

STUDY OF TILTING EFFECT ON THE MELTING PARAFFIN PROCESS CONTAINED IN A SQUARE CAVITY

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Abstract, Thermal energy storage improve the energy efficiency in different applications by reducing the mismatch between supply and demand. For this purpose, phase change materials PCM are particularly attractive since they provide a high-energy storage density at a constant temperature, which corresponds to the phase transition temperature of the material. The large number of PCMs is studied in the literature, paraffins are considered to be promising for latent heat storage because of their appropriate thermal properties and their chemical stability. Recent work is trying to understand the mechanisms that take place during the melting of PCMs in order to accelerate the heat transfer process and improve their low thermal conductivity (especially for paraffins). The interest of this work is to realize an experimental procedure to visualize the phase change process in a square thermal cavity and to study the effect of the inclination of the heated surface. The aim is to analyze the behavior of thermo-convective flow in the liquid phase and its effect on the melting speed. An acceleration of 3 hours and 20 minutes are obtained with heating cavity by bottom compared to the cavity heated vertically and titled, respectively.

Keywords: Thermal Storage, Latent heat, PCM, Paraffin, Convection

1. Introduction

Using PCM in the thermal industries has become a key area of research during the three past decades. During the phase change process of PCM large amounts of heat can be stored or released. Thus, PCMs can play an important role, since excess energy available during off-peak periods can be stored in PCM devices for later use. Due to the advantages of the durability of the physical and chemical properties and the cooling phenomenon, organic PCMs were commonly chosen for the application of phase change energy storage in previous works. However, most organic PCMs have poor thermal conductivity, this delays the duration of the thermals charge and discharge. Researchers have used different methods to solve this problem, including adding finned tubes of different configurations, inserting a metal matrix into the PCM, injecting nano-conductors, distributing different materials with high conductivity and microencapsulation of PCM [1].

Arasu et al. [2] have studied numerically the melting of paraffin wax dispersed with a nanoparticles Alumina (Al₂O₃) that is heated from one side of a square enclosure with dimensions of 25 mm × 25 mm. They found that the fluid flow and the interface shape depend on the liquid layer thickness during the progress of melting. There are multi cellular flow patterns in horizontal bottom wall heating while there is only one cell flow pattern in vertical wall heating. The melting rate decreases with the increase in the volumetric composition of alumina (Al₂O₃) for both horizontal wall and vertical wall heating cases.

Korti et al. [3] studied experimentally the process of charging and discharging of thermal energy in a latent heat storage unit. Three different types of paraffins are tested as PCM and water is used as a heat transfer fluid (HTF). The study concluded that the inlet temperature has a significant effect on the performance of the thermal unit and can accelerate the charging phase by about 55 % and delay the discharging phase by about 49 %. Adding engine oil to paraffin can improve the velocity of the charging and discharging process by about 43 and 66% respectively.

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Senthil et al. [4] studied numerically the thermal behavior of PCM in a quadrant cavity at various inclinations from 0° to 360° . The tilting of an orientation of PCM container accelerate the melt fraction considerably with improvement in convection dominated melting process. However, the orientation has less effect during the solidification process. The total melting time for the 45° inclination and bottom heating was 35% and 53% less than the vertical heating. 225° inclination took the shortest time for complete melting.

Madruga et al. [5] simulated the melting process on the PCM n-octadecane in squared geometries in the presence of natural convection and including thermocapillary effects. For Bond number ($Bo = 8.3$) that adding thermocapillary effects decreases the total melting time 18% with a heated wall at 50°C and 28% with 100°C . At $Bo = 33$, the influence of thermocapillary effects weakens with a decrease of the total melting time of 4.2% with a heated wall at 50°C and 6.3% with 100°C . Then, the thermocapillary effects at small Bo are a very relevant mechanism to enhance the heat transfer rate on n-octadecane, especially when subjected to high external temperatures.

