD system. It is noted that the fins temperature in vertical position is higher than the PCM temperature. This could be attribute to the melting of PCM close to the lower surface of the circular fins and their separation from the fins.

Figures 7 illustrate the time variation of the temperature during water discharging process. The radial temperature of the PCM at the particular radial position gradually decreases with time until the temporal variation becomes radially consistent after a while. The figures clarify that the temperature decreases particularly in the areas touching the copper tube and fins as a result of good thermal conductivity of the copper. However the rate of discharge of heat varies according to the fins profiles variety. The decreasing rate of the PCM temperature of the WFWD system has been found to be 22%, in the LFWD system was 34%, whereas in CFWD system was 37%, and 32% with SFWD system.

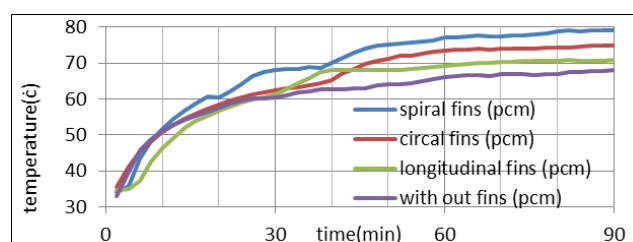


Figure 5. PCM transient temperature response during charging process.

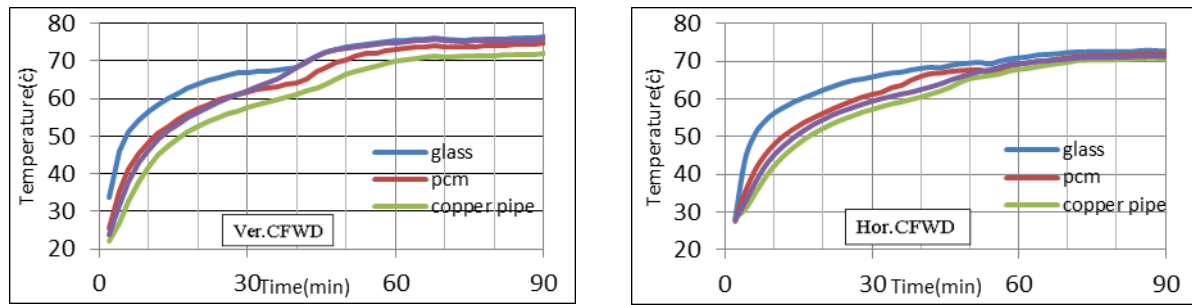


Figure 6. Measured radial temperature distribution inside CFWD system during charging process.

