ENHANCEMENT OF PHASE CHANGE ALONG THE LONG TUBES OF A LATENT HEAT STORAGE UNIT

by

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This paper presents the results of an experimental study on the solidification along a long horizontal tube submersed in liquid phase change material (PCM) and the enhancements due to the use of a turbulence promoter. The experimental rig consists of a long copper tube fixed coaxially inside a larger PVC tube filled with liquid PCM (water). The working fluid at a temperature lower than the PCM phase change temperature flows inside the copper tube provoking the solidification of PCM over its surface. The PVC tube is fitted with three windows along its length for observation and photographing the solidified PCM interface. The tests were realized for values of Reynolds number from 741 to 2280 and temperatures varying from –5 to –20 ºC with and without turbulence promoter showed their effects on the interface position, the solidification velocity and how they were enhanced because of the turbulence promoter.

Key words: *solidification enhancement, phase change, energy storage, turbulence promoter, phase change material, thickness distribution*

Introduction

Energy storage is important in many thermal systems such as energy conservation systems, intermittent energy generation and/or utilization where the energy demands do not coincide with the energy generation. Different thermal energy storage systems of latent heat type are widely preferred because of the high energy density and the small temperature drop during the charge and the discharge processes. There are many design concepts for the latent heat storage but the shell and tube type seems to be more developed from the engineering point of view.

Heat transfer in the thermal energy storage systems can be represented by a transient conjugate phase change-forced convection model. Since phase change heat transfer is non-linear due to the moving solid-liquid interface, analytical solutions are only available for a few moving boundary problems with simple geometry and simple boundary conditions. Numerous approximate methods were developed and applied to a variety of geometries and boundary conditions.

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Because of the difficulties and the associated limitations of the analytical and semi analytical solutions, many numerical approaches were devised to achieve adequate representation of the specific phase change problem and obtain sufficiently accurate solution for heat transfer in the latent thermal storage units. The most common methods used for solving phase change problems are the enthalpy methods and temperature-based equivalent heat capacity methods. Esen and Ayhan [1] reported the results of a model developed to describe the performance of a storage tank with the phase change material (PCM) contained in a set of tubes while the working fluid flows parallel to them. In a subsequent work [2] Esen *et al.* optimized two storage geometries, the one described above and another where the working fluid passes in the tubes submersed in the PCM. Esen [3] presented the results of a study where the PCM storage tank was used in conjunction with a heat pump for space heating application. Other methods have been used by many authors as can be verified from the literature reviews, as in [4- 6] and many others.

There are many experimental studies and reports on the solidification of PCM into and around encapsulating elements, but very little was found about phase change along long tubes. Ismail *et al.* [7] realized a numerical and experimental study on the solidification of PCM around a vertical axially finned isothermal cylinder. In the numerical study they used a pure conduction model, the enthalpy approach and finite volume discretization technique. They validated their numerical predictions with experiments and found good agreement.

Mohamed [8] reported the results of a study on the solidification of PCM on vertical cylindrical surface with injected air bubbles to enhance the heat transfer rate and ice layer growth. The effect of the of air bubbles agitation was found to increase the ice layer growth rate and the solidification front velocity by about 20-45% and the energy stored increased by 55-115%.

A very interesting work was reported by Habeebullah [9] in which he presented the results of experimental study on the solidification of ice around long tubes. He found that the axial growth rate is distinct at low values of the coolant Reynolds number and short freezing times. The axial slope of the ice thickness showed moderate dependency on time but varied with coolant flow rate, and with Stanton and Biot numbers.

Kalaiselvam *et al.* [10] reported the results of experimental and analytical investigation of solidification and melting characteristics of PCM inside cylindrical encapsulation. They presented analytical solutions to determine the position of the interface and complete phase change time and compared their results with experiments validating the models and the numerical predictions

Abdel-Rehim [11] reported the results of a study on a packed bed storage system of spherical PCM capsules and obtained results for the charging and discharging modes. The time for complete charging process was reduced by the increase of the working fluid entry temperature and its mass flow rate, while the complete solidification time was found to be longer compared to the melting time. The charging and discharging rates were found to be higher for PCM capsules of smaller radius compared to those of larger radius. Ezan, *et al.* [12] reported the development of a method to determine the solidification interface in a thermal storage unit by measuring the electric conductivity changes during the PCM phase change. The precision of the method is found to be 3% in relation to the photography method.

As can be seen the literature on phase change along long tubes is scarce and most of the publications treat solidification and fusion external to tubes and does not take into account the practical implication of the length of the tubes and the shape of the solidified PCM along the tube length.

This paper presents the results of a study on the solidification process along long tubes and how the solidified PCM and the solidification velocity are affected by the variation of the mass flow rate of the secondary working fluid and by its temperature.

To enhance the PCM solidification process a helical coil was inserted in the horizontal copper tube and the solid-liquid interface and the solidification velocity were investigated.

The experimental rig

The experimental rig is composed of the test section where a horizontal copper tube is installed, a compression refrigeration system working with Freon R 22 and a heat exchanger to cool the secondary working fluid to the desired temperature. The experimental rig is shown in fig. 1.