Madruga et al. [6] studied numerically the melting dynamics of n-octadecane within square geometries with periodic boundary conditions along the horizontal direction heated from below with different sizes. They have identified four different regimes over time: (i) conductive regime, (ii) linear regime, (iii) coarsening regime and (iv) turbulent regime. The first two regimes appear at all domain sizes. However, the third and fourth regimes require a long advance of the solid/liquid interface (greater than 3.5 cm). Finally, the turbulent regime leads to a very irregular solid/liquid interface with strong fluctuations of the amplitude (Rayleigh-Bénard instability).

Madruga and al. [7] performed a comparative analysis of experimental results and numerical simulations for using the aluminium material of thermal collector by introducing a novel design to enhance heat transfer performance, which is assembled in PVT and PVT-PCM systems. Maximum cell temperature reduction of 8.3 and 8.1°C in case of PVT, and 12.8 and 12°C is achieved in the case of the PVT-PCM system from the PV module. The electrical efficiency of PV, PVT and PVT-PCM numerically is achieved 13.72, 13.85 and 14% and for the experimental investigation; it is obtained as 13.56, 13.74 and 13.87% at 200 W/m^2 respectively.

This study presents an experimental work of a square thermal cavity made by glass in order to understand and visualize the thermal behavior of a PCM (paraffin) during melting. The aim is to analyze the behavior of thermo-convective flow in the liquid phase and its effect on the melting speed for three different inclination of thermal cavity (vertically, bottom and 45°).

2. Experimental Study

Initially, the molten paraffin (PCM) is poured into a square thermal cavity with dimensions of $12\text{ cm} \times 12\text{ cm}$ and a thickness of 4.5 cm. The cavity is made by glass to allow the visualization of PCM behavior during melting (Fig. 1). After the PCM has completely solidified, one face of the cavity is heated by an electric heater (Fig. 2). The other faces are isolated using rockwool. Nine thermocouples (type K) are immersed in the paraffin and distributed uniformly (space 3 cm) in order to measure the thermal evolution of the paraffin during melting. Also, a thermographic instrument (infrared camera) is used to record a thermal field of the paraffin during melting. The temperature measurement can be used to adjust the thermographic measurements. In order to see the effect of the cavity orientation on the behavior of the thermo-convective flow during paraffin melting, three θ angles are used 0° (vertically heating), 45° (inclined heating) and -90° (bottom heating).



Figure 1. Thermal cavity isolated by Rockwool.

