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ENHANCING STORAGE PERFORMANCE IN A TUBE-IN SHELL STORAGE UNIT BY ATTACHING A CONDUCTING FIN TO THE BOTTOM OF THE TUBE

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Abstract: In this experimental study, melting behavior of paraffin in a storage unit of the horizontal shell-and-tube type is investigated. In order to enhance melting rate, a conducting fin is attached to the bottom of the inner tube. At first, the tube without a fin is tested. Then, the tubes with fin of four different heights (h=10, 20, 30 and 40 mm) are examined. Experiments are conducted at constant values of the inlet temperature and the inlet mass flow rate of the heat transfer fluid (HTF). As phase change material (PCM), paraffin (solidification range of 56−58 C) is used. For each case tested, transient variations of the temperature at some specific radial points inside the phase change material (PCM) are obtained. For the case without a fin, natural convection recirculation is shown to be weak in the lower half region of the annulus when compared to that in the upper half region. Results show that attaching a conducting fin to the bottom of the inner tube intensifies the recirculation of liquid PCM in the lower half and, in follows, enhances the melting rate about 72.8% for the fin height of 40 mm when compared to without fin (h=0 mm)

Keywords: thermal energy storage, tube-in-shell, finned tube, PCM, melting enhancement

HALKASAL GEOMETRİYE SAHİP SİLİNDİRİK BİR DEPONUN ISI DEPOLAMA PERFORMANSININ İYİLEŞTİRİLMESİ: KANATÇIK İLAVESİ

Özet: Bu çalışmada, yatay olarak konumlandırılan silindirik halka aralık bir geometri içerisindeki faz değiştiren maddenin (FDM) erime (şarj) davranışı deneysel olarak incelenmiştir. Erime sürecinin iyileştirilmesi amacıyla ısı transfer borusuna kanatçık ilavesi yapılmıştır. Kanatçıksız durum (h=0 mm) ve dört farklı kanatçık yüksekliği (h=10, 20, 30 and 40 mm) için deneyler gerçekleştirilmiştir. Deneyler, sabit bir hacimsel debide ve tek bir akışkan giriş sıcaklığında yapılmıştır. FDM olarak katılaşma sıcaklığı 56−58 C olan parafin kullanılmıştır. Her bir durum (h) için FDM içerisinde tanımlanan radyal yerel noktalardan zaman bağımlı sıcaklık ölçümleri alınmıştır. Kanatçıksız duruma ait veriler incelendiğinde halka aralığın alt yarı bölgesindeki doğal taşınım mekanizmasının üst yarı bölgeye kıyasla daha zayıf olduğu görülmüştür. Sonuç olarak, ısı transfer borusunun (iç boru) alt kısmına yapılan kanatçık ilavesinin halka aralığın alt bölgesindeki sıvı FDM sirkülasyonunu kuvvetlendirdiği görülmüştür. Kanatçık yükseklikliğinin maksimum olduğu durum (h=40 mm) için erime hızında kanatçıksız duruma (h=0 mm) kıyasla %72.8 oranında iyileşme sağlandığı ortaya konmuştur.

Anahtar Kelimeler: termal enerji depolama, halka aralık geometri, kanatçıklı boru, FDM,erimenin iyileştirilmesi.

INTRODUCTION

The mismatch between energy availability and demand can be eliminated using a proper thermal energy storage (TES) method. Among various thermal energy storage methods, the latent heat thermal energy storage (LHTES) systems utilizing phase change materials (PCMs) is particularly attractive due to its advantages of high energy storage capacity and its nearly isothermal operating characteristics during energy delivery. TES using PCM is also a fast developing research area in buildings (Kenisarin and Mahkamov 2016; Song etal. 2018). In order to have a better view on the studies existing in the literature, the readers are referred to see the excellent reference books by Lane (1983), Garg et al. (1985) and Dincer and Rosen (2002) and the extensive reviews by Abhat (1983), Hasnain (1998), Zalba et al. (2003), Ettouney et al. (2004), Sharma and Sagara (2005), Felix Regin et al. (2008), Agyenim et al. (2010), Xu etal. 2015. More recently, Reddy etal. 2018 and Abdulateef etal.2018 review functional principle, PCMs, heat transfer and thermal conductivity enhancement and energy-exergy analysis for LHTES.

Among the various latent heat energy storage unit, the tube-in-shell is a common and effective storage unit, in which the PCM is kept in the concentric annular space while the heat transfer fluid flows through the inner tube because of simplicity and minimal heat loss (Agyenim et al. 2010). Many studies, mostly experimental and numerical, have been conducted on this geometry. Most of them have been focused on predicting performance of various PCMs and of various working parameters such as inlet temperature or mass flow rate of heat transfer fluid have been studied (Sarı and Kaygusuz 2001a, Sarı and Kaygusuz 2001b; Sarı and Kaygusuz 2002; Akgun et al. 2007; Trp 2005; Tao and He (2011); Rösler and Brüggemann 2011; Hosseini etal. 2012; Jesumathy etal. 2012; Avci and Yazici 2013; Wang etal. 2013; Hosseini etal. 2014; Seddegh etal. 2015; Seddegh etal. 2016; Tao and Carey 2016; Wang etal. 2016; Han etal.2017; Seddegh 2017). Since most PCMs have unacceptably low thermal conductivity, leading to slow charging and discharging rates, heat transfer enhancement techniques are required for most LHTES applications (Agyenim et al. 2010). Either from the scientific or practical viewpoint, research efforts should be concentrated on improving or enhancing storage performance. By enhancing, our ultimate goal is "storing energy as much as possible in a time as short as possible". Enhancing storage performance can be via active or passive ways. Active methods such as mixing require usage of additional energy. However, passive methods just require some geometrical orientations. Using extended surfaces is a passive way to improve performance in a tube-in-shell storage geometry.

