Experimental study on ice formation around finned tubes

Kamal A. R. Ismail, Fatima A. M. Lino

Abstract— **Phase change materials are being used for energy storage, thermal insulation of buildings and equipments due to their high storage capacity and isothermal behavior during the phase change processes. Their low thermal conductivity is a limiting factor for possible wider range of applications. The present study has the objective of investigating fins for enhancing the thermal performance of PCM storage systems. Experimental set-up was designed and instrumented to allow investigating the effects of the cooling fluid temperature, its mass flow rate, and diameter of the fin on the interface position, interface velocity and the solidified mass. The results indicate that reducing the tube wall temperature enhances the solidification velocity and increases the solidified mass. The increase of the mass flow rate has similar effects on the phase change process. The increase of the fin diameter increases the interface position, solidified mass of PCM and the interface velocity.**

Index Terms— *Terms*—**Finned tube, PCM, phase change, solidification.**

I. INTRODUCTION

Phase change materials as thermal energy storage media are attractive due to their high thermal capacity and their isothermal behavior during phase change processes. However, their low thermal conductivity results in a reduced charging and discharging rates implying in long charging and discharging periods. Therefore, effective enhancement methods for phase change heat transfer are essential to make PCM more adequate for practical applications and consequently this directed intensive research to this area.

Zhang and Faghri [1] investigated the enhancement of heat transfer in a latent heat thermal energy storage system by using internally finned tubes while Velraj, et al. [2] analyzed methods to enhance heat transfer in latent heat storage systems. They conducted some experiments to augment heat transfer and reported their findings.

Horbaniuca et al. [3] studied analytically the solidification of PCM around a finned heat pipe immersed in latent heat storage system and calculated the interface positions for different fin numbers, compared and discussed the results.

Silva et al. [4] treated the phase change problem in a rectangular enclosure, used one–dimensional model and the enthalpy method to describe the process and showed that the simplified numerical model can be used to predict the dynamic performance during phase change.

Stritih [5] studied experimentally the heat-transfer characteristics of a latent-heat storage unit with a finned surface, compared the results with those of a plain surface and concluded that finned surface was more effective during the phase change processes. Similarly, Liu et al. [6] reported the results of a study on a heat pipe heat latent heat storage. They operated the storage system in three different modes; charging, discharging and simultaneous charging/discharging. Their experimental results showed that the storage system can efficiently store and release thermal energy.

A numerical and experimental investigation was realized by Kayansayan and Acar [7] on a cold energy storage system involving a fluid flow finned tube surrounded by PCM. They validated their numerical predictions with experimental measurements and reported good agreement.

Mettawee and Assassa [8] carried out experiments to enhance the thermal conductivity of paraffin wax by embedding aluminum powder in it. They reported charging time reduction of approximately 60%. In the discharging process they reported a useful heat gain increase when adding aluminum powder in the wax as compared to the case of pure paraffin wax. A similar study was reported by Jegadheeswaran and Pohekar [9] and their results indicated a significant improvement in the performance of the storage unit with dispersed high conductivity particles.

Numerical studies were realized by Al-Abidi et al. [10], Jmal and Baccar [11], Ismail et al. [12] and Ismail et al. [13], on heat transfer enhancement by using internal and/or external fins for PCM melting in a heat exchanger. Their results indicated that the complete melting time was affected by the number of fins, fin length, fin thickness, Stefan number, and the phase change material.

Wang et al. [14] investigated the efficiency and heat storage rate in a shell and finned tube latent heat storage unit and found that the fin pitch, fin height and the fin thickness affected the efficiency and the heat storage rate of the unit.

The objective of the present paper is to investigate the effects of radial fins on the enhancement of solidification and reduction of time for complete solidification during the phase change process around tubes. Experimental rig is designed and instrumented to allow investigating the effects of the fin geometry and temperature and fluid flow rate of the working fluid on the solidified mass and the time for complete phase change.