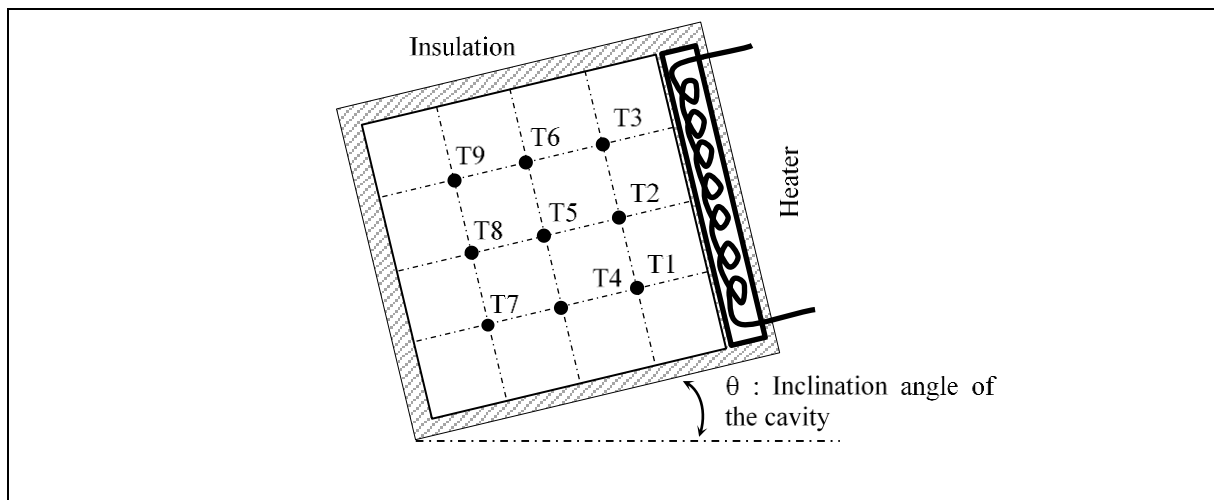


Figure 2. Schematic diagram of the experimental procedure

3. Results and Discussions

Figure . 3 shows the photos of the time evolution of the melting process and thermal field of the paraffin heated vertically ($\theta = 0^\circ$). The melting of paraffin begins near the heated wall after about 10 min and the solid-liquid interface, which is parallel to the heated wall, shows the start of the formation of liquid paraffin wax vertically. The isotherms are in the form of straight lines parallel to the heated wall and are in the range of 40 and 50 °C. The thermal stratification reports a heat transfer dominated by thermal conduction. After 27 min, the melting front advances with a curvature registered at top. This phenomenon results in the gradually development of natural convection in liquid wax. Indeed, the liquid paraffin absorbs the heat from the heated wall and goes up by buoyancy effect. The heat flow accelerates the melting at the top of the thermal cavity and delays it at bottom. Afterwards, natural convection dominates the heat transfer and the curvature of the melting front becomes important. The results show that the mushy zone lies in a temperature range between 48 and 54 °C. It noted that a cap form of paraffin solid develops at the top of cavity. This phenomenon causes the formation of an air pocket on the upper surface which results from the shrinkage phenomenon of paraffin during solidification. The complete melting of the paraffin is achieved after about 5h20. Also, the results show that paraffin melting is accompanied by a volumetric expansion around 3 %.