Lacroix (1993) numerically and experimentally analyzed the tube-in-shell storage geometry oriented horizontally with annular fins around circumference of tube. Effects of the shell radius, the mass flow rate and inlet temperature of the HTF and the presence of fins attached to the inner tubes were investigated. It was concluded that the annular fins showed better performance at moderate mass flow rates and small inlet temperatures. Choi and Kim (1995) experimentally investigated heat transfer characteristics of magnesium chloride hexahydrate in circular finned- and un-finned tube systems oriented vertically. They reported that heat transfer coefficient showed a negligible increase for the finned case when compared to the un-finned case since the fins partially suppressed natural convection of liquid PCM. Zhang and Faghri (1996) numerically studied latent heat thermal energy storage system of externally radial finned tube. The effect of the tube wall, initial subcooling and the height of the fins on the heat transfer were investigated. Erek et al. (2005) investigated the energy storage performance of a tube-in-shell system with circular-finned tube. They developed a 2D numerical model to predict the effect of the fin dimensions and the operation parameters (fin space, fin diameter, Reynolds number and inlet temperature) on the solidification and melting process of the PCM. Agyenim et al. (2009) examined the performance of a horizontal latent heat thermal energy storage system in three-experimental configurations, a concentric tube system with no fins, an extended surface with circular and longitudinal fins. Longitudinal fins provided the most performance during the charging process and reduced sub-cooling during the discharging process. Their findings showed that heat transfer contribution due to convection was not sufficient enough to increase melting rate in circular finned system. Ismail and Lino (2011) experimentally performed the effects of radial fins and turbulence promoters on the enhancement of phase change heat transfer external to a horizontal tube submersed in the PCM with the working fluid flowing through it. Inlet temperature of heat transfer fluid, mass flow rate and fin height were examined. They observed that there was an optimum fin diameter for the time to complete solidification. The use of the turbulence promoters resulted in high interface velocity and decrease in solidification. Hamdani et al. (2012) experimentally studied melting characteristics of latent heat thermal storage system with longitudinaly and radial finned tube during melting. The longitudinal fin showed better thermal performance when compared to the radial ones. Cylindrical latent heat storage system with radial fins were studied numerically by Ogoh and Groulx (2012). Effects of the number and distribution of fins on the performance of storage unit was investigated. They reported that the fin addition played a significant role (10 fins or more), on the thermal performance of the system. Al-Abidi et al. (2013) numerically and experimentally investigated the melting behavior of PCM in a horizontal triplex tube heat exchanger (TTHX) for internal and external fins configurations. Effect of fin number, fin length, fin thickness, Stefan number, TTHX material, and the phase change material (PCM) unit geometry on melting were examined. They concluded that the effect of fin thickness on melting time was small when compared to the fin length and fins number. Al-Abidi et al. (2014) experimentally investigated the melting process of PCM in the same geometry for internal-external longitudinal fin configuration. Their results showed that inlet temperature of heat transfer fluid had a considerable effect on the melting process when compared to the mass flow rates. An experimental study of the phase change inside a horizontal cylindirical LHTES with longitudinal fins (straight and angular fin configuration) was carried out by Liu and Groulx (2014). They reported that the use of angled fins resulted in slightly lower total melting time (at 50 C inlet temperature) when compared to the straight fins. Rathod and Banerjee (2015) studied the effect of longitudinal fins on the thermal performance of a PCM-based heat storage unit. Melting and solidification processes of PCM were experimentally conducted under various fluid inlet temperatures and flow rates of HTF. They reported that the use of inserted longitudinal fins increased melting and solidification rates. More recently, Cao et al. (2018) conducted a numerical study to investigate the effect of the fin number on the melting rate, Nusselt number, and wall heat flux for different wall temperatures in a horizontal annular phase-change unit with longitudinal fins.

Preceding review reveals that a considerable amount of research has been done related to the effect of adding multiple fins on the thermal performance of shell and tube latent heat storage systems. However, those studies aimed at increasing heat transfer area with fins, and in follows, in transfer rates. Their motivations were not the melt flow. It should be also noted those fins sometimes decreased charging effectiveness, deteriorating the natural convection currents. Without extending heat transfer surfaces, i.e. increasing heat transfer area, storage performance could be enhanced through optimizing geometries according to the physics of the phase change process. In this way, research interest should be directed to investigate novel geometrical designs or innovative modifications on the existing designs by considering the regarding phase change behavior of PCMs. Hence, in this study, a conducting fin with different heights is attached vertically to the bottom of the HTF tube in order to enhance natural convection currents in the lower half of the annulus which are otherwise very weak when compared to the upper half. To evaluate the thermal performance of the heat storage unit for each fin height configuration, the time history of temperatures inside the unit are measured in detail and compared with the un-finned configuration.

EXPERIMENTAL APPARATUS AND PROCEDURE

The experimental setup schematically shown in Fig. 1 consists of two loops namely: the primary and the secondary loop. The primary loop includes a constant temperature circulating bath (LABO DX-300) having a temperature range of −20 to 120 C with temperature stability of ±0.03 C, a flow meter, a hydrodynamic entry section, a horizontal test module (PCM storage container), a return piping for the HTF and a data acquisition unit. Distilled water is used as the heat transfer fluid. As it is shown, the HTF is firstly circulated through the secondary loop in order to adjust its desired inlet temperature before entering the test module. Then, the HTF flows through primary loop and the charging process in the test module is started. This process is assumed to end when all the temperature recordings in the test module (PCM storage container) present higher values than the melting temperature of the PCM.

The test model is composed of a polypropylene (PP) shell having a circular cross section of 110 mm (i.d.), and a length of 500 mm and a finned copper tube with an outer diameter of 28 mm located centrally in the shell (Fig. 2). For the finned tube geometry, four different fin heights of 10, 20, 30 and 40 mm are considered. All the fins, made of copper, were soldered vertically to the bottom surface of tube having the same length of 490 mm and thickness of 1.5 mm. To achieve a good thermal contact between the tube and the fin, a copper based electrode (BR 1204) is used for soldering. To reduce the heat loss to the environment, the outer wall of the test module is insulated with 38.1 mm thick fiberglass layer having an average thermal conductivity of 0.038 W/mK.