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II. EXPERIMENTAL ANALYSIS

In order to validate the model and the numerical predictions an experimental set up is constructed and instrumented as shown in Fig. 1. The test set up is composed of a compression

Kamal A. R. Ismail, State University of Campinas, Faculty of Mechanical Engineering, Department of Energy, Mendeleiev street, 200, Postal Code 13083-860, Cidade Universitária "Zeferino Vaz", Barão Geraldo, Campinas, SP, Brazil, Phone: +55 19 35213376

Fatima A. M. Lino, State University of Campinas, Faculty of Mechanical Engineering, Department of Energy, Mendeleiev street, 200, Postal Code 13083-860, Cidade Universitária "Zeferino Vaz", Barão Geraldo, Campinas, SP, Brazil, Phone: +55 19 35213376

refrigerant circuit, secondary fluid circuit, coiled tube heat exchanger submersed in the secondary fluid tank, the test section of the finned tube which is connected to the secondary fluid circuit. The secondary fluid is Ethanol cooled by the refrigerant flowing through the coiled tube heat exchanger and its temperature and mass flow rate are controlled as required. The test section is of rectangular shape built from 15 mm thick acrylic sheet with the test tube extended across the test section filled with PCM (water) whose initial temperature can be varied as desired. High resolution digital camera is used to photograph the finned tube and the reference scale to be used to convert the image dimensions to real values as will be explained later. Calibrated K type thermocouples are fixed at entry and exit of the finned tube, in the PCM test tank, along the finned tube and in the secondary fluid tank. The thermocouples were calibrated to within ±0.5 ^{o}C, image conversion precision to within ±0.1mm while the mass flow rate (measured by a calibrated orifice plate) to within $\pm 10^{-4}$ kg/s.

Figure1 Experimental rig.

Measurements were usually taken when the desired testing conditions were achieved, that is the temperature of the working fluid in the finned tube, temperature of the Ethanol tank, temperature of the PCM, and the mass flow rate of the secondary fluid. Under these initial conditions the chronometer is started after all initial conditions are registered. During the first two hours each 5 minutes period all measurement points are registered and a photograph of the finned tube is taken. During the third hour measurements are registered each 15 minutes interval. After that the time interval is increased to 30 minutes until the end of the test. The test is considered terminated when no change in temperature or interface position is registered during three successive time intervals.

A typical photograph of the finned tube is shown in Fig. 2 where the interface position is tracked and converted to real dimension by using the free available commercial program "Tracker".

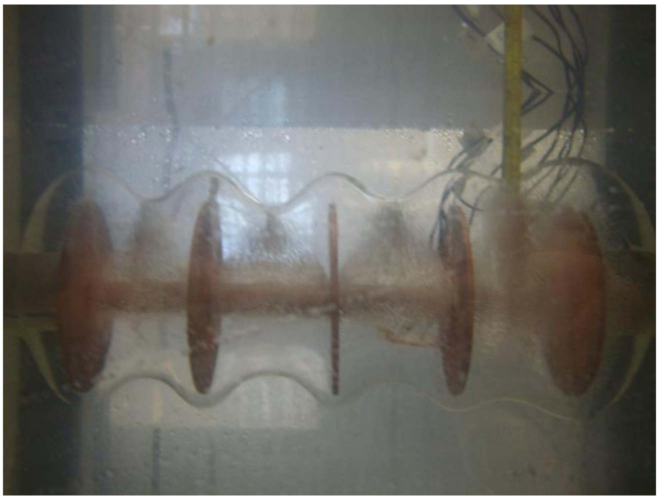

Figure 2 Photograph of the finned tube showing the solidified PCM and thermocouples for temperature measurements.

III. RESULTS AND DISCUSSION

A. *Variation of interface position and velocity with time*

Fig. 3 shows the variation of the interface position with time for a fin of 120 mm diameter and for different mass flow rates of the working fluid. Initially the solidification process is fast because of the high temperature gradient between the tube wall and the liquid PCM. With the increase of time more PCM is solidified increasing the thermal resistance and relatively slowing down the heat exchange rate between the working fluid and the PCM and the curve inclination decreases continually as can be seen. The effect of increasing the mass flow rate is to increase the heat transfer coefficient on the internal side of the tube and hence increasing the rate of PCM solidification. Similar result is shown in Fig. 4 for the case of fin diameter of 40 mm.