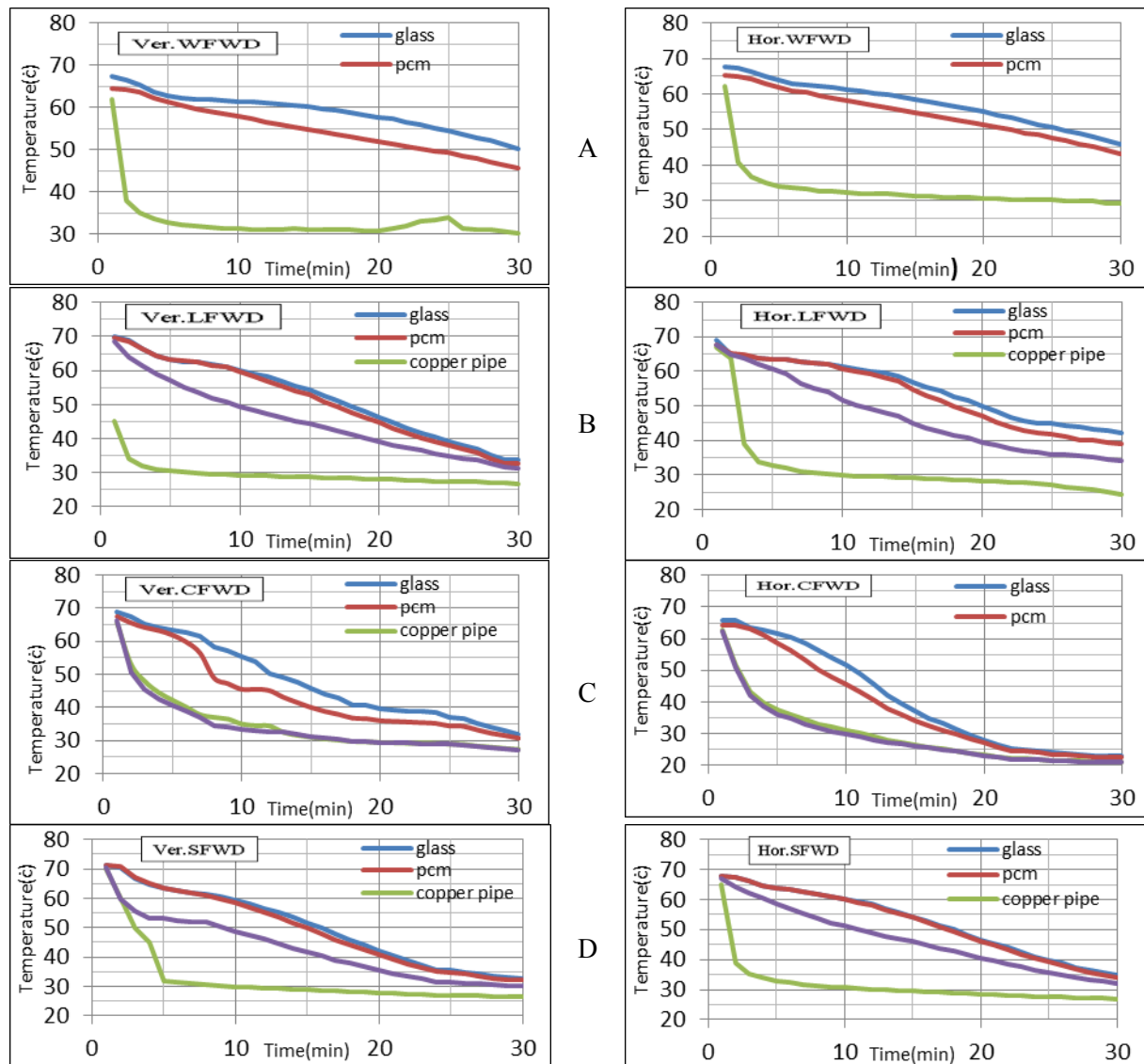


Figure 7. Measured radial temperature distribution inside WD systems during discharging process.

Figure 8 illustrate the water inlet and outlet temperature in both vertical and horizontal positions. It is clear that the curves rapprochement and divergence depends on the gained PCM temperature through the charging process. From results of water discharge system, it is clear that the thermal response of longitudinal and without fins systems showed better performance in horizontal position, whereas, spiral and circular fins system showed better performance in vertical position.

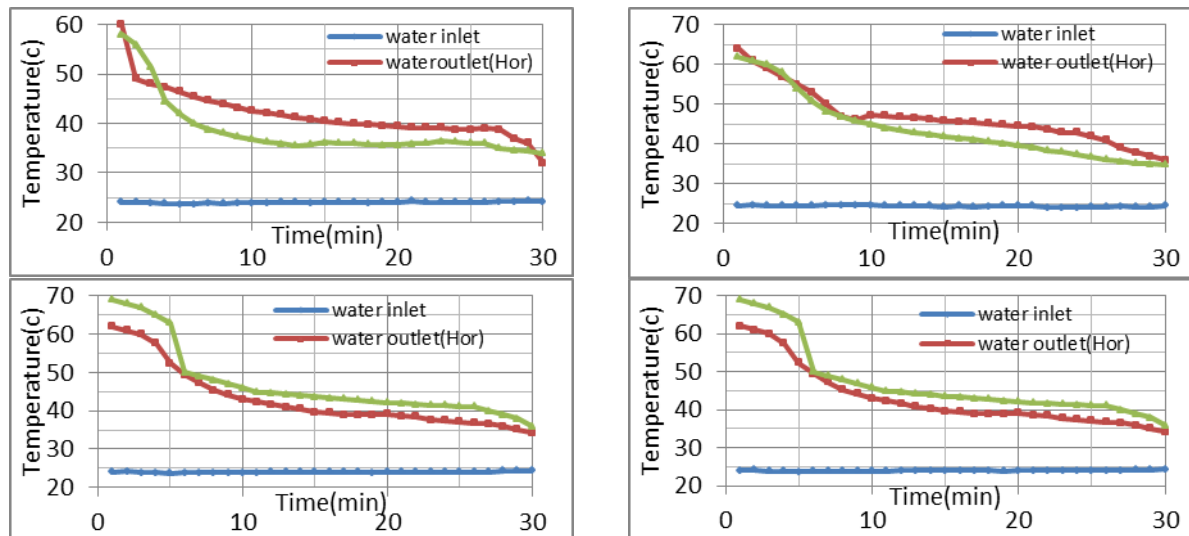


Figure 8. Transient water temperature during discharging process for FWD systems.

4. Conclusions

In general, it is found that using various fins profiles play an important role on enhancing the heat transfer through PCM. As compared to the WFWD system, the FWD systems have been found to increase the PCM temperature gain during charging process of about 15.3% for SFWD system; 8.2% for CFWD system; and 4.3% for LFWD system. During discharging process, when PCM started to lose heat to the water, the decreasing rate of the PCM temperature of the WFWD system has been found to be 22%, in the LFWD system was 34%, whereas in CFWD system was 37%, and 32% with SFWD system.

Results showed different thermal enhancement response between vertical and horizontal arrangement for FWD systems under investigation. Longitudinal and without fins systems showed better performance in horizontal position, whereas, spiral and circular fins systems showed better performance in vertical position. In the horizontal layout, about 1.3% increase in gained PCM temperature has been found with WFWD system and 1.6% in LFWD system as compared to the vertical one. However, CFWD and SFWD systems showed more PCM temperature gain in the vertical layout than horizontal one, of 2.6% and 8.3% respectively. Overall, the developed SFWD system in vertical position has been found to exhibit the most effective type due to the fastest PCM melting and solidification.

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