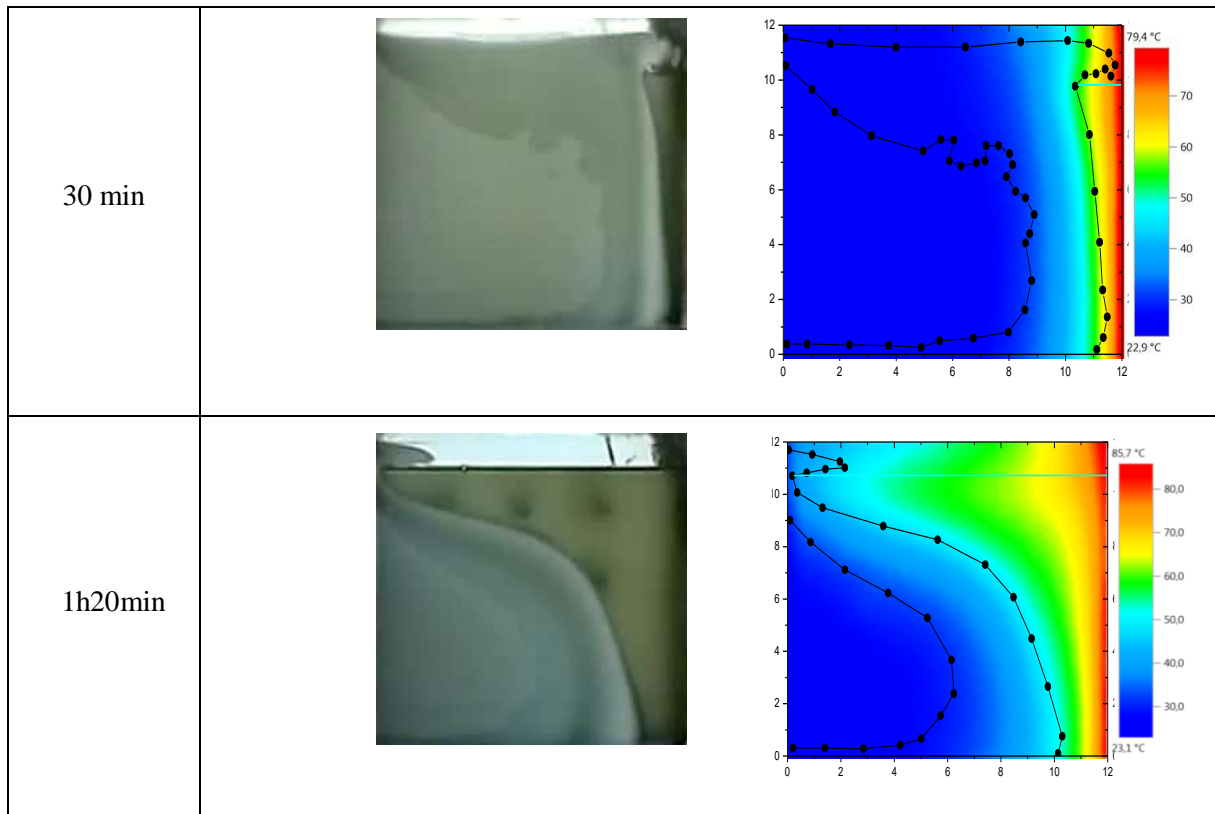


Figure 3. Time evolution of the melting process (left) and thermal field (right) of the paraffin heated vertically.

Figure. 4 shows the photos of the time evolution of the melting process and thermal field of the paraffin heated from bottom. At the start of the melting process, the molten paraffin appears at bottom and the melting front is parallel to the heated wall. The temperature stratification shows that heat transfer is dominated by thermal conduction. After 30 min, the interface remains almost parallel to the heated wall and the liquid phase occupies the entire lower part. However, the fusion front presents instabilities caused by the development of the Rayleigh-Benard natural convection. In fact, natural convection flow develops between two parallel walls (heated wall and melting front) in the form of multi cellular flow patterns (counter-rotating rollers). The number and shape of these rollers depend on the temperature gradient and the size between the two parallel walls. At this time, around eleven counter-rotating rollers are observed in the liquid phase. However, the rise of the melting front leads the increase of the liquid phase height, the number of the counter-rotating rollers decreases. Note that the temperature gradient in the liquid phase is significantly greater than in the solid phase. Thus, the heat convection flow accelerates the heat transfer in the liquid phase. In the solid phase, the heat transfer is poor caused by heat conduction and the low thermal conductivity of paraffin. At the end, the melting front becomes more stable with the presence of a single dominant cell in the liquid phase. The complete melting of the paraffin is achieved after 2h20, it's represent 3 h before the heated vertically case.