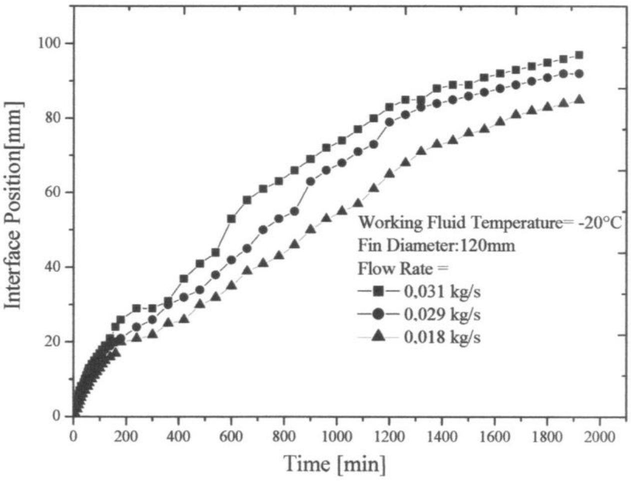

Figure 3 Variation of the interface position as function of time for working temperature of -20°C.

Fig. 5 shows variation of the interface velocity with time for the case of fin with 40 mm diameter and for different mass flow rates of the working fluid. As can be seen initially the interface velocity is large due to low initial thermal resistance and as the time goes by the thermal resistance is increased due to the formation of PCM solid layer and hence the heat flow rate is reduced and consequently the interface velocity. This process continues leading to continuous reduction of the interface velocity as indicated. Similar result is shown in Fig. 6 for the case of fin diameter of 180 mm.

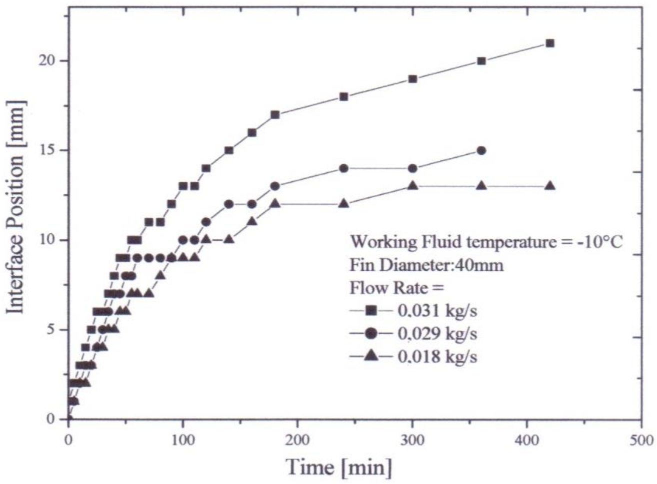

Figure 4 Variation of the interface position as function of time for working temperature of -10°C.

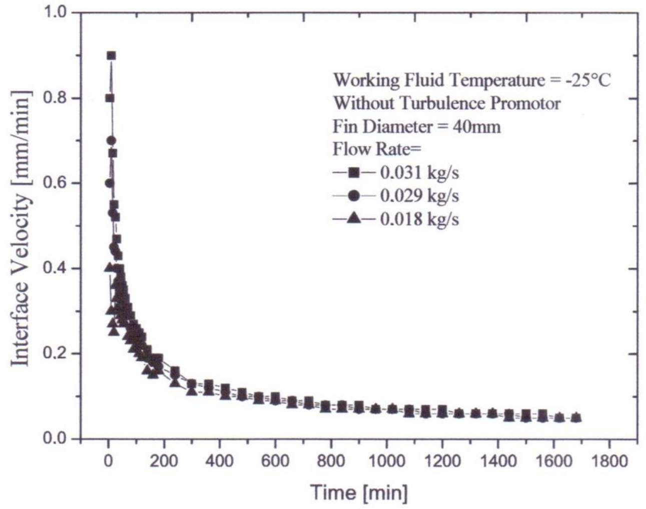

Figure 5 Variation of the interface velocity with time.