The test section is made up of a copper tube of 20 mm internal diameter 22 mm external diameter and 2200 mm length. The copper tube is installed concentrically between the two end flanges of a PVC tube of 290 mm internal diameter, 300 mm external diameter and 2100 mm length. The rest of the copper tube length passes through the PVC end flanges where it is connected to the secondary fluid flow circuit as shown in fig. 1. The liquid PCM (water) is placed in the PVC tube. The test section is fitted with three windows for observation and photographing the interface solid-liquid. The windows are localized at 0.68, 1.18, and 1.65 m from the entry section. A high resolution digital camera is used to photograph the interface with a precision linear scale fixed near the copper tube. The photographs of the interface position at the three windows are digitalized and the real physical position of the interface is obtained by comparison with the linear precision scale.

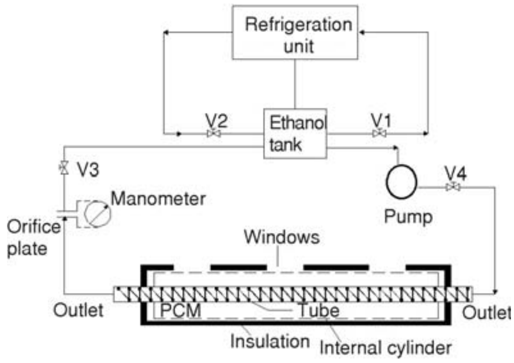

Figure 1. Experimental rig

A compression refrigeration system working with R22 circulates the refrigerant through a coiled tube submersed in a tank full with the ethanol used as a secondary working fluid. The secondary fluid is pumped from the ethanol tank, circulated in the copper tube and returned back to the ethanol tank. The temperatures at entry, at exit and at seven positions along the copper tube are measured by calibrated thermocouples to within 0.5 °C.

When the cold secondary fluid circulates in the copper tube it exchanges heat with the liquid PCM in the PVC tube forming a layer of solidified PCM over the surface of the cooper tube. The flow of the secondary working fluid is adjusted manually by a precision control valve and measured by a calibrated orifice plate. Table 1 shows the uncertainties of the measured parameters while tab. 2 shows the thermo physical properties of the PCM (water).

Table 1. Uncertainty of the measured parameters

Parameters	Uncertainty
Temperature	±0.5 °C
Flow rate	$\pm 2.1510^{-6}$ m^3/s
External diameter	±0.01 mm
Ice thickness, [mm]	±0.1 mm

The tests were realized according to the following procedure:

(1) The liquid PCM at nearly the phase change temperature 0.5 ºC is pumped to the PVC concentric tube until the copper tube is equally covered on all sides.

Table 2. Thermo physical properties of the PCM (water)

Variables	Units
Density	998.2 kg/m^3
Kinematic viscosity	$1 \cdot 10^{-6}$ m²/s
Latent heat of solidification	353.52 kJ/kg
Solidification temperature	0 °C
Specific heat	4182 J/kgK
Thermal conductivity	0.6 W/mK

(2) The thermocouples fixed at entry and exit of the copper tube and along its length are connected to the data acquisition system and the camera system is adjusted and focused on the copper tube. Both the main refrigeration system and the secondary fluid circulating pump are switched on with the entry valve of the ethanol cooling system open and its temperature control set at the required value. When the temperature of the ethanol is stabilized, its flow rate is adjusted to the value required for the test.

(3) The temperature measurements and photographs are registered automatically each 5 minutes during the first hour, then at intervals of 30 minutes during the next 5 hours, then at each hour until the end of the experiment. The experiment is finalized when the last two measurements of the interface position indicate equal values to within 0.5 mm. The time counted since the start of the experiment is considered as the time for complete solidification. The system is then shut down to change the test conditions and restart a new test.

(4) To enhance the heat transfer between the circulating secondary flow and the PCM, a turbulence promoter is tightly placed inside the copper tube. The promoter is made of a stainless steel wire of 0.5 mm diameter twisted in coil form of 19 mm diameter and 95 mm pitch as can be seen in fig. 2. This promoter causes a local disturbance, increases the local turbulence and consequently the local heat transfer coefficient.

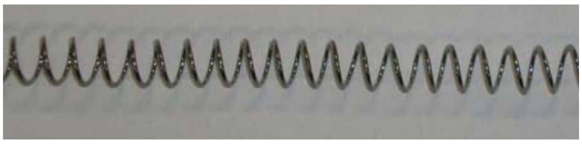

Figure 2. Turbulence promoter used in the experiments

Results and discussion

Figure 3 shows the variation of the position of the interface as function of time for the test conditions of temperature and flow rate secondary fluid of –15 ºC and 70.0 ml/s, respectively.

Initially the temperature of the secondary fluid at entry is –15 ºC and the PCM is at ±0.5 ºC. This corresponds to the maximum temperature gradient, maximum heat transfer rate between the circulating secondary flow and the liquid PCM forming a layer of solid PCM over the copper tube external surface which increases the thermal resistance between the PCM and circulating fluid. As the time passes, more PCM is solidified, increasing the thermal resistance and reducing the heat transfer rate from the liquid PCM to the circulating fluid reducing the solidification rate of the PCM. After a relatively long time, the thickness of the solidified layer is so large and nearly the solidification process stops.

