Investigation of Thermal Performance of Finned,Water-PCM,Double Tube Heat Recovery

Asst. Prof. Dr. Mohammed H. Mahmoud

Mechanical Engineering Dept, College of Engineering, University of Al-Mustansiriyah

Dr. Maathe A.Theeb

Mechanical Engineering Dept, College of Engineering, University of Al-Mustansiriyah

Ali S. Golam

Mechanical Engineering Dept, College of Engineering, University of Al-Mustansiriyah

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 Finned, Water-PCM, Double tube (FWD) system 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. Transient 3-D, numerical simulations using (ANSYS Fluent14.0 software) have been developed to predict the thermal behavior for all types of FWD systems under investigation. 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, 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. Also, comparisons between numerical and experimental results for both (measurement data and thermal camera photos) have been found reasonably matched.

Keywords: *Waste heat recovery, Air–conditioner, Phase change material, ANSYS.*

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الأداء الحراري لمنظومة استرجاع الطاقة مكونة من انبوب مزدوج مزعنف

أ.م.د. محمد حامد محمود د. معاذ عبد الواحد ذيب علي شكر غلام

قسم الهندسة الميكانيكية

كلية الهندسة ، الجامعة المستنصرية

الخلاصة

في هذه البحث تم التركيز على خزن الطاقة الكامنة للهواء الخارج من منظومة تبريد لاستعمال هذه الطاقة لاحقا . لانجاز هذا الهدف، تم تصنيع منظومة خزن الطاقة الحرارية (FWD)لاستخلاص طاقة الهواء الخارج من مكثف مكيف هواء . هذه المظومة لها القابلية على خزن الطاقة الحرارية واعادة تحريرها الى منظومة الماء عند الحاجة .تم اختبار اشكال مختلفة لزعانف بعد تثبيتها الى منظومة (FWD) لغرض زيادة الموصلية الحرارية لمادة متغيرة الطور (PCM) داخل المنظومة. الأشكال تشمل منظومة ثنائية الانابيب ذو زعانف دائرية (CFWD)، منظومة ثنائية الانابيب ذو زعانف طولية (LFWD)، منظومة ثنائية الانابيب ذو زعانف لولبية (SFWD)، و منظومة ثنائية الانابيب بدون زعانف (WFWD). تم أنشاء موديل الأختبار العملي الذي يحوي على (FWD) ومن ثم تثبيته على منظومة تبريد الهواء بترتيب عامودي وافقي خلال عملية الشحن والتفريغ. ايضاً تم بناء نظام محاكاة عددي باستخدام (ANSYS Fluent 14.0) لتخمين التصرف الحراري لمختلف انواع منظومات(FWD) التي تحت الدراسة . النتائج أظهرت تحسين هام عند أستعمال زعانف لولبية ودائرية أثناء عملية الشحن عند الوضع العمودي اما بالنسبة للزعانف الطولية وبدون زعانف أظهرت أداء افضل عند الوضع الافقي . عموماً، نظام SFWD في الموقعِ العموديِ وُجِدَ لعَرْض النوعِ الأكثر فاعليةِ بسبب ذَوَبان وتجمّدِ PCM الأسرع . تطور ملحوض بالأداء عند استعمال منظومات SFWD,CFWD,LFWD مقارنة بمنظومة WFWD. بصورة عام نسب الزيادة الحاصلة في درجة الحرارة المكتسبة لل PCM كانت 4.3%، 8.3%، و15.3% على التوالي بالمقارنة مع المنظومة بدون زعانف . كذالك وجد بان المقارنة بين النتائج النظرية والعملية متناظرة الى حد معقول.

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. PCM can be used to store waste heat resulting from industry, furnace, air conditioner, etc .Changing the phase of PCM can be done by placing it in a container and passing heat transfer fluid (HTF), which is heated by waste heat, through the container. In spite of this great potential, the practical feasibility of latent heat storage with PCM 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.

Different studies have been accomplished regarding optimizing the use of these systems. Gu ***et al. 2004*** **[1]** have been developed a heat recovery system using PCM to recover the rejected heat and produce low temperature hot water for washing and bathing. They concluded that the heat recovery system decreases the consumption of primary energy for heating hot water. ***Groulx and Ogoh. 2009*** **[2]** utilized COMSOL software for studying a cylindrical container filled with paraffin wax, through which a copper pipe with circle fins is inserted. It was concluded from results that melting will occur close to the pipe regardless of the number of fins. ***Medrano et al.2009*** **[3]** 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 and Taha. 2012*** **[4]** 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. ***Lokapure1 and Joshi. 2012*** **[5]** 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. Also, a reduction of thermal prolusion was achieved. ***Mat et al .2013*** **[6]** performed a numerical study to investigate the melting process in fined 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 and Groulx. 2014*** **[7]** 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 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. Numerical Simulation.

The finite volume method as described by Patankar[8] has been utilized with using enthalpy-porosity formulation to solve the mass, momentum and energy equations. The enthalpy-porosity technique treats the mushy region (partially solidified region) as a porous medium. Thus, porosity in each cell is set equal to the liquid fraction in that cell. Fluent 14.0 computational program was used to simulate the FWD waste heat recovery system and predict the thermal response. Three dimensions (r, Θ, Z) of the cylinder tube were created by Solid Work software and meshed using Gambit geometric modeling software. A tetrahedron mesh was used in this model .Choosing the optimum grid size of the mesh was achieved by testing different grid size and then transported to FLUENT software program. The results of the liquid fraction of the tested grids were compared to choose the optimum grid size for each type of FWD systems under investigation. Physical representation of the FWD system as shown in figure (1).

A Finned, Water-PCM, Double-tube (FWD) systems have been used to recover waste heat from A/C unit. This system will be numerically investigated using (Fluent 14.0) CFD simulation software to solve the conservation equations for mass, momentum and energy, as described by Golam[9].

- **Continuity equation**

$\nabla \rho\vec{V} = 0$ ……. (1)

- **Momentum equation**

The enthalpy-porosity technique treats the mushy region (partially solidified region) as a porous medium. Thus, porosity in each cell is set equal to the liquid fraction in that cell. The momentum sink due to the reduced porosity in the mushy zone takes the following form:

$S = \frac{(1-ß)^2}{(ß^3+\varepsilon)} A_{mush} (\vec{V}-\vec{V}_P)$ …… (2)

Where:

ß=liquid volume fraction.

Ɛ=small number (0.001) to prevent division by zero.

$\vec{V}_P$=solid velocity due to the pulling of solid material out of the domain.

A_{mush}=mush zone constant.

- **Energy equation**

The enthalpy of a material is computed as the sum of the sensible, h, and the latent heat, ΔH:

$H=h+\Delta H$ …… (3)

Where:

$h=h_{ref}+\int_{T_{ref}}^{T} C_p \, dT$

h_{ref} =reference enthalpy

T_{ref} =reference temperature

C_P=specific heat at constant pressure

The liquid fraction, ß, can be defined as

ß=0 if $T \leq T_{solidus}$

ß=1 if $T \geq T_{liquidus}$ …….. (4)

$ß=\frac{T-T_{solidus}}{T_{liquidus}-T_{solidus}}$ if $T_{solidus} < T < T_{liquidus}$

The latent heat content can now be written in terms of the latent heat of the material, L:

$\Delta H = ß.L$ ……… (5)

The latent heat content can vary between zero (for a solid) and 1 (for a liquid).

For solidification /melting problems, the energy equation is written as

$\frac{\delta}{\delta t}(\rho H) + \nabla.(\rho \vec{V} H) = \nabla.(k \nabla T) + S$ ……… (6).