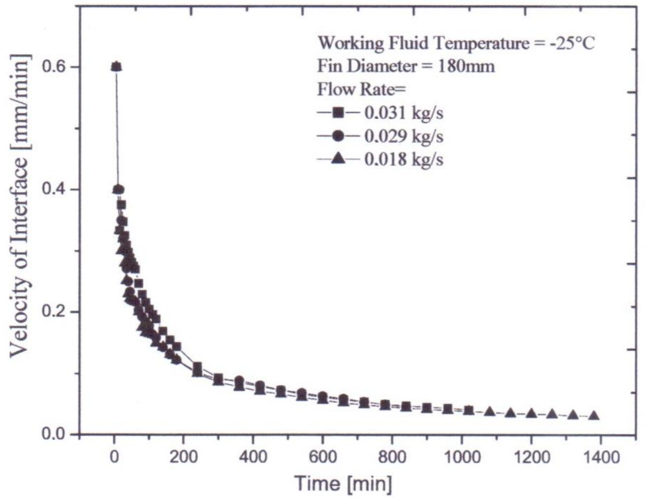

Figure 6 Variation of the interface velocity with time.

B. Effect of the mass flow rate of the cooling fluid

The effect of the mass flow rate of the cooling fluid on the interface position for the case of fin diameter of 120 mm is shown in Fig. 7. As can be seen the increase of the mass flow rate increases the heat transfer coefficient of the internal flow due to the increase of Reynolds number and this increases the interface position.

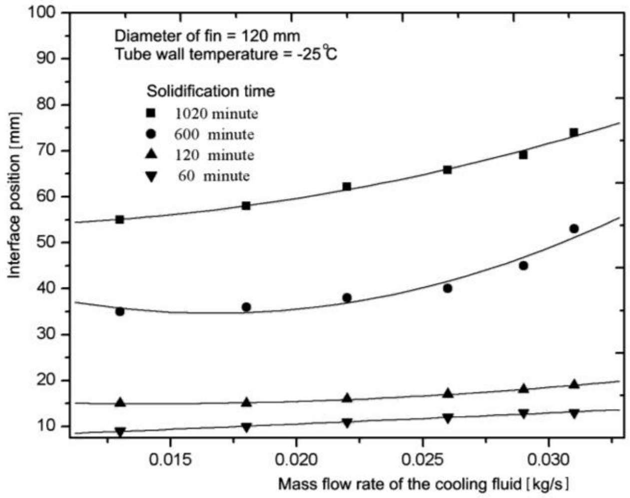

Figure 7 Effect of the mass flow rate of the cooling fluid on the solidified mass for a fin of 120 mm diameter.

The effect of the mass flow rate of the cooling fluid on the interface velocity is shown in Fig. 8 for case of diameter of fin of 40 mm, respectively. As can be seen increasing the mass flow rate increases the internal flow Reynolds number and this increases the heat transfer coefficient on the internal side of the tube. This leads to increasing the global heat transfer coefficient and consequently the interface velocity and the solidification rate. Lowering the cooling fluid temperature enhances the interface velocity since it increases the temperature gradient between the flowing fluid and the PCM which increases the heat flow rate and hence increases the interface velocity.

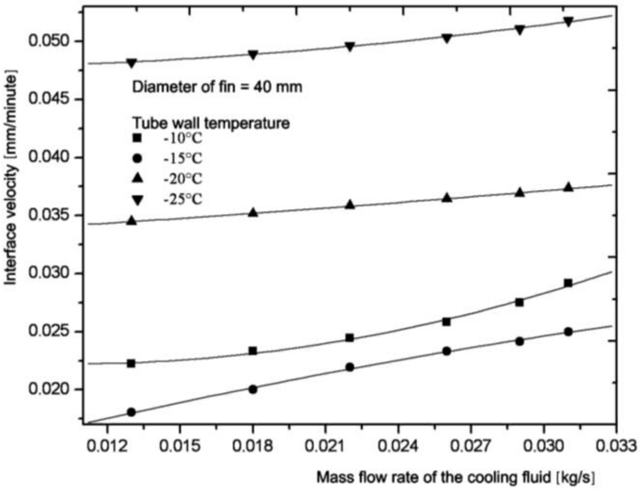

Figure 8 Effect of the mass flow rate of the cooling fluid on the interface velocity for a fin of 40 mm diameter.