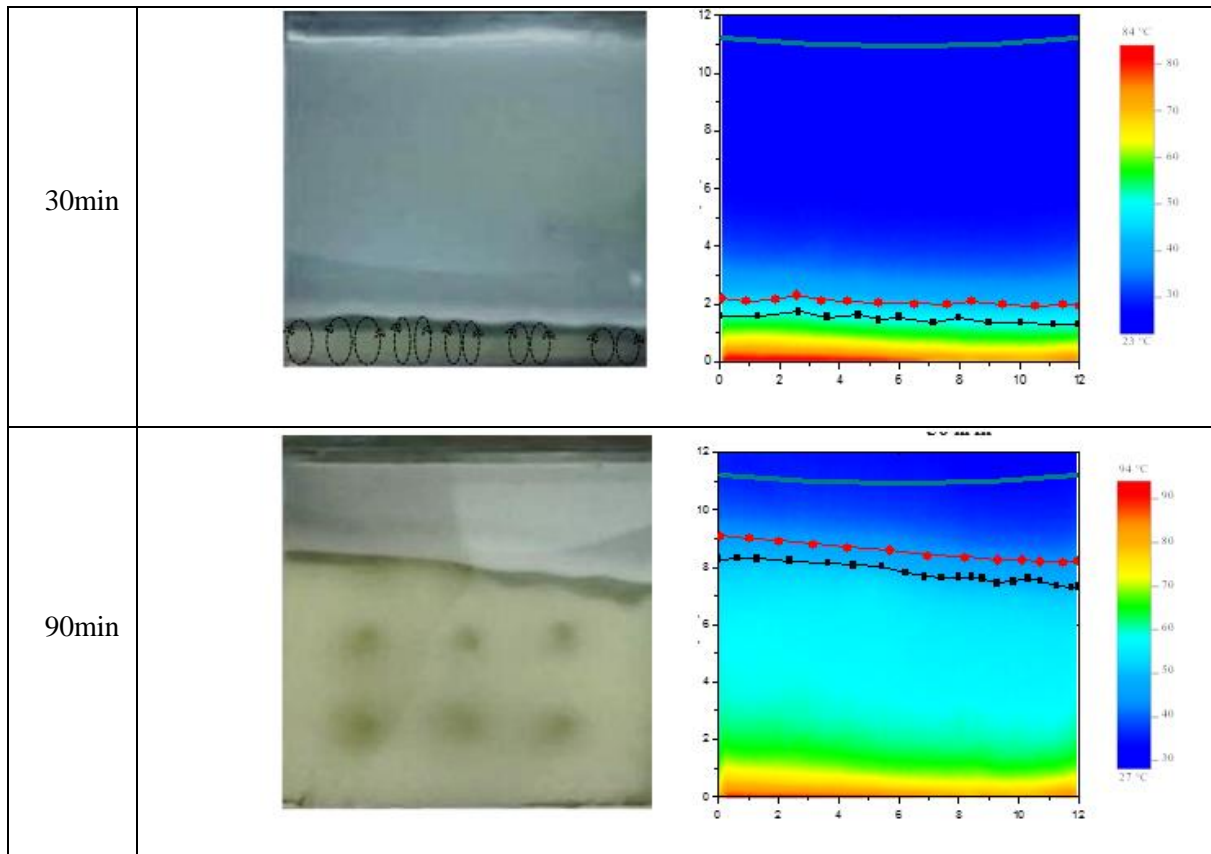


Figure 4. Time evolution of the melting process (left) and thermal field (right) of the paraffin heated by bottom.

Figure 5 shows the photos of the time evolution of the melting process and thermal field of the paraffin heated with an inclination of ($\theta = 45^\circ$). At the beginning, the paraffin begins to melt at the vicinity of the heated wall, there is no convection movement in the liquid phase and the solid/liquid interface is developed parallel to the heated wall. Heat transfer throughout the paraffin is dominated by conduction. Until 30 min, the isotherms are always stratified and the convection flow starts to dominate gradually the heat transfer in the liquid phase. The instability observed at the molten front indicates the presence of multi cellular flow patterns, about six counter-rotating rollers. Thus, the number of rollers has decreased compared to the heated wall by bottom. The instabilities at the fusion front decreases and the number of rollers decreases. The phenomenon of Rayleigh-Benard natural convection existed between heated wall and fusion front is lower than the case of the heated wall by bottom. At 90 min, we notice the acceleration of heat transfer through the right wall of the cavity. This shows the development of a single-cell flow in the liquid phase of paraffin which promotes the creation of the cap phenomenon. Thus, the liquid paraffin tends to goes up along the heated wall (at the right) by the effect of buoyancy and creates mono-cellular heat convection. The heat transfer in the liquid phase remains dominated by a single-cell convection flow until the end of fusion. The complete melting of the paraffin is achieved after 2h35, it's represent 2h35 before the heated vertically case.

Figure. 6 shows the comparison between the time evolutions of the paraffin liquid fraction for different inclinations. The results show that the melting process goes through two different steps. At the beginning, the conduction dominates heat transfer and the melting rate is so identical for different inclinations. After, the effect of convection increases and dominates gradually the heat transfer in the liquid phase. The inclination of the cavity can, depending on the case, accelerates or delays the melting speed. Therefore, it is possible to choose the inclination of the cavity to optimal improve the fusion. We also note that a cavity heated from bottom more accelerates the melting process compared to a cavity inclined by 0° and 45° . In fact, the end of the fusion is reached after 5h20, 2h45 and 2h20 min in the 0° , 45° and -90° inclinations, respectively.