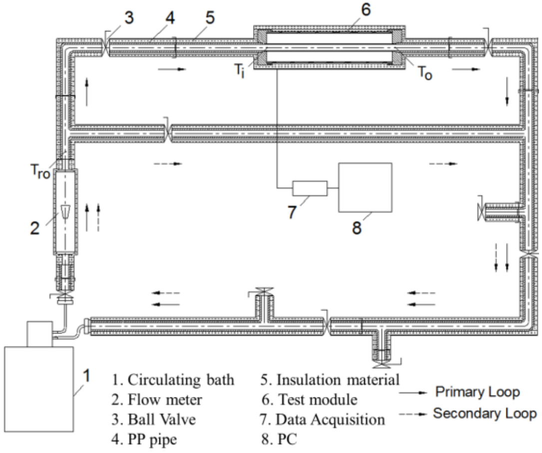


Figure 1. Schematic view of the experimental setup.

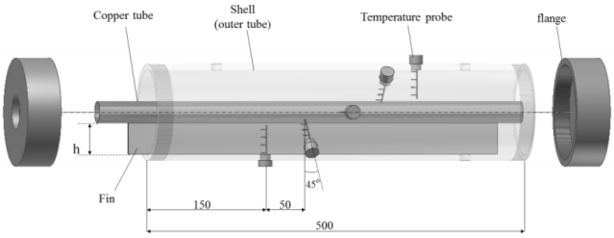


Figure 2. Construction details of the test module.

As PCM, paraffin of P56−58 (solidification range of 56−58°C) is used, which is supplied from the MERCK. The thermo-physical properties of the paraffin used in the study are given in Table 1. The amount of PCM quantity filled in annular space between the copper tube and the shell is 3.3 kg. An air gap (15% of the total volume) is left at the top of the each module to accommodate the volume increase of the PCM during melting process.

Table 1. Thermo-physical properties of of the paraffin used in the study (Akgun et al. 2007).

Melting point (°C)	58.06
Solidification range (°C)	56−58
Latent heat (kJ/kg)	250
Density (kg/m^3)	880 (30°C), 762 (80°C)
Specific heat (kJ/kg °C)	1.84 (25°C), 2.37 (80°C)

Five identical temperature probes are imbedded in PCM with spacing between each successive probes of 50 mm to measure the radial temperatures. Each probe includes four 0.1 mm outer diameter T-type thermocouples spaced at 10 mm apart. In order to eliminate the flow resistance effect to be resulted from the probes, the axial distance and the angular position among these holes is kept 50 mm and 45°, respectively. The detailed view of the thermocouple locations is shown in Fig. 3. In addition to PCM temperature field, the HTF temperatures at the inlet (T_i) and the outlet of the test module (T_o) and at the exit of the rotameter (T_{ro}) are also measured (see Fig. 1). All the thermocouples (T type) which have measuring range of −10 to 100°C and an accuracy of ±1.0°C are checked by using a constant temperature circulating bath (LABO DX-300). These tests showed that the long-term stability of the thermocouples are less than ±0.2°C. The temperatures of all the thermocouples are read and recorded by Keithley 2701 (Multimeter/Data Acquisition/Switch Systems) is used with 7708 module (40-channel differential multiplexer module with maximum 0.8°C uncertainty) at scaning intervals of 60 second. The volumetric flow rate of the HTF is controlled by changing the gate opening of the valve at the downstream of the flow meter.

All the experiments were carried out in a conditioned room, where the ambient temperature was 30°C. The experiments were repeated at least three times with similar results. The uncertainty level of the temperature readings was found to be within ±2.38%.