The effect of variation of the mass flow rate of the cooling fluid on the time for complete solidification is shown in Fig. 9. As can be seen the increase of the mass flow rate of the cooling fluid increases the internal heat transfer coefficient and consequently the overall heat transfer coefficient. This leads to increasing the interface velocity and reducing the time for complete solidification.

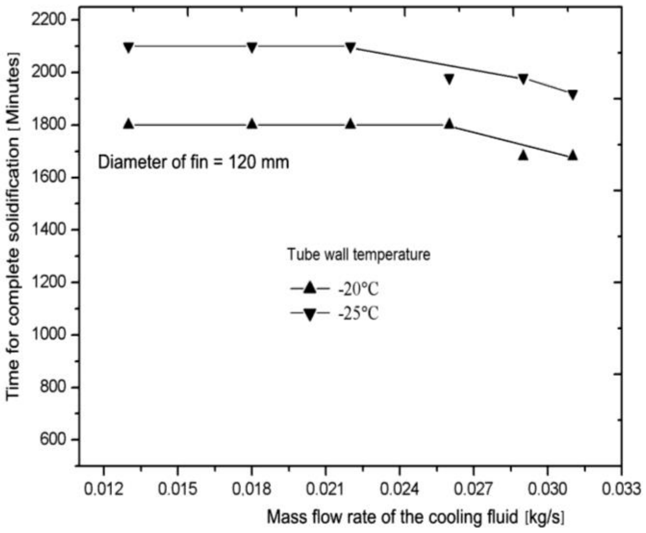

Figure 9 Effect of the mass flow rate of the cooling fluid on the time for complete solidification for a fin of 120 mm diameter.

C. *Effect of the Tube Wall Temperature*

The effect of the temperature of the cooling fluid on the the interface position can be seen in Fig. 10 for fin diameter of 120 mm. As can be seen reducing the temperature of the cooling fluid increases the temperature gradient between the tube wall temperature and the PCM, which increases the interface velocity and consequently the interface position.

Fig. 11 shows the effect of varying the tube wall temperature on the interface velocity. As can be seen reducing the tube wall temperature increases the temperature gradient between the tube wall and the PCM. This increases the heat transfer rate and consequently the interface velocity. One can also observe that increasing the mass flow rate of the cooling fluid while keeping its temperature constant increases the Reynolds number of the flow inside the tube. This increases the internal heat transfer coefficient and consequently the overall heat transfer coefficient, increases the heat transfer rate and the interface velocity as can be seen in Fig. 12.

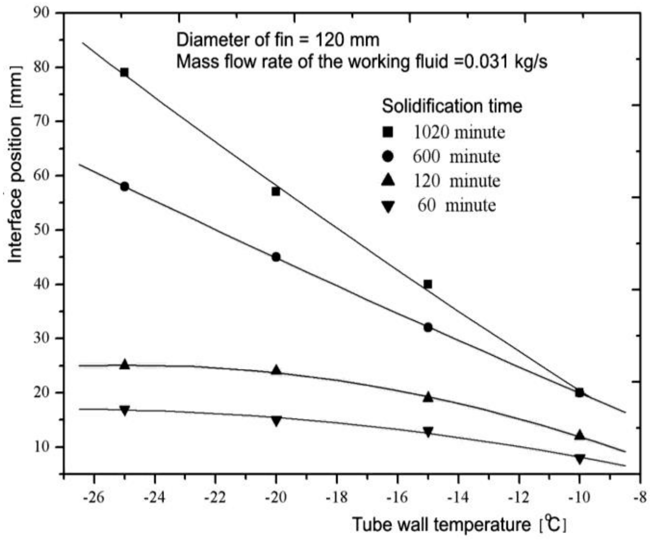

Figure 10 Effect of the temperature of the cooling fluid on the interface position for a fin of 120 mm diameter.