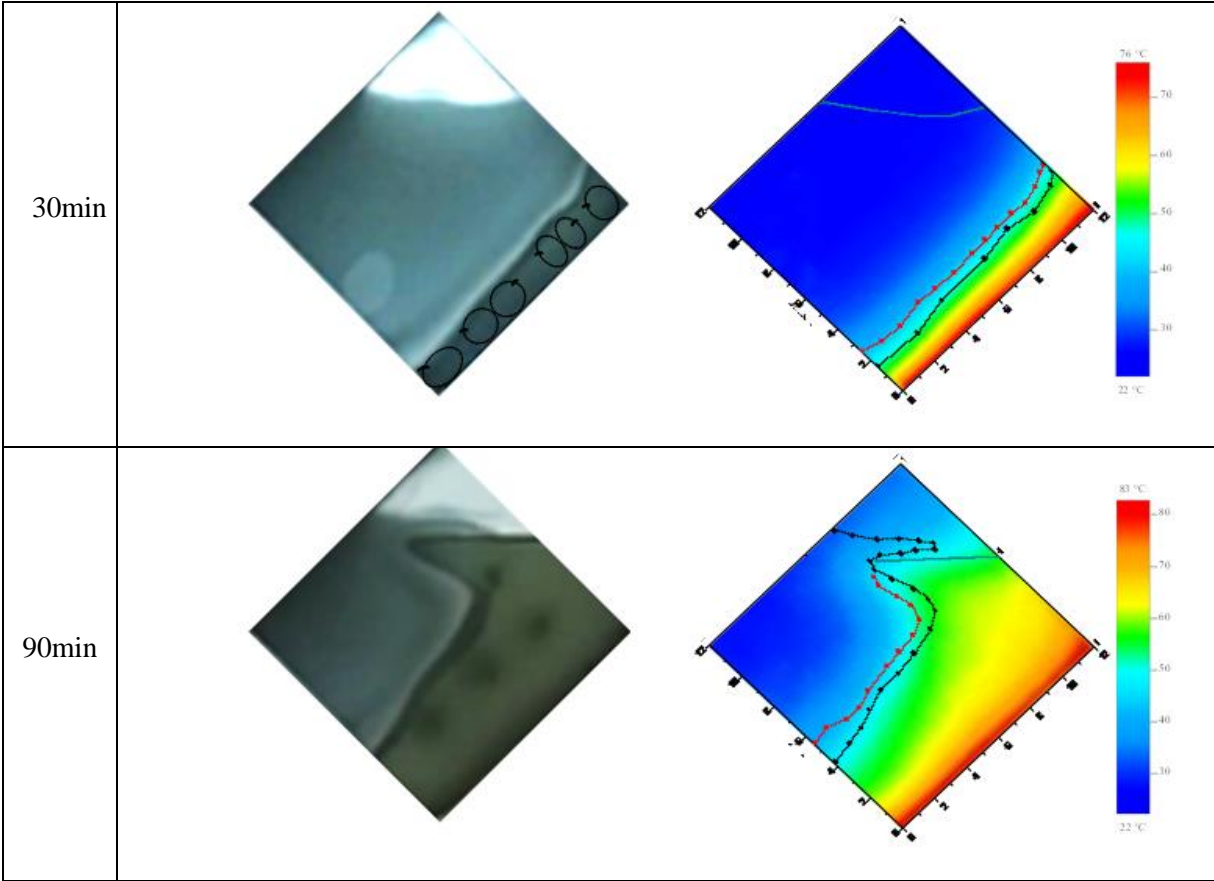


Figure. 5 Time evolution of the melting process (left) and thermal field (right) of the paraffin with an inclination heating