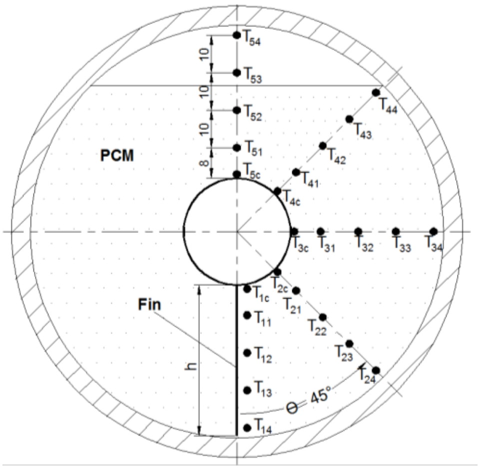


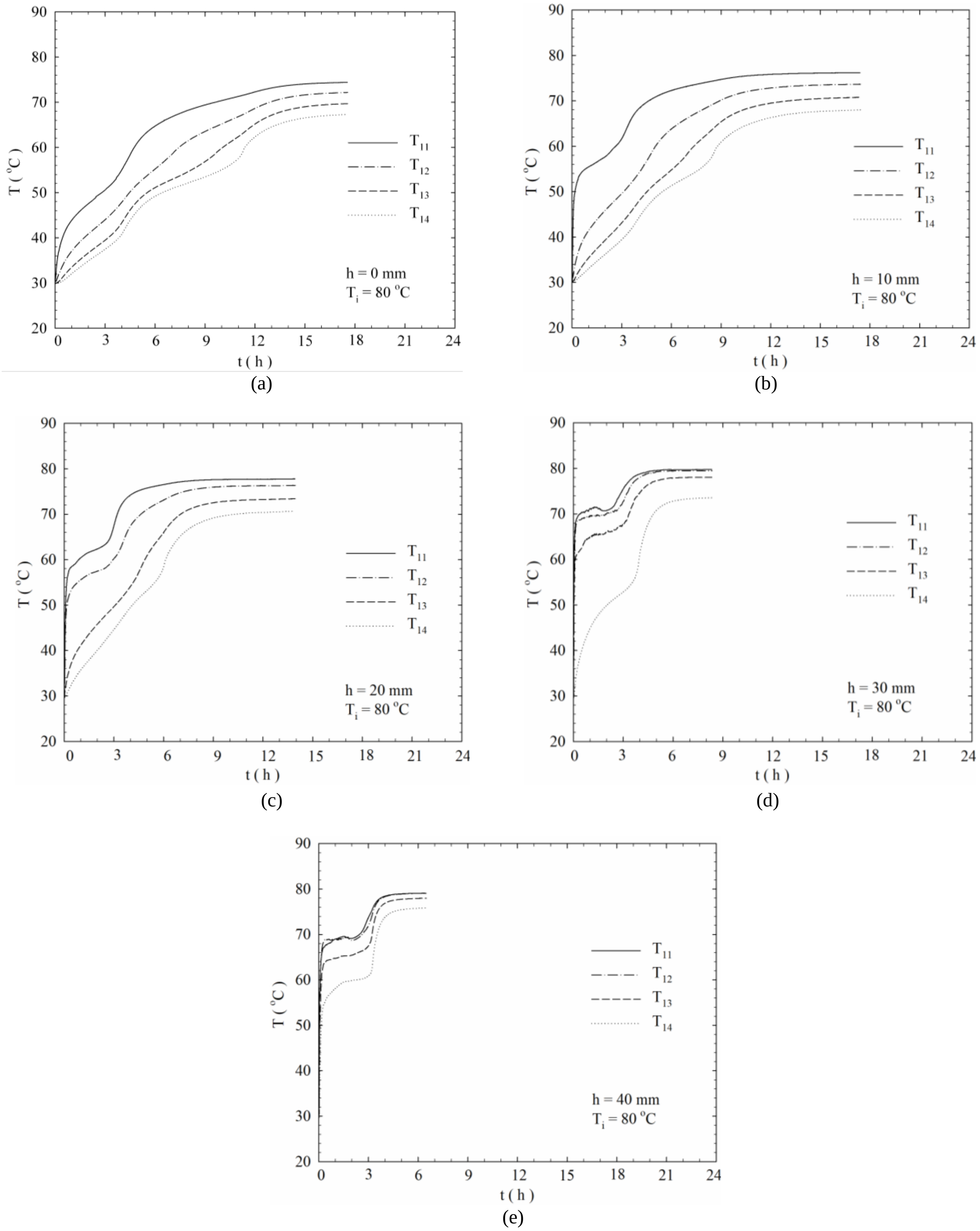
Figure 3. The points of the temperature measurements inside the PCM.

EXPERIMENTAL RESULTS AND DISCUSSION

The main motivation of the study is to enhance melting inside by attaching a fin vertically to the bottom of the HTF tube. Hence, it is aimed to increase convective heat transfer in the lower half of the annulus. The fin height is the main parameter of the study. At first, the case without fin is considered. In the following, four different values of the fin height are considered: h=10, 20, 30 and 40 mm. Melting (i.e. charging) experiments are conducted by following the experimental procedure described above. The experiments are performed for a constant value of the inlet temperatures of the HTF, water, (80°C), which is above the melting temperature of the paraffin tested. A constant value of the mass flow rate, 280 kg/h, is considered. The case of finned HTF tube is compared to experimental data results for LHTES without conducting fin by Avci and Yazici (2013).

For the case without the conducting fin and for four values of the fin height tested, temporal variations of temperature at different radial points given in Fig. 3 are plotted in Figs. 4−8. Melting behavior of PCM, for the case without conducting fin, discussed elaborately in the previous study of authors (Avci and Yazici, 2013). As seen clearly from the figures, for the case without fin, melting starts peripherally near the wall of the HTF tube as a result of conduction outward. Conduction is the dominant heat transfer regime in the earlier period of the melting. Then, melting process extends radially to outwards. However, melting behavior dramatically differs for the upper half region of the annulus than the lower half one. The melted PCM ascends to the upper half part of the storage container as a result of natural convection currents. The melt region extends radially upward, which results in the fact that the points in the upper half region reach the melting temperatures earlier than those in the lower half region. That is why a conducting fin is attached to the bottom of the HTF tube. Hence it is aimed to enlarge convection-affected volume in the annular space. The fin behaves like a heated vertical plate about which natural convection exists.

In the case of conducting fin, initially, the conduction is the dominant mechanism of the heat transfer. Then, there is a bulk motion of the molten PCM due to the buoyancy forces induced by the density gradients as a result of temperature differences in the liquid PCM. As time progress, heat transfer dominated by natural convection depends on liquid PCM fraction. Effect of conducting fin to the HTF tube can be observed with enhanced heat transfer rate. With an increase in the fin height, more heat is transferred to the PCM. It is clearly seen from figures that higher temperatures are observed in the lower half when compared to the case of without conducting fin. Moreover, the temperatures at the radial points of the lower region (at θ=0 , 45) decrease with the increase of fin height since the amount of heat absorbed by the PCM is well spread. It is also shown for the case of conducting fin that there is no considerable change on the temperature distribution in the upper region of the annulus when compared to the case without conducting fin. As time progress (t>3h), temperature values of all measurements points at 90 , 135 , 180 , for both cases (with and without a fin) converge to HTF fluid temperature, which is 80 C. Hence, it is an evidence that conducting fin enhances the natural convection currents in the lower half of the system.