Where:

H=enthalpy $\vec{V}$=fluid velocity

ρ=density S=source term

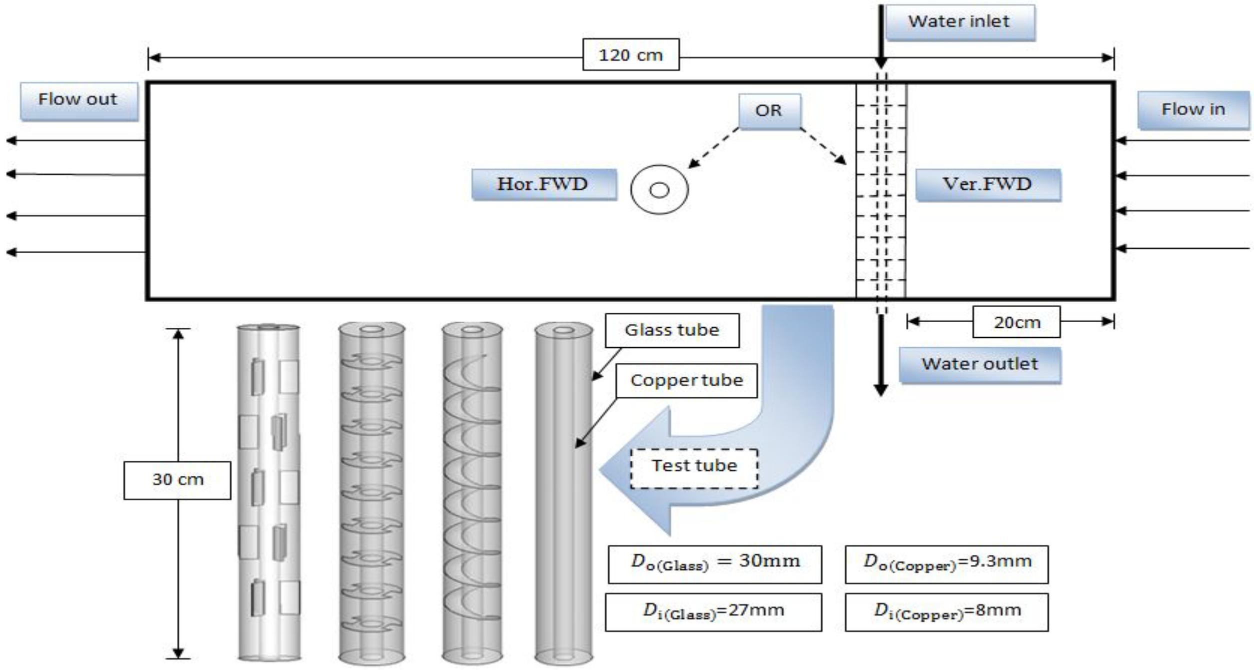


Figure (1): Physical representation of the FWD system

3. Experimental Work

To accomplish experimental investigation, the test rig is designed and manufactured as shown in figure (2). An air conditioner with a capacity of 24000 BTU/hr, with three speed level for condenser blower 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.

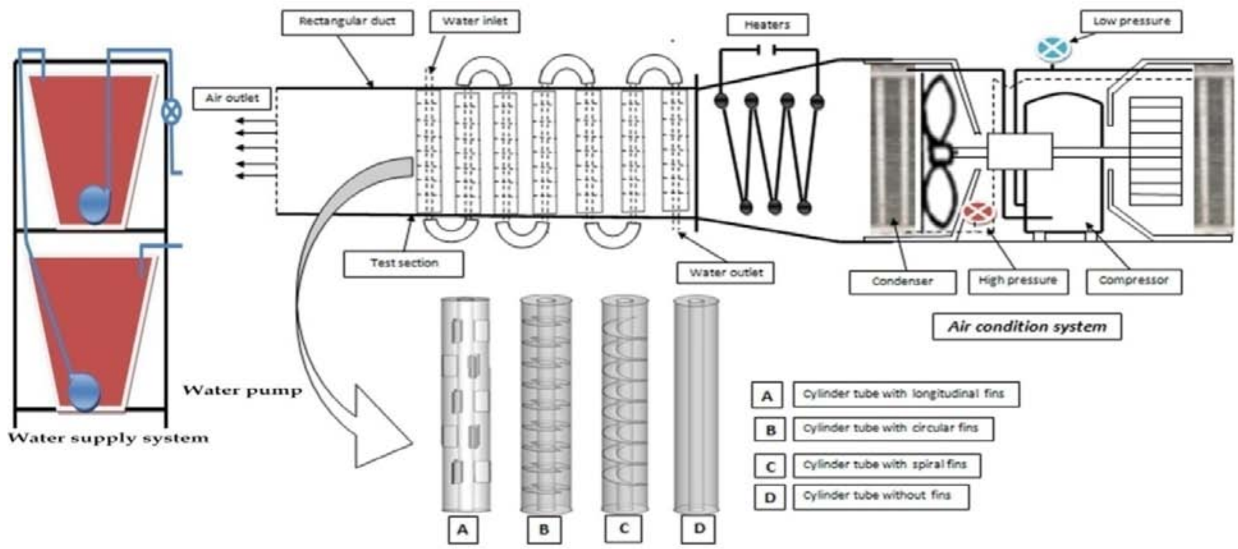


Figure (2): Experimental of the test rig.

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 (3). 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.

The second part is the test tubes with a total number of 32 double-tube 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 (Grade-B 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 (4). 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 (4) shows selected thermocouples positions of the test tubes. A thermal camera (Ti32) was also used to measure the surface temperature of the test tubes.

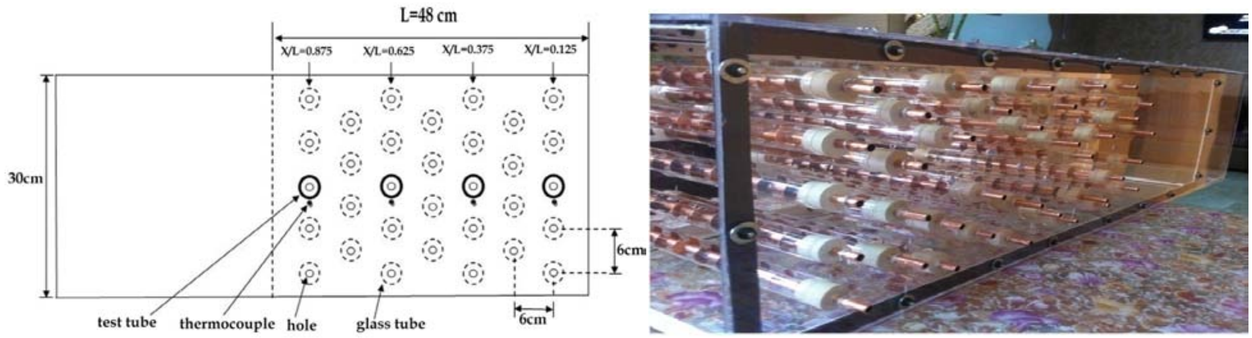
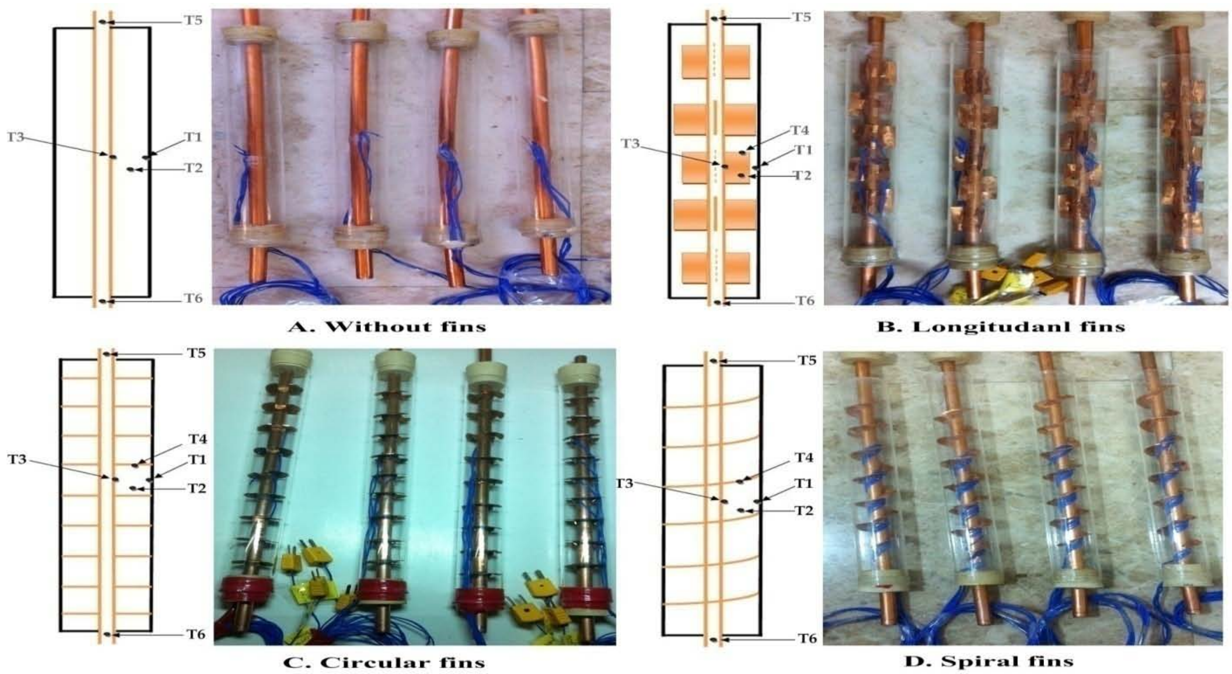


Figure (3):Double–tubes arrangement of the FWD system.