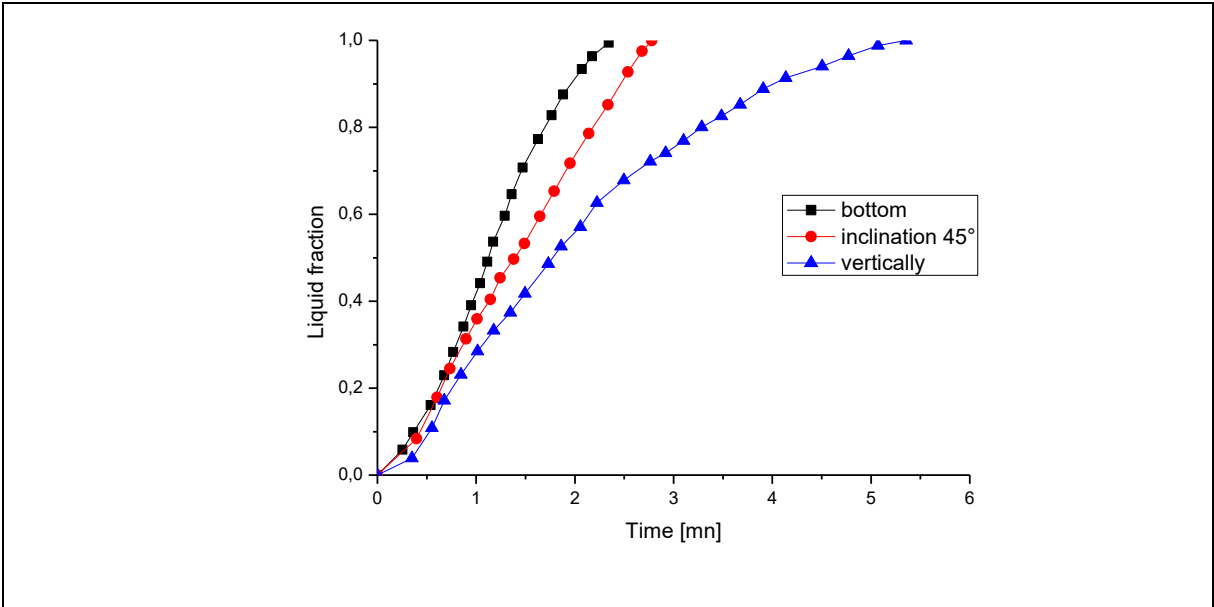


Figure. 6 Time evolution of the volume fraction of liquid

Conclusions

The present work concerns the realization of an experimental study of the fusion process of a phase change material (paraffin) in a square enclosure made of glass. One side is heated and the other sides are insulated. The experimental study allowed drawing the following conclusions:

- Two modes of heat transfer dominate the fusion process, namely conduction and natural convection. Conduction governs fusion at the start of the process and controls the development of fusion in the PCM. During time, the volume of the fusion fraction increases and the fusion is gradually dominated by natural convection.
- A cavity heated from bottom accelerates the overall melting time by about 25 min and 3 hours compared to the cavity inclined at 45 ° and the cavity heated vertically.
- A single vortex dominates natural convection in the cavity heated vertically. The Rayleigh-Benard phenomenon dominates natural convection developed in the cavity heated by bottom. For an inclination of 45 °, the two phenomena react to each other and the number of cells decreases from eleven to six rolls.

References

- [1], Y., Rousse, D.R., Ben Salah, N., Lassue, S. and Zalewski, L. (2011). A review on phase-change materials: Mathematical modeling and simulations, *Renewable and Sustainable Energy Reviews*, **15**, 112–130
- [2] Valan, A.A. and Arun, S.M. (2012). Numerical study on melting of paraffin wax with Al₂O₃ in a square enclosure, *International Communications in Heat and Mass Transfer*, **39**, 8-16
- [3] Korti, A.N. , Tlemsani, F.Z. (2016). Experimental investigation of latent heat storage in a coil in PCM, *Journal of Energy Storage*, **5**, 177–186.
- [4] Senthil, R. and Cheralathan, M. (2017) Natural heat transfer enhancement methods in phase change material based thermal energy storage, *International Journal of Chem Tech Research*, **9**, 563-570
- [5] Madruga, S. and Mendoza, C. (2017). Enhancement of heat transfer rate on phase change materials with thermocapillary flows, *The European Physical Journal Special Topics*, April, **226**(6), 1169–1176
- [6] Madruga, S. and Curbelo B. (2018). Dynamic of plumes and scaling during the melting of a Phase Change Material heated from below, *International Journal of Heat and Mass Transfer*, **126**, 206-220
- [7] Madruga, S., Haruki, N. (2018), Experimental and numerical study of melting of the phase change material tetracosane, *International Communications in Heat and Mass Transfer*, **98**, 163-170