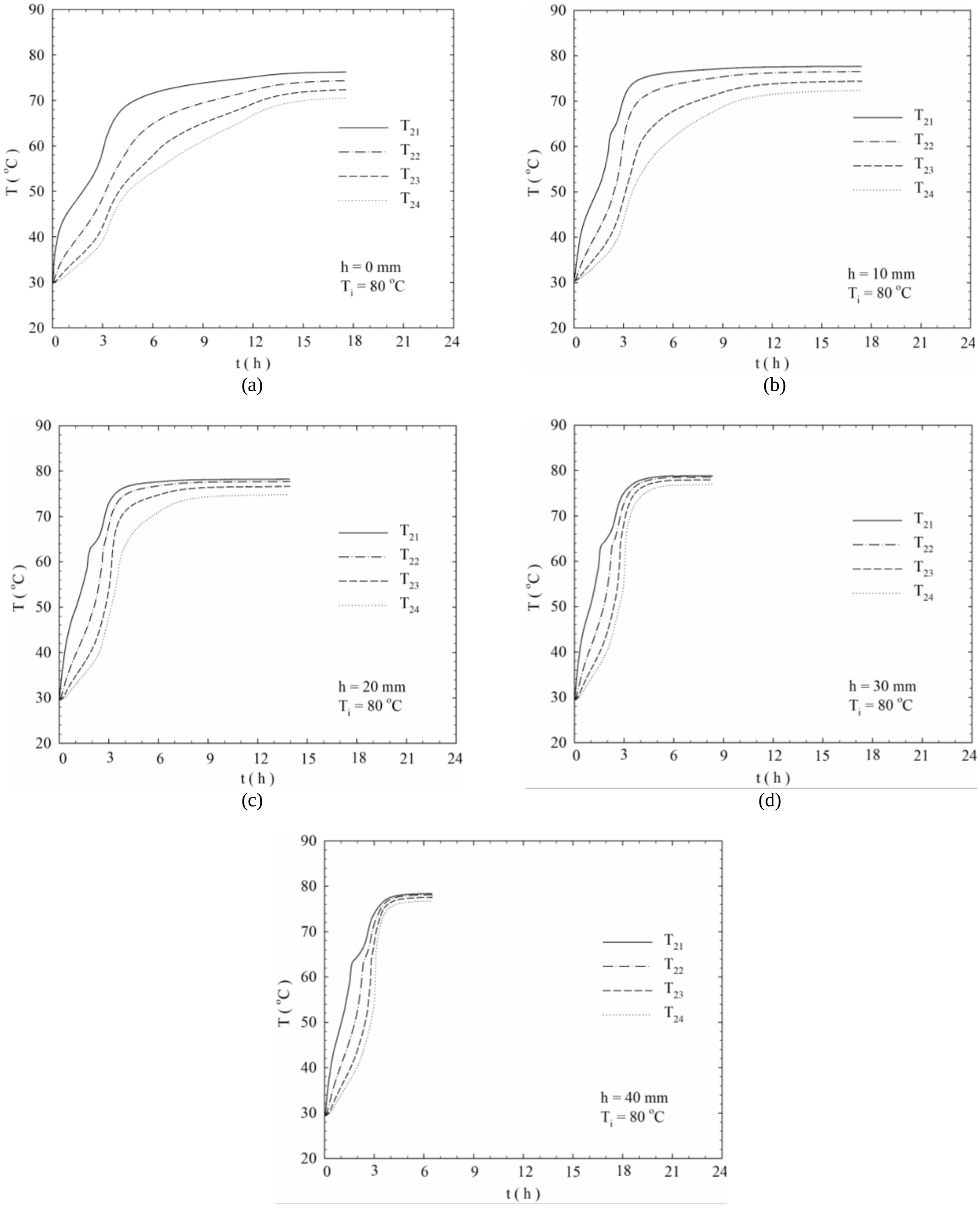


(a) (b)

(c) (d)

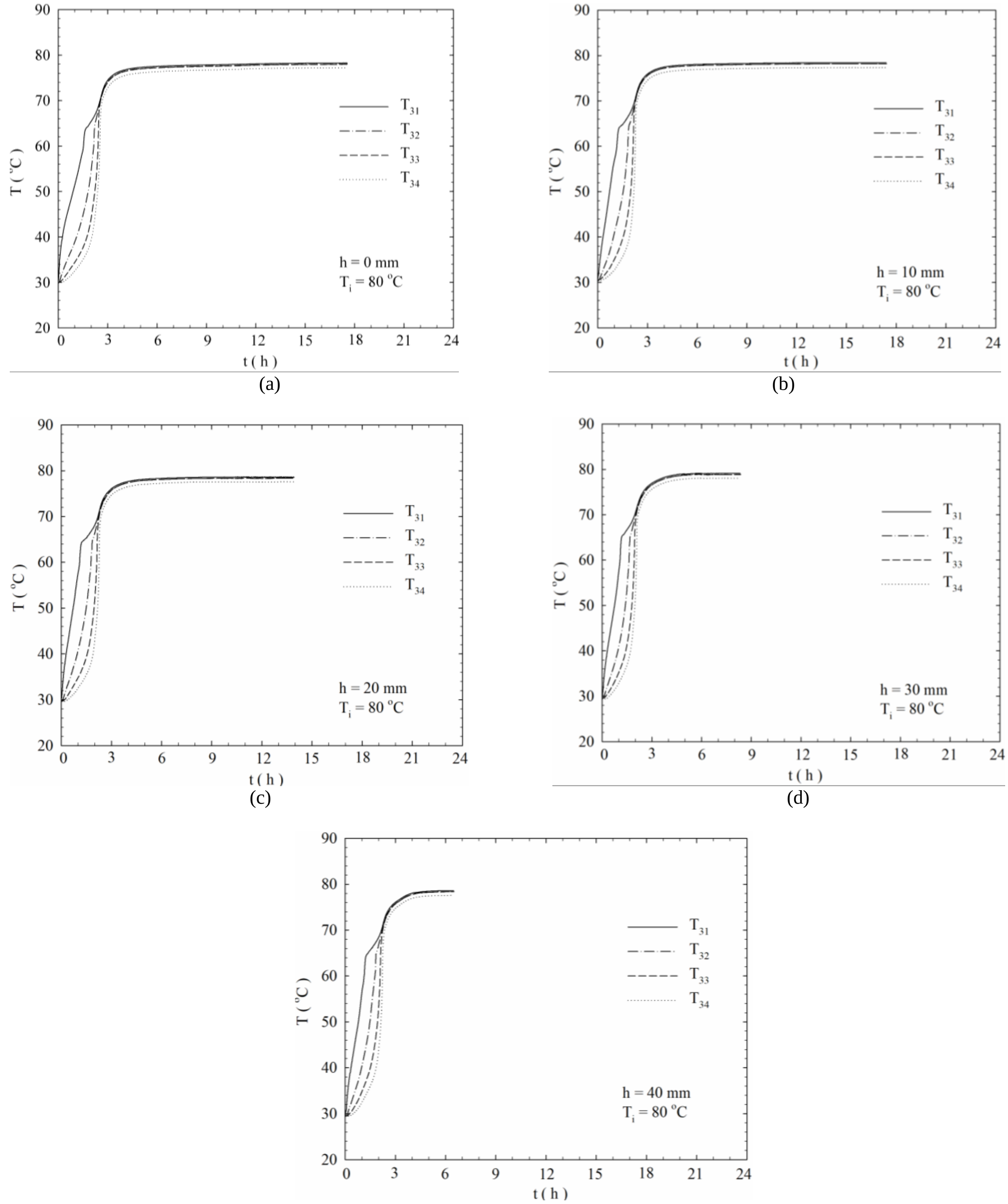
(e)

Figure 4. Effect of the fin height on the transient temperatures of different radial points at θ=0 : h=0 mm (Avci and Yazici, 2013) (a), h=10 mm (b), h=20 mm (c), h=30 mm (d) and h=40 mm (e).