Figures (4):Thermocouples positions of the test tubes.

4. Results and Discussions.

The thermal response of various number of tube lines have been tested experimentally. In this work, the total number of tube lines have been found to be (32).The increase in the number of tubes is not recommended because the PCM of the last row will not reaching the melting point for all types of tube under investigation. Initial experimental tests have been performed to determine the optimum distance between the test tubes without any obstacles to the air flow coming from the air conditioner. Figure (5) shows the selected distance between test tubes and their effect on high and low pressure of the air conditioning unit as compared to the normal operation of the unit without WD recovery system. The optimum distance is found to be 3cm. This distance will be used in all experimental and numerical tests throughout this work.

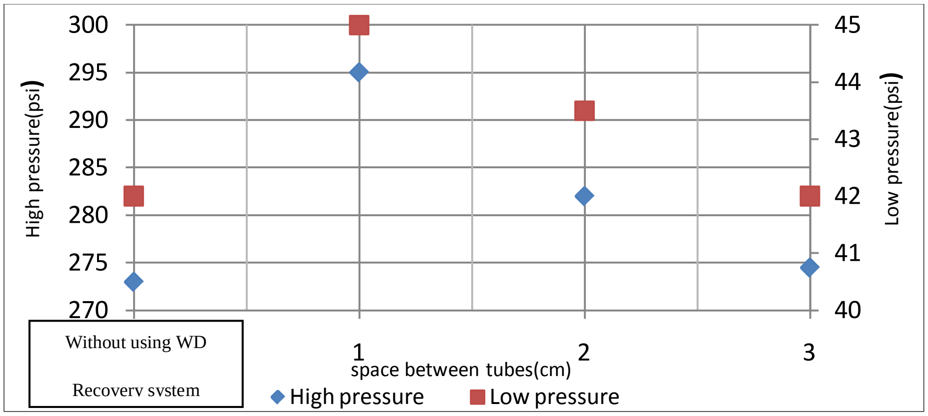


Figure (5): Effect of space between tubes of the WD system on low and high pressure of the air conditioning unit.

Figures **(6)** to (**9**) illustrate the liquid fraction and the temperature contours during the charging and discharging process of the horizontal and vertical FWD systems with different fins profiles. The non-uniform distribution of the PCM is clear due to the low thermal conductivity.

In the **vertical position** of the FWD systems, the heat transfer occurs between the tube and the solid surface of the PCM by conduction which dominated the early melting process and formed a thin layer of liquid in a narrow melting area. For SFWD system, convection cells were produced and subsequently expanded to the upper part of the tube; whereas the rest of the PCM were remained solid lacking any phase change at tube bottom. Eventually, cell convection emerged and facilitated the formation of two large convection cells. The hotter liquid of the PCM was pressed upward to the top of the tube because of the natural convection effects driven by buoyancy. On the other hand, the solid part of the PCM was squeezed down to the tube bottom as a result of heavier density.

In the **horizontal position** of the FWD systems, the liquid was formed in the areas touching the outside of test tube and fins. Then abundant circulations formed at the bottom region of the annulus on account of the small melting area after 60 minutes. Conversely, large convection cell formed in the upper part of the annulus. Complete melting was achieved after 90 minutes but the rate of melting varies according to the fins profile. However, it is clear that the complete melting of PCM is depending on the fins profiles as shown in these figures. The melting rate inside FWD systems is found to be faster utilizing spiral fins as compared with other types of fins during the same periods.

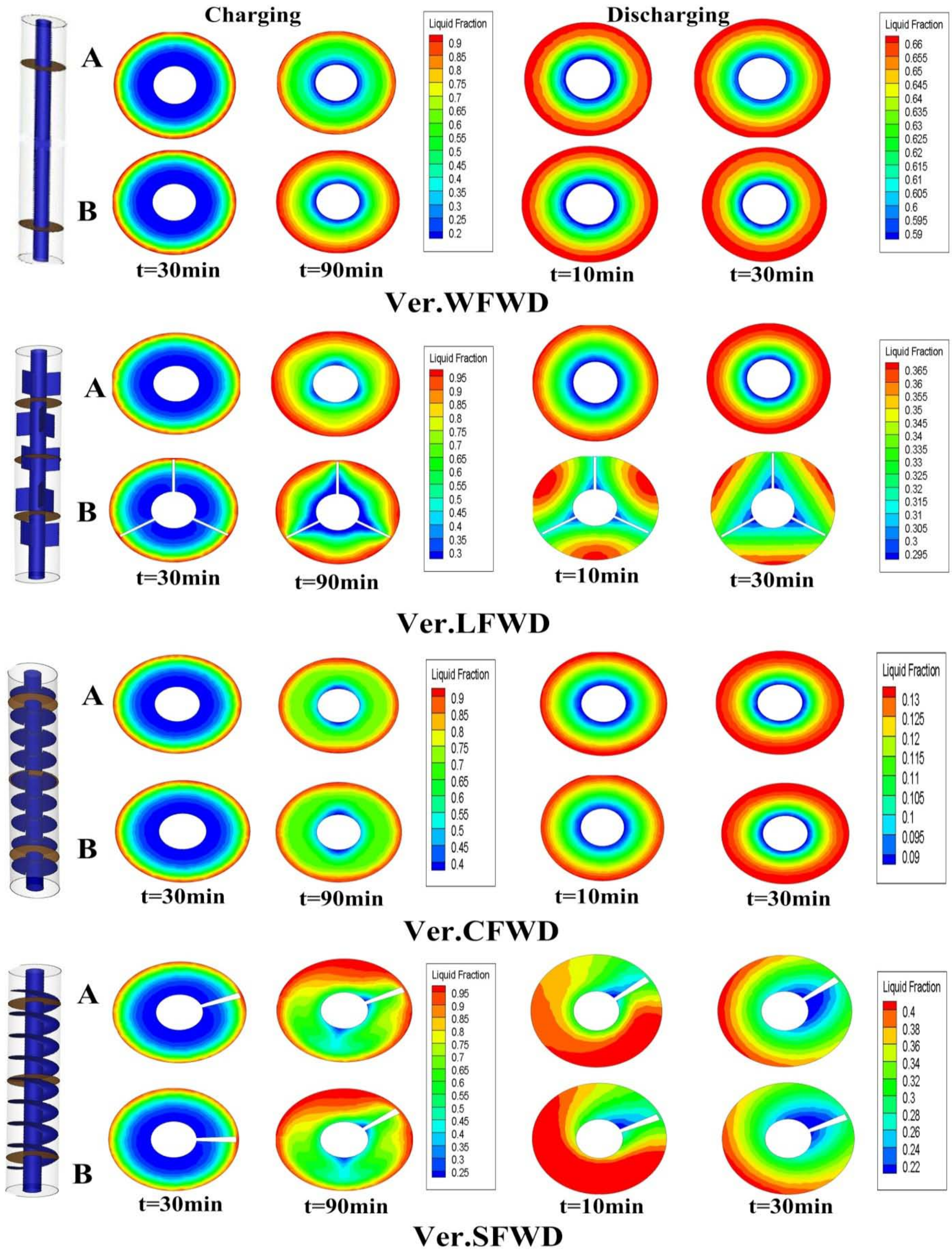


Figure (6): Transient liquid fraction contours of PCM inside various vertical FWD systems.