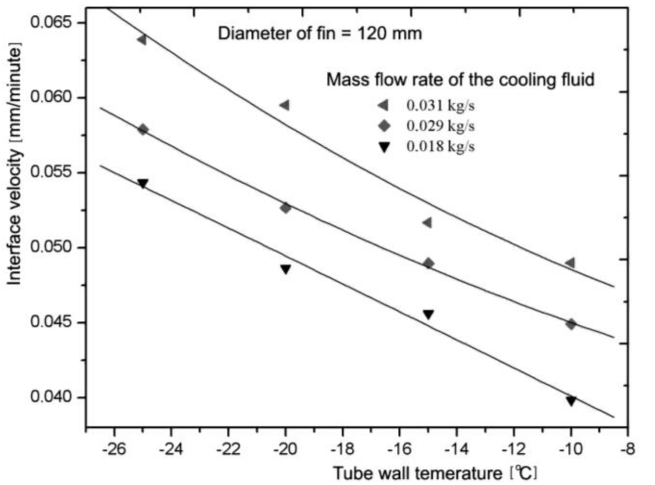

Figure 11 Effect of the temperature of the cooling fluid on the interface velocity for a fin of 120 mm diameter.

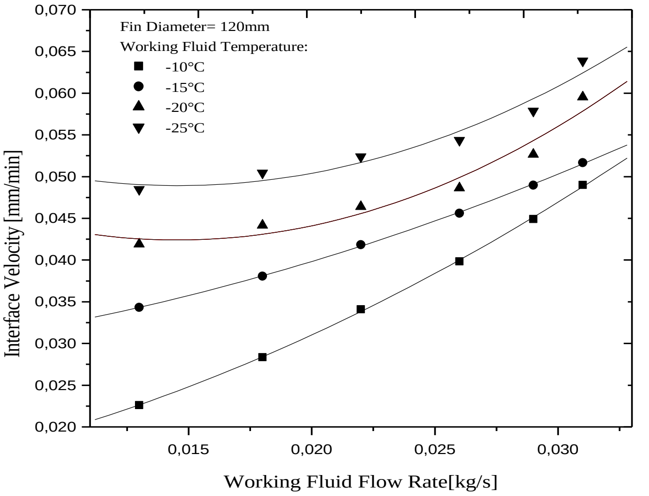

Figure 12 Effect of the working fluid flow rate on the interface velocity.

Fig. 13 shows the effect of varying the fin diameter on the interface position. The increase of the fin diameter increases the heat transfer area in contact with the PCM and this enhances the heat transfer rate between the combined tube-fin arrangement and the PCM causing causing increase of the interface position.

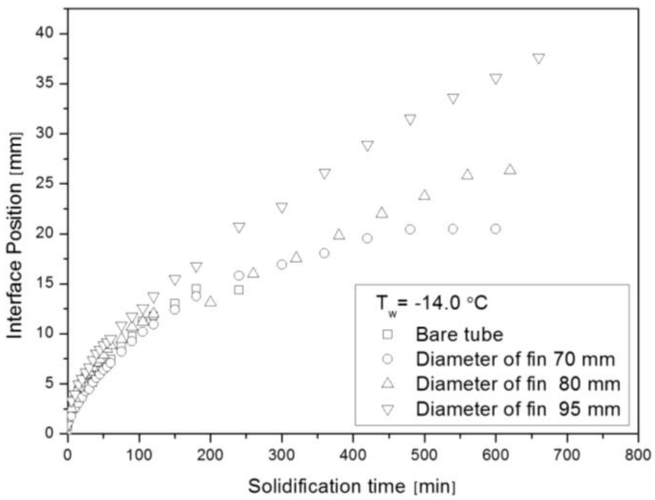

Figure 13 Variation of the interface position with the fin diameter.

With the increase of time more PCM is solidified causing increase of the thermal resistance between the tube wall and the PCM. This leads to decreasing the heat transfer rate and gradually decreasing the advance of the phase change front, Fig. 13, resulting in continuous reduction of the interface velocity as can be seen in Fig. 14.Fig. 15 shows the variation of the solidified mass due to variation of the fin diameter. As can be seen the increase of the fin diameter enhances the solidified mass due to the increase of the heat transfer area in contact with the PCM.