(a) (b) (c) (d) (e)

Figure 5. Effect of the fin height on the transient temperatures of different radial points at θ=45 : h=0 mm (Avci and Yazici, 2013) (a), h=10 mm (b), h=20 mm (c), h=30 mm (d) and h=40 mm (e).

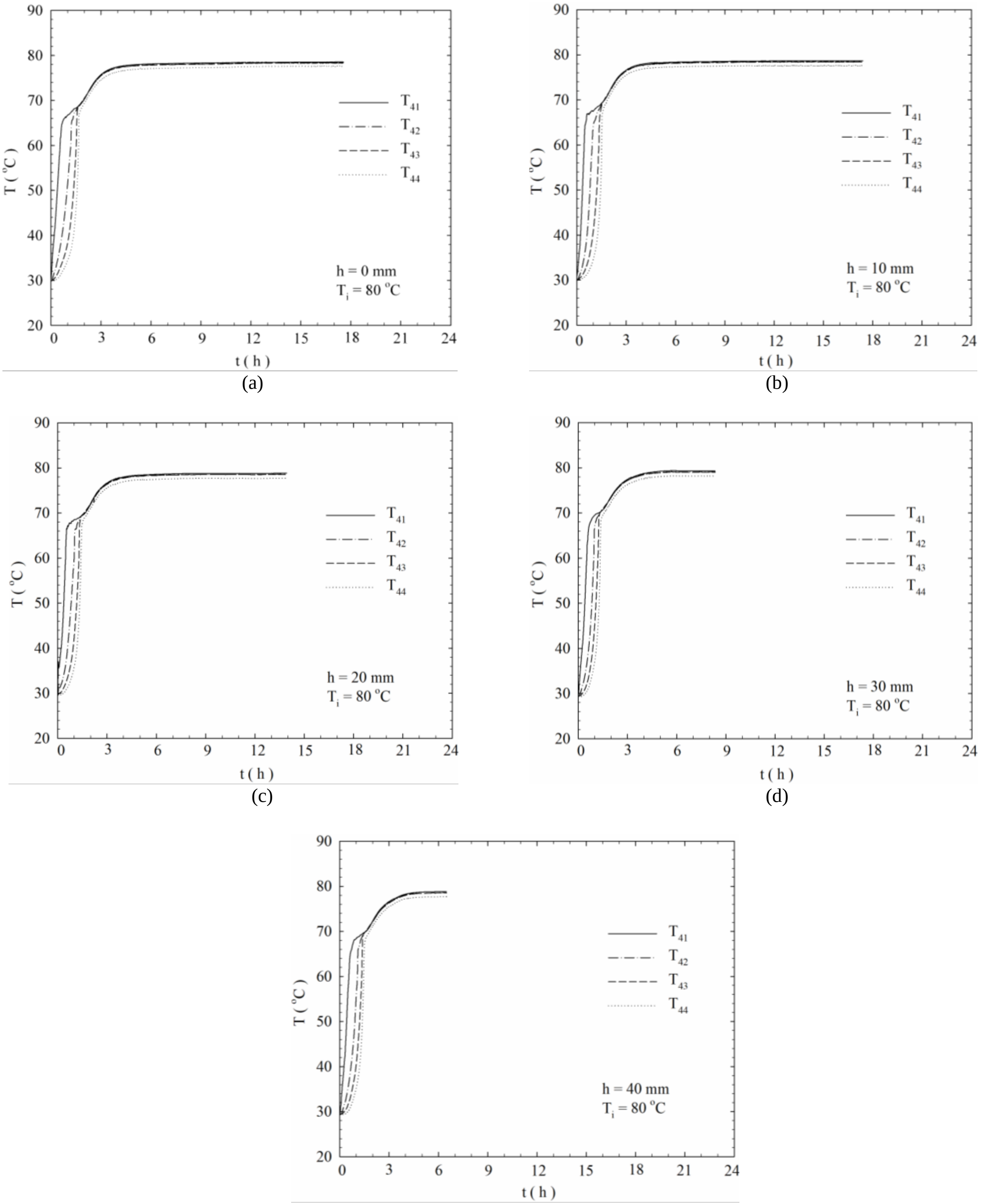


(a) (b)

(c) (d)

(e)

Figure 6. Effect of the fin height on the transient temperatures of different radial points at θ=90 : h=0 mm (Avci and Yazici, 2013) (a), h=10 mm (b), h=20 mm (c), h=30 mm (d) and h=40 mm (e).