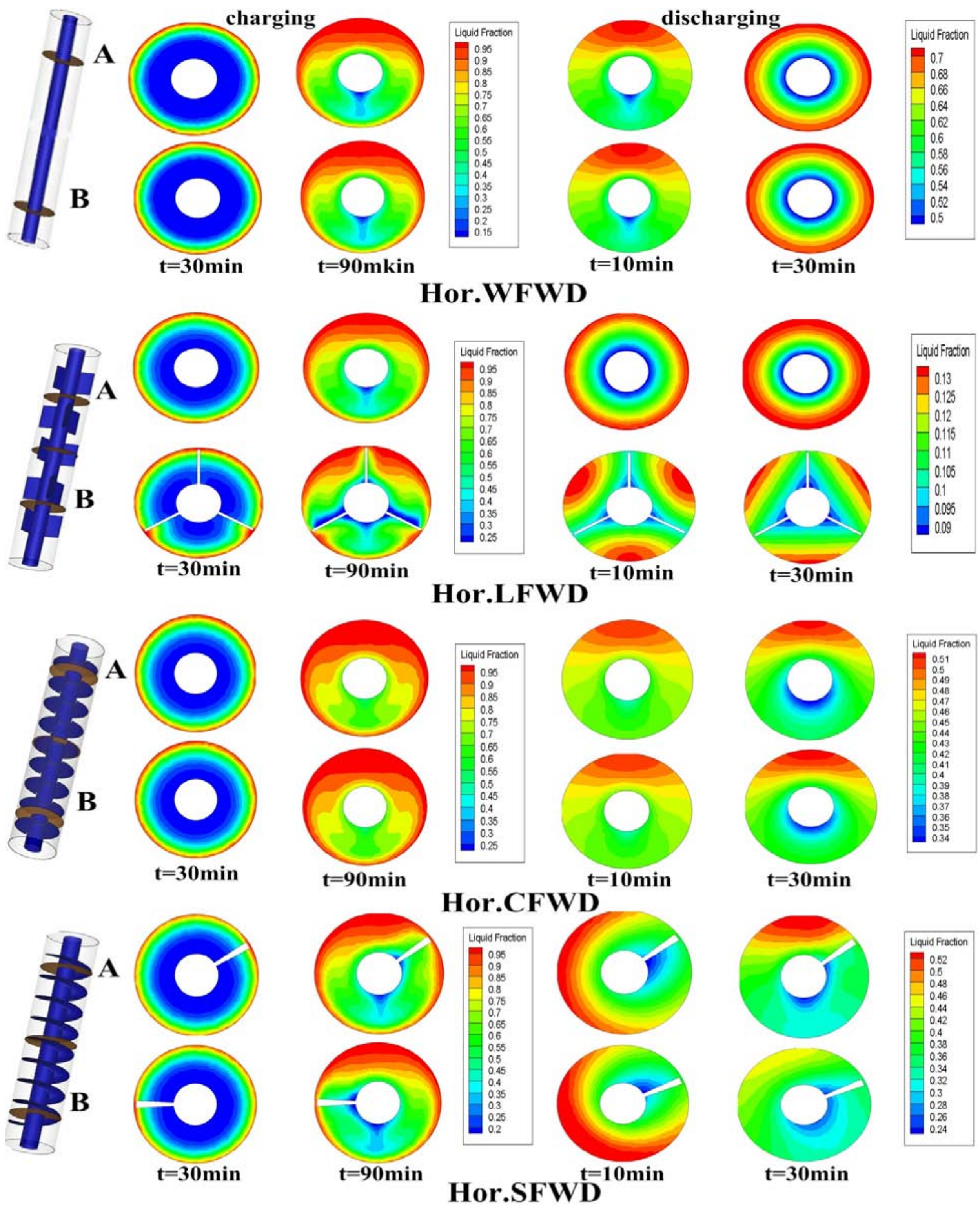


Figure (7): Transient liquid fraction contours of PCM inside various horizontal FWD systems.

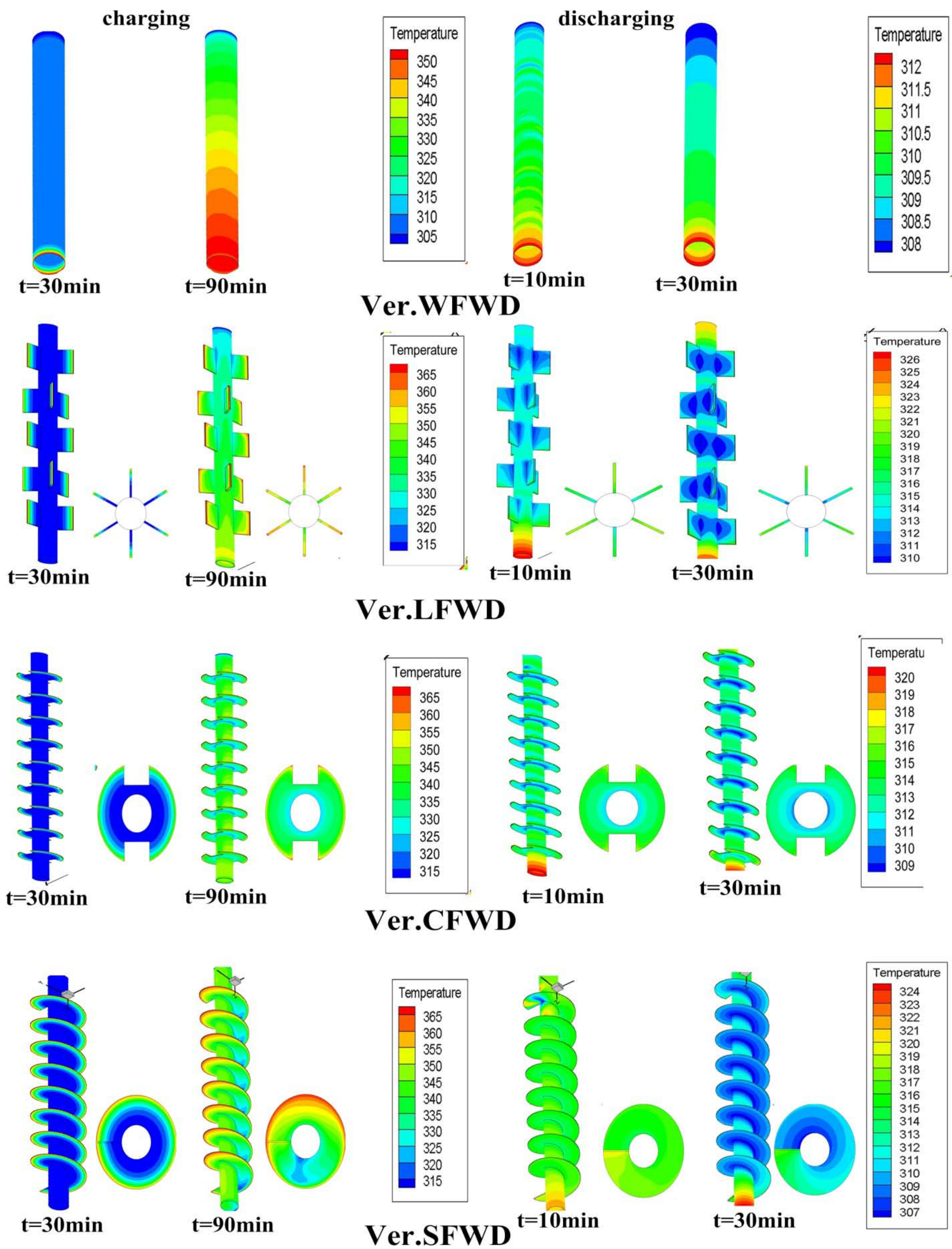


Figure (8) Transient temperature contours of PCM inside various vertical FWD systems.