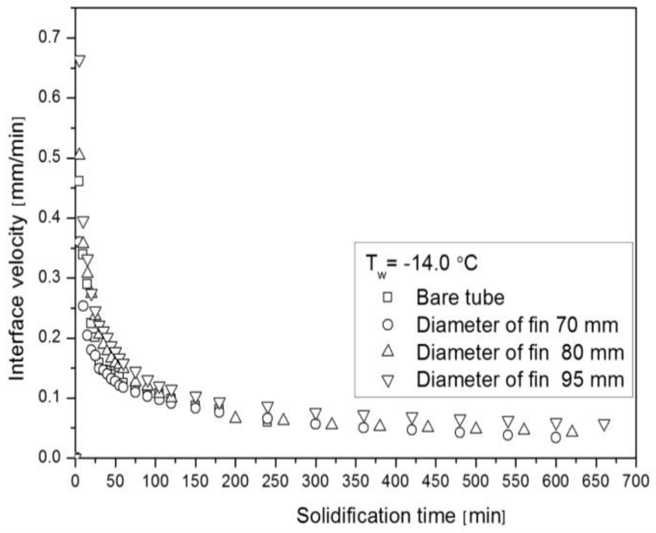

Figure 14 Effect of the fin diameter on the interface velocity.

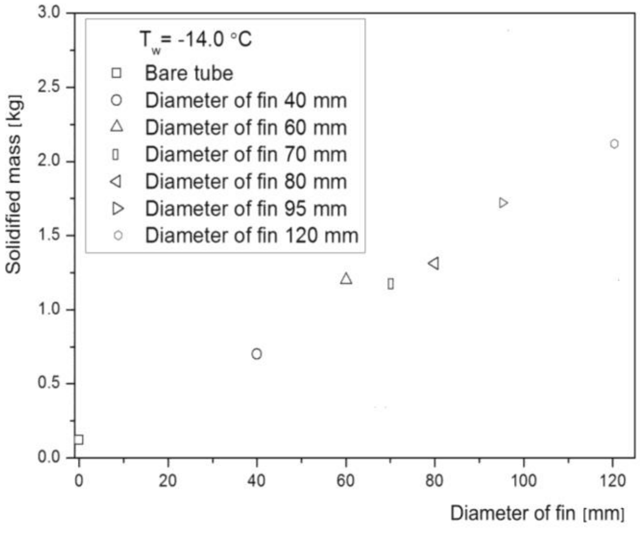

Figure 15 Variation of the solidified mass with the fin diameter.

IV. CONCLUSIONS

Solidification of water around a tube with radial fins was investigated experimentally to illustrate the effects of the fin geometry and the working conditions of the cold fluid on solidification of PCM. Experimental measurements revealed that increasing the fin diameter increases the interface position, velocity and solidified mass. Reducing the temperature of the cooling fluid and increasing its mass flow rate enhance the interface position and increase the solidified mass.

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Kamal A. R. Ismail is a full professor of Mechanical Engineering since 1980, he has a B.Sc. and M.Sc. in Mechanical engineering and a Ph. D. in aeronautical Engineering. He authored 22 books in undergraduate and research in instrumentation, aerodynamics, energy storage, heat transfer with phase change, and aircraft performance, Compressible flow and aerodynamics and undergraduate teaching equipments. He authored and co-authored 358 articles in scientific Journals, conferences and congresses. Current interests includes engineering education while current research areas include energy storage systems, phase change heat transfer e applications, aerodynamics and hydrodynamics (small wind turbines, hydrokinetic turbines, UAV, small propellers, contra-rotating propellers).

Fatima A. M. Lino has a M.Sc. in Energy Planning and Doctorate degree in Mechanical Engineering, coauthor of 5 books in Engineering, 26 articles in specialized scientific journals and congresses. Current research interests include solid waste management and treatment, wastewater management, Waste-to-Energy projects, renewable energy resources, solar energy systems, PCM and applications in storage systems and buildings