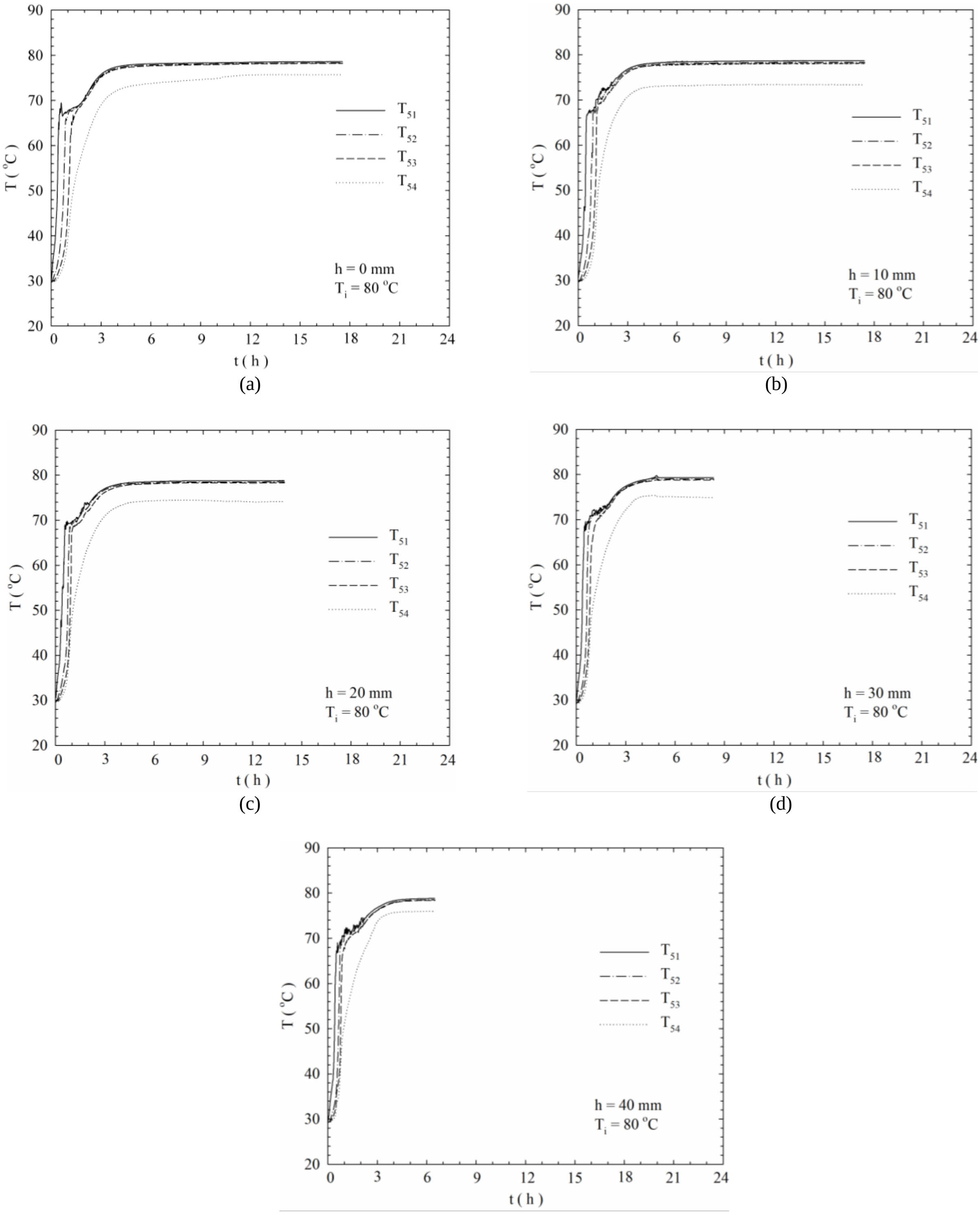


(a) (b)

(c) (d)

(e)

Figure 7. Effect of the fin height on the transient temperatures of different radial points at θ=135 : h=0 mm (Avci and Yazici, 2013) (a), h=10 mm (b), h=20 mm (c), h=30 mm (d) and h=40 mm (e).



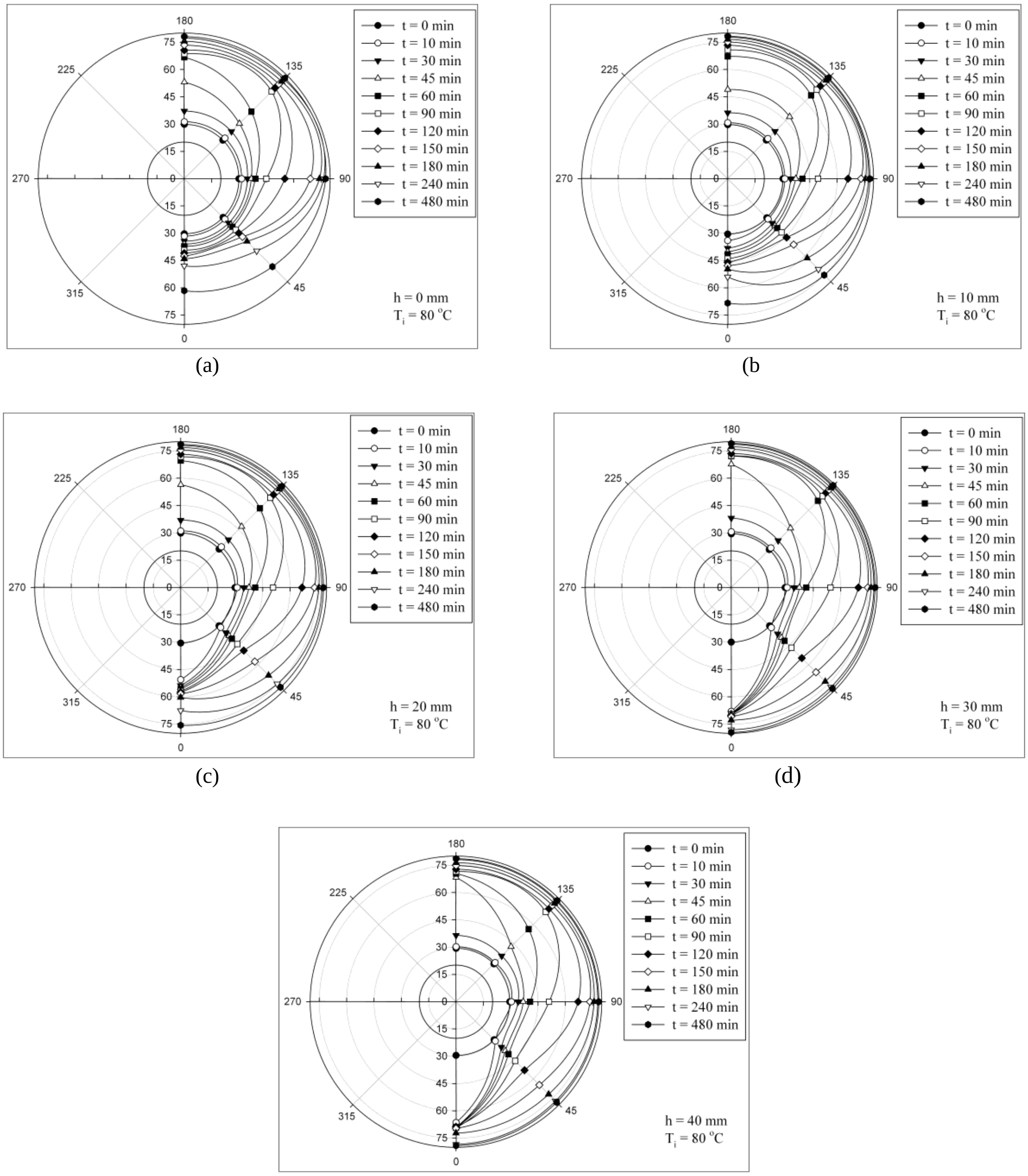
(a) (b) (c) (d) (e)