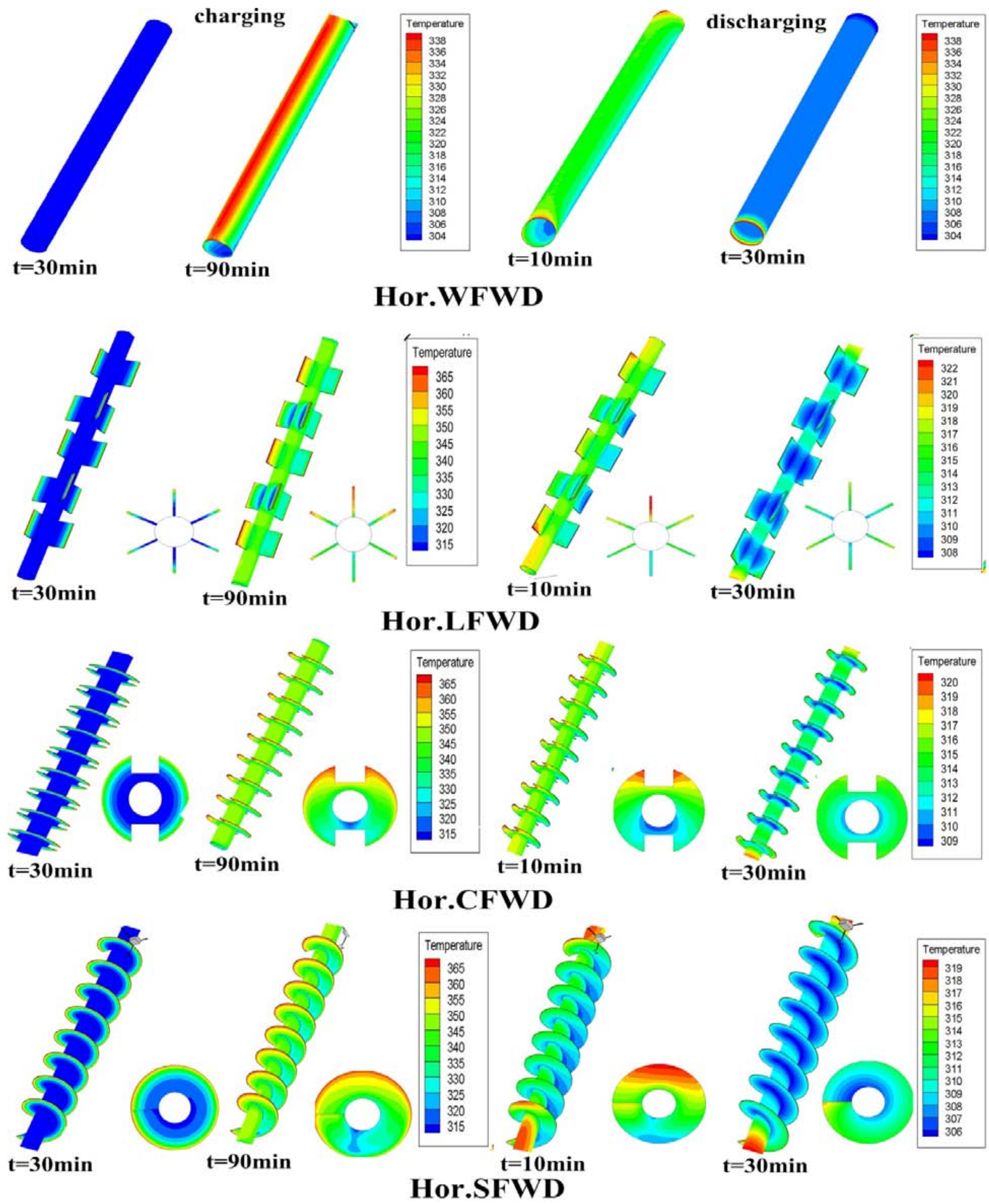
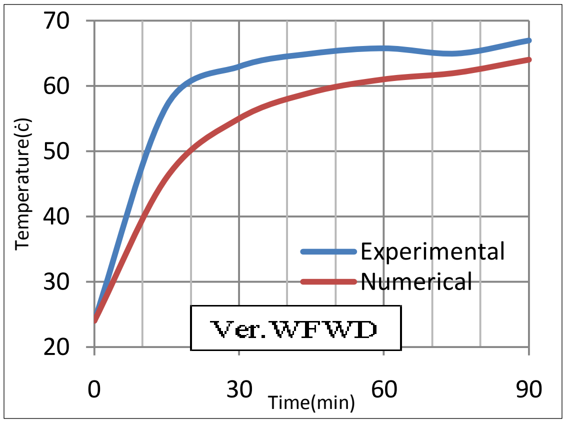
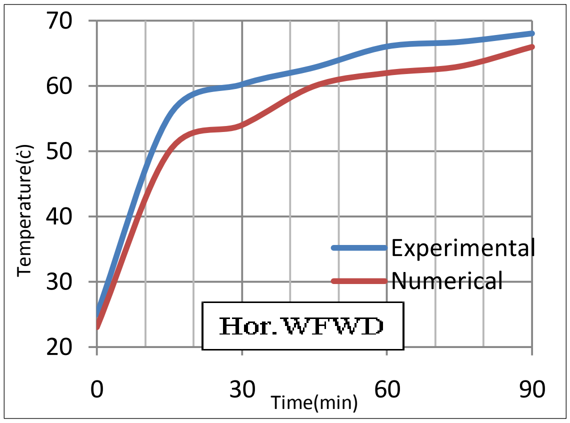


Figure (9): Transient temperature contours of PCM inside horizontal vertical FWD systems.

Figure (10) represents comparison between the numerical and experimental results obtained for temperature history of PCM during charging process for WFWD arranged in vertical and horizontal positions. As it can be noticed, the numerical and the experimental temperature history during melting process are reasonably matched .The initial numerical results have been used in the design of the experimental setup.



Vertical WFWD.



Horizontal WFWD.

Figure (10): Comparison between experimental and numerical results for WFWD system during melting process

Besides recording the temperature distribution inside FWD systems, the phenomenon of PCM melting and solidification were captured by high resolution digital camera and also by thermal camera. The propagation of melting and solidification fronts of PCM with different types of fin profiles are shown in figure (11).From this figure, it is found that spiral and circular fins have more significant enhancement during charging process of vertical position. However, longitudinal and without fins showed better performance in horizontal position. Overall, from both numerical and experimental results, spiral geometry fins have been found to exhibit the most effective type due to the faster PCM melting and solidification.

Figure (12) demonstrates comparison between the results of thermal camera and ANSYS numerical analysis during water discharging process at vertical and horizontal positions with different fins profile. A satisfactory match can be seen between the results in the horizontal position while an acceptable match in the results of the vertical position.