Figure 8. Effect of the fin height on the transient temperatures of different radial points at θ=180 : h=0 mm (Avci and Yazici, 2013) (a), h =10 mm (b), h=20 mm (c), h=30 mm (d) and h=40 mm (e).

In order to have a more detailed insight into the physics of the melting process, temporal variation of radial temperature distribution at the radial points located radially equal distance to the HTF tube wall is illustrated in Fig. 9. As shown, the radial temperature of the PCM at the specified radial position gradually increases with time. As seen, initially, temporal variation becomes radially nearly uniform. This is the due the fact that conduction is initially effective on the heat transfer (for t ≤ 30 mins). Then, natural convection suppresses the conduction. For the case without fin (h=0 mm), the natural convection currents are more effective in the upper half of the annular storage container (t > 30 mins). Usage of the fin attached to the bottom of the HTF tube enhances the natural convection currents in the lower half, too. Increasing the fin height intensifies the natural convection currents in the lower half, which also contributes to the strength of the upper half circulation.

For the various values of the fin height, at the critical point (i.e. the point that melts lastly or where the total melting ends), temporal variation of the temperature is plotted in Fig. 10. As the fin height is increased, melting performance has been observed to improve at the critical point.

For a better view, the variation of the total melting time with the fin height is depicted in Fig. 11. As shown, the total melting time decreases dramatically and considerably with an increase in the fin height. The fin with largest height among the tested ones, h=40 mm, presents the lowest melting time. This is just due to increased convective heat transfer coefficient. With an increase in the fin height, convection-dominated region expands to the whole region in the annulus. When compared to the storage geometry without the fin, the geometry with the fin with h=40 mm leads to about a 72.8 % decrease in the total melting time. Such an enhancement is very considerable and credible from the practical viewpoint.



(a)

(b

(c)

(d)

(e)

Figure 9. Transient temperatures during melting at the second radial measurement stations (T_{12}, T_{22}, T_{32}, T_{42}, T_{52}) h=0 mm (Avci and Yazici, 2013) (a), h=10 mm (b), h=20 mm (c), h=30 mm (d) and h=40 mm (e).

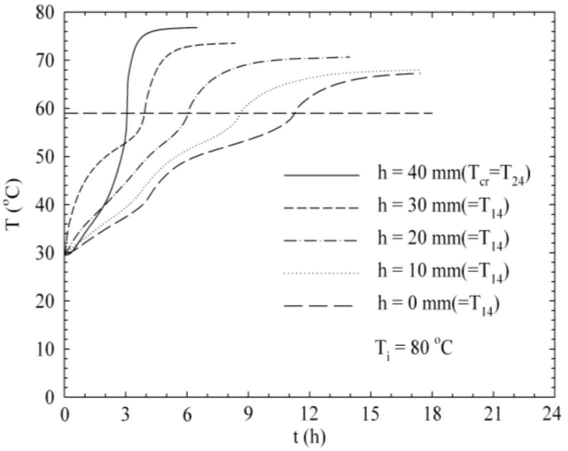


Figure 10. Effect of the fin height on the transient temperatures of the critical stations

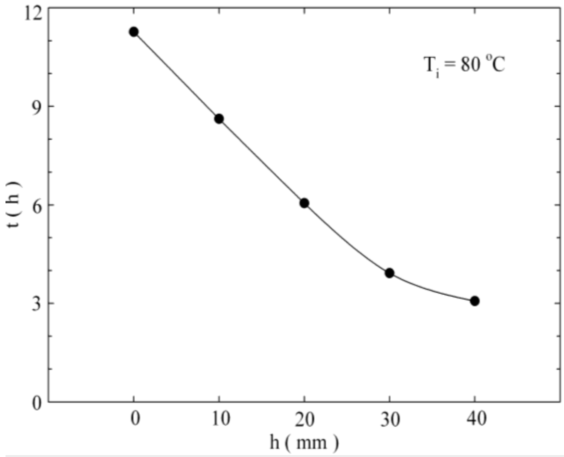


Figure 11. Effect of the fin height on the total melting time.

CONCLUSIONS

The melting or charging characteristics of paraffin in a horizontal shell-in-tube thermal energy storage unit have been investigated experimentally. In order to enhance melting inside the annulus, a conducting fin was attached vertically to the bottom of the HTF tube. Both the cases without fin and with fin of various heights are tested. For all the cases considered, conduction is the dominant heat transfer mechanism at the beginning of the melting, which is then suppressed by natural convection. For the case of without fin, melt recirculation intensity in the upper half of the annulus was much more higher than that in the lower half because of the ascending melt flow due to the buoyancy-induced or natural convection. Therefore, a conducting fin is attached to the bottom of the inner tube and hence natural convection-dominated volume is extended to the lower half of the annulus and, in follows, melt recirculation inside is totally intensified considerably. It is disclosed that convection-dominated region expands to the whole region in the annulus and, in follows, melting rate is significantly improved with an increase in the fin height. As a remarkable example, the storage geometry with the fin of h=40 mm leads to about a 72.8% decrease in the total melting time when compared to the un-finned configuration. Such an enhancement is very valuable and credible from the practical viewpoint.

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