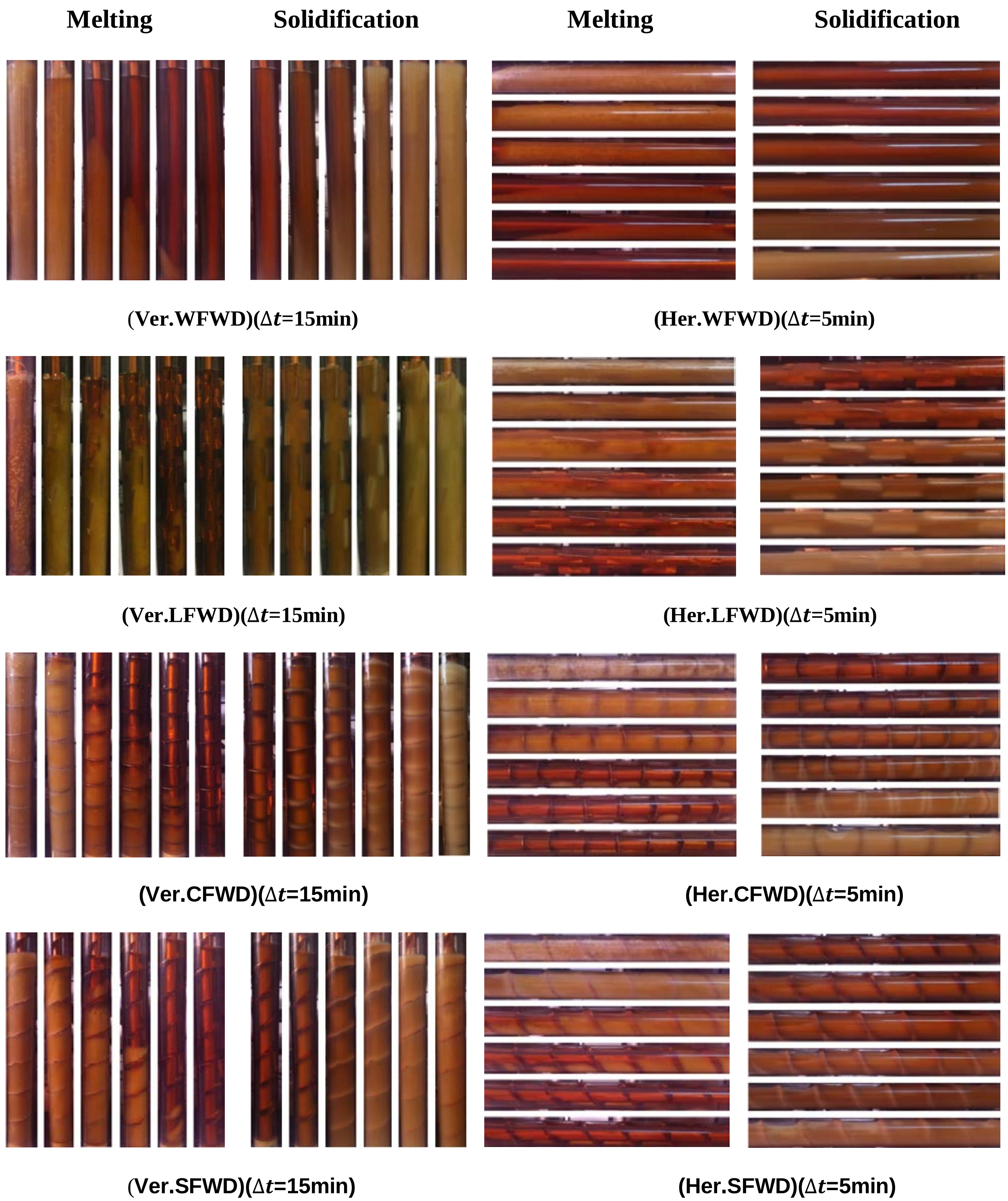
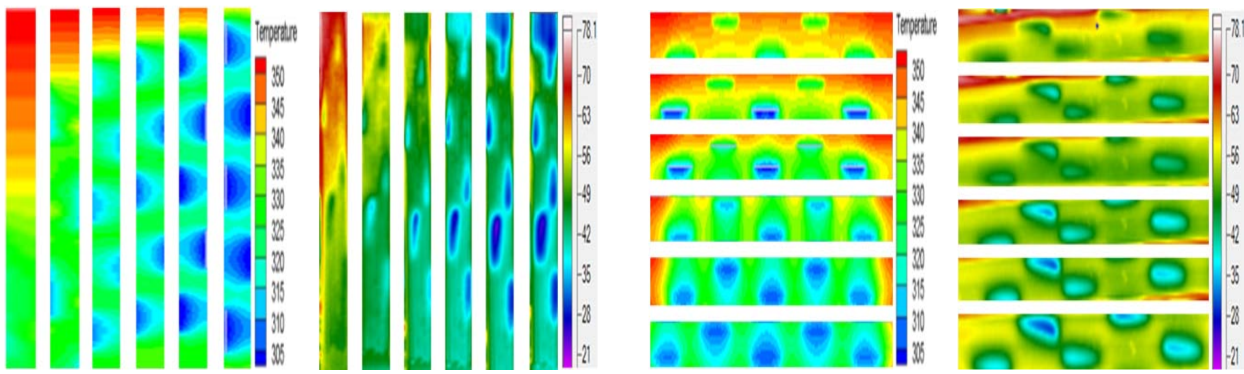
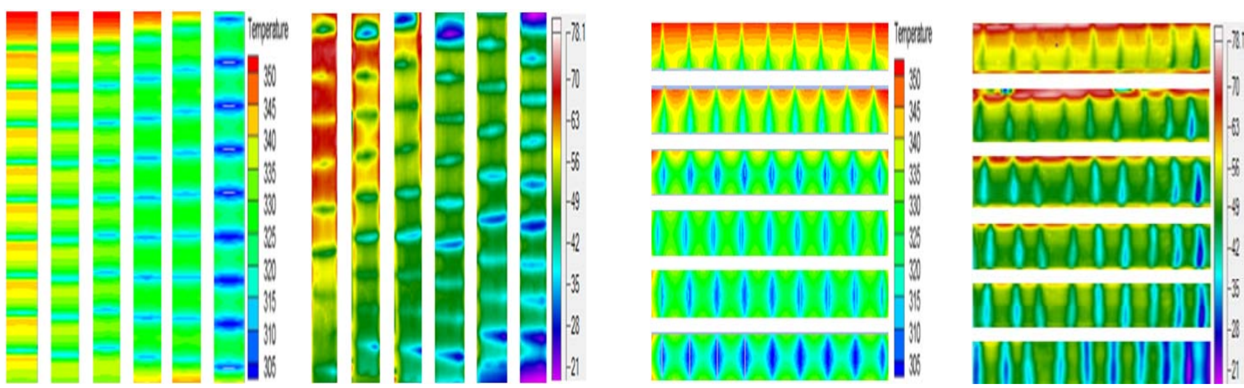


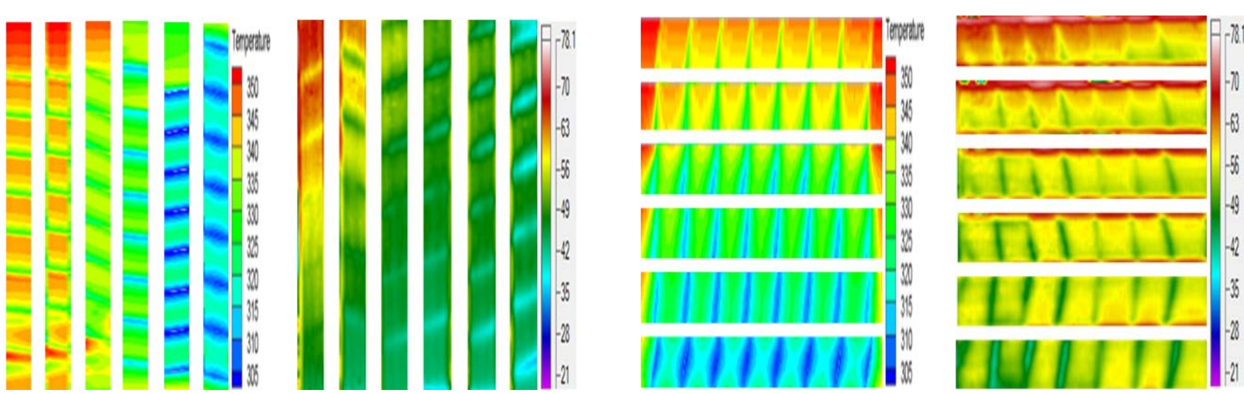
Figure (11): Propagation of melting and solidification fronts of PCM with different types of fin profiles.



Ver.LFWD, (numerical) Ver.LFWD, (thermal camera) Hor.LFWD, (numerical) Hor.LFWD, (thermal camera)



Ver.CFWD, (numerical) Ver.CFWD, (thermal camera) Hor.CFWD, (numerical) Hor.CFWD, (thermal camera)



Ver.SFWD, (numerical) Ver.SFWD, (thermal camera) Hor.SFWD, (numerical) Hor.SFWD, (thermal camera)

Figure (12): Comparison between the results of ANSYS numerical software with photos of thermal camera for single FWD during discharging process. ($\Delta t = 5$min)

Figure (13) 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.

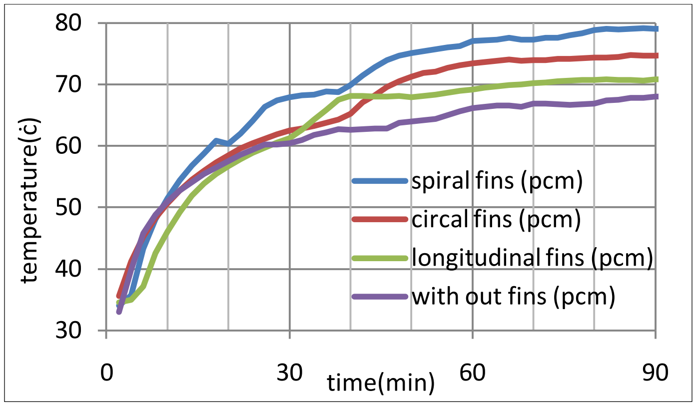


Figure (13): PCM transient temperature response for each type of WD recovery systems during charging process.

Figures (14) shows the transient radial temperature distributions during charging process from hot waste gas of the A/C unit through vertical and horizontal systems. It can be seen that the melting initiates peripherally near the wall of the outer tube then expands inside. It is clear that, the melting of the PCM occurs in non-isothermal process. Just after charging process initiation, regions close to the surface of the tube reach to the melting temperature by conduction. For 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. It is clear that large amount of heat can be transferred and stored in PCM relatively to WFWD.

Figures (15) illustrate the time variation of the temperature during water discharging process. Operating the system during discharge process introduces sudden changes in the temperature as a result of larger temperature difference between the PCM and water. 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%, where as in CFWD system was 37%, and 32% with SFWD system.

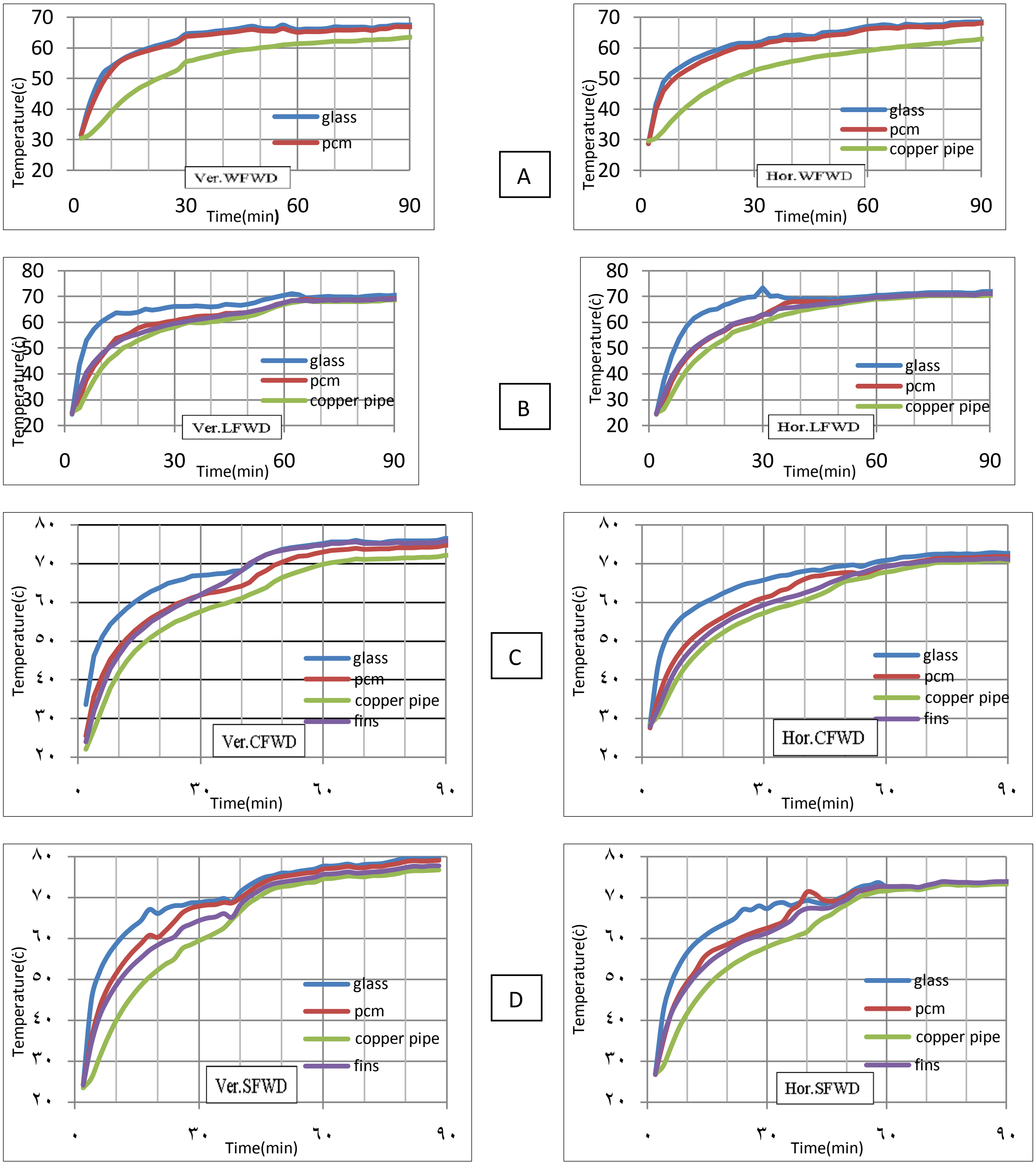


Figure (14): Measured radial temperature distribution inside WD systems during charging process.

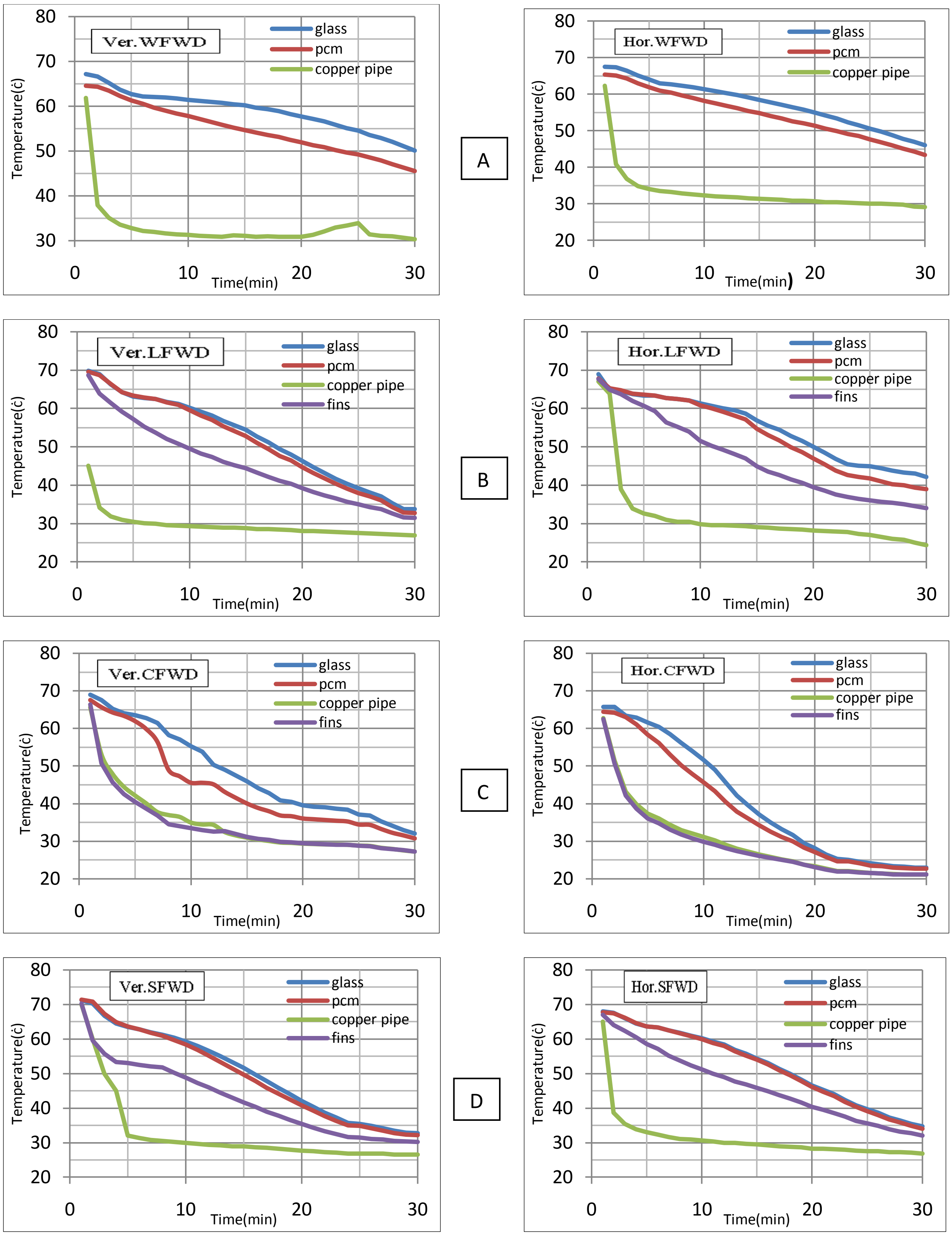


Figure (15): Measured radial temperature distribution inside WD systems during discharging process.

Figure (16) 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.

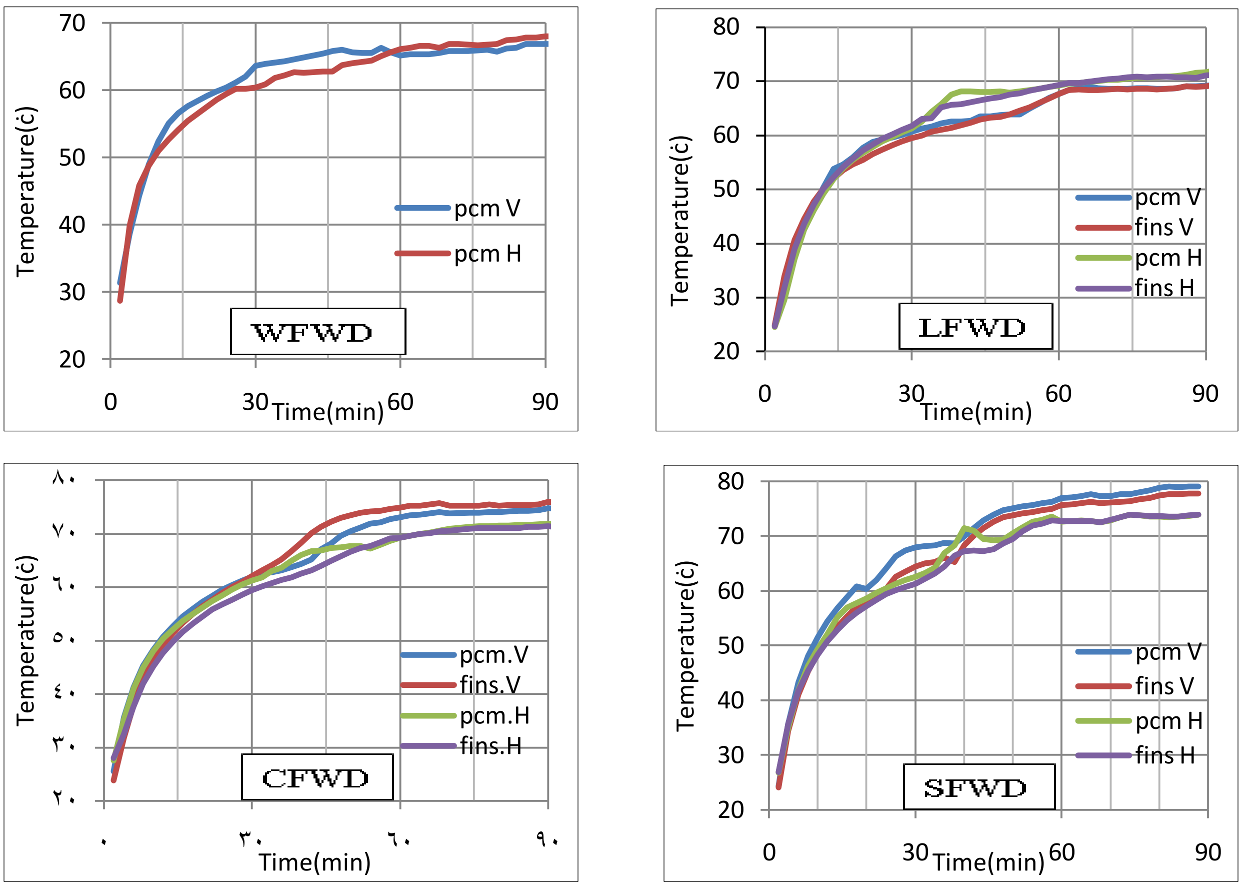


Figure (16): Comparison between vertical and horizontal position thermal response inside WD recovery system

Figures (17) 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.

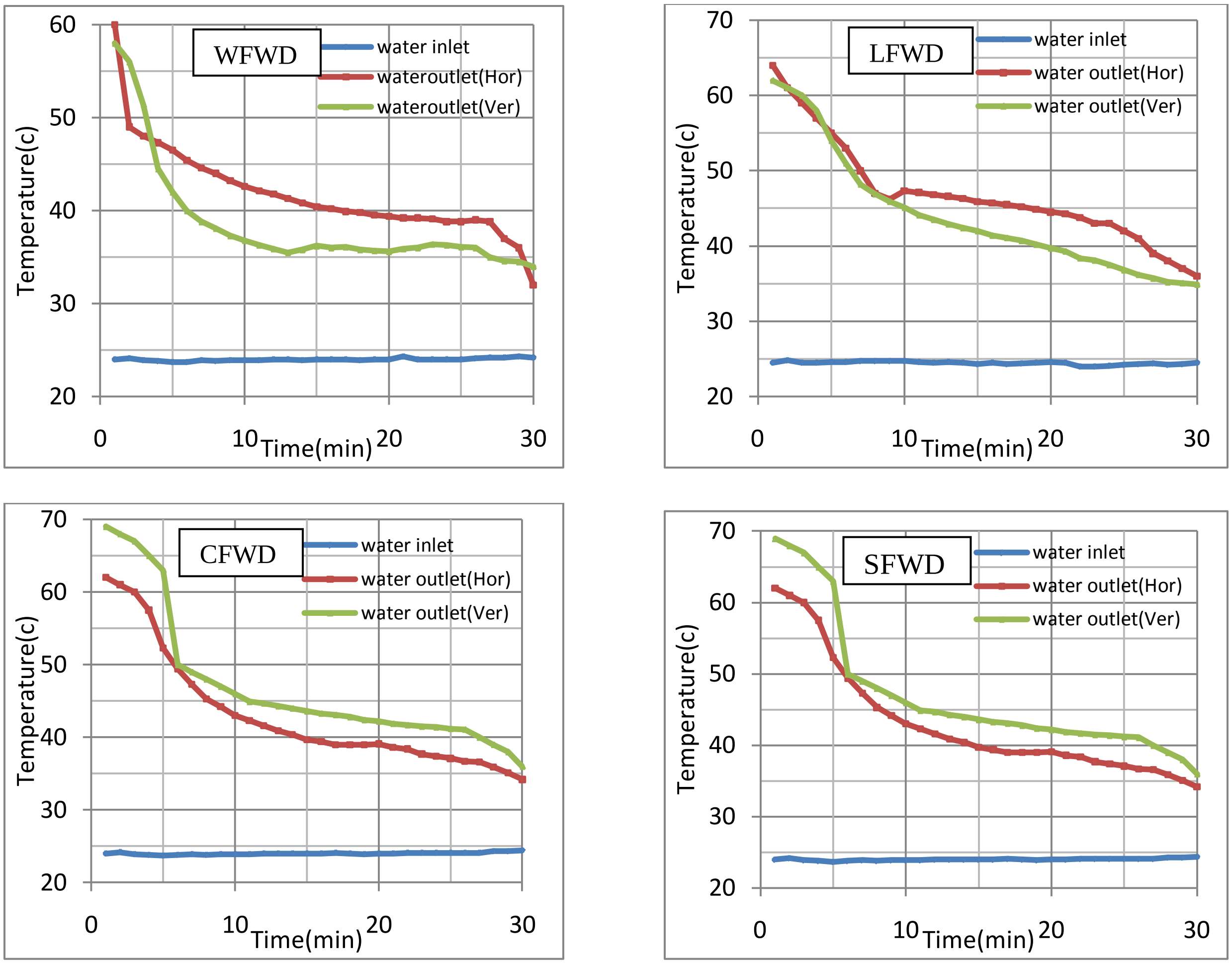


Figure (17): Transient water temperature during discharging process for FWD systems.

5. Conclusions

1- A minimum distance of 3 cm between tubes of the WD recovery system has been found to exhibit a normal performance for the air-conditioning unit. However, the increase in the number of tubes lines is found to be not recommended for all types under investigation because the PCM gained temperature was not reaching the complete melting point.
2- For horizontal position, a satisfactory match has been found between thermal camera and numerical results. However, an acceptable match was noticed with the vertical position.
3- 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%, where as in CFWD system was 37%, and 32% with SFWD system.

4- Results showed different thermal enhancement response between vertical and horizontal arrangement for FWD systems under investigation. Longitudinal and without fins showed better performance in horizontal position. Whereas, spiral and circular fins 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.

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