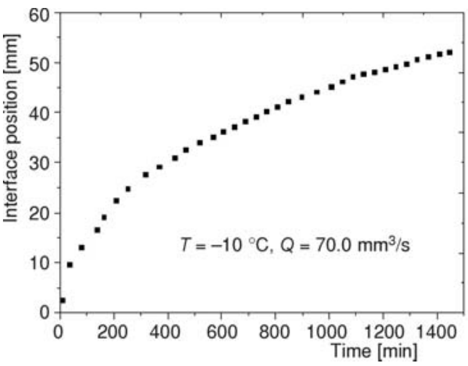

Figure 3. Variation of the interface position with time for a long tube

The results of fig. 3 are obtained from the photographs taken during the tests. These photographs were digitalized and by comparison with the precision linear scale fixed near the copper tube the real interface position was determined. Initially the inclination of the curve is steep, and gradually decreases, where near the end of the process the inclination is almost zero and the solidification process stops.

Figure 4 presents the variation of the interface velocity with time. The values of the interface velocity shown in fig. 4 are calculated from the digitalized real interface position and the corresponding time. Initially, when the solidified layer is relatively thin, the thermal resistance is small and the heat transfer rate is high leading to high solidification velocity. As the solidified layer increases with time, the thermal resistance also increases and this reduces the rate of heat transfer, and consequently the interface velocity. Towards the end of the process, the thermal resistance is so high that the rate of heat transfer is very small resulting in a small interface velocity.

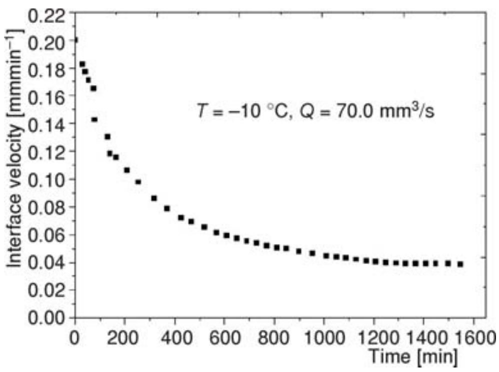

Figure 4. Variation of the interface velocity with time

Figures 5 and 6 show the variation of the position of the interface at three positions along the copper tube, where position 1(window 1) refers to the point near the entrance of the cold secondary fluid and position 3 (window 3) refers to the point near exit.

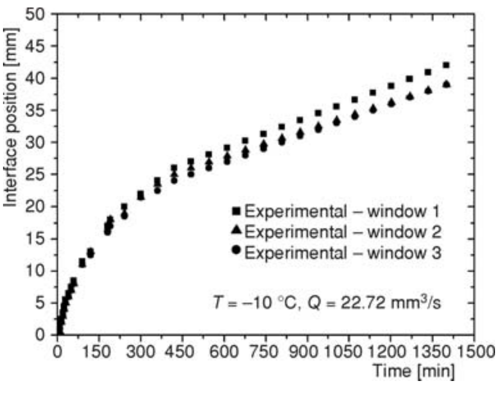

Figure 5. Variation of the interface position at three axial positions along the tube

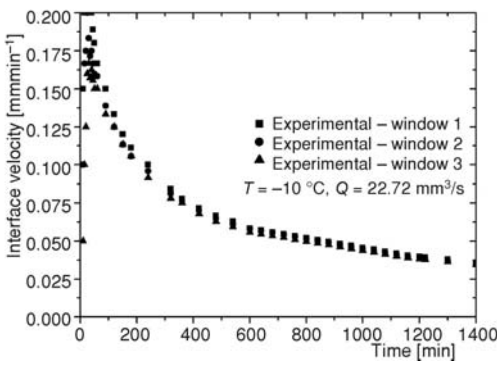

Figure 6. Variation of the interface velocity at three axial positions along the tube

As can be seen the thickness distribution along the tube is nearly conical bigger at entry of cold secondary fluid and decreases towards the tube exit. At entry the temperature gradient is bigger than at exit and hence the heat transfer from the liquid PCM to the working fluid is bigger than that at exit and consequently more solidified mass at entry as can be verified from fig. 5.

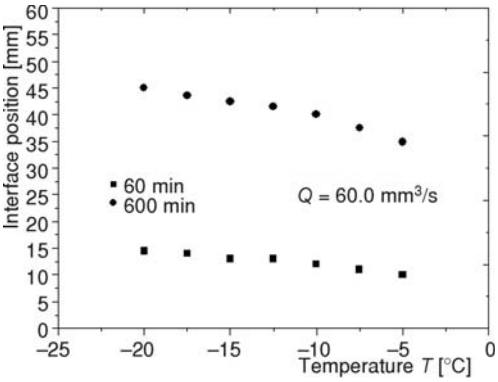

Figure 7. Variation of the interface position as function of the secondary fluid temperature

The interface velocity calculated at the first window is more than that calculated at the third window due to the fact that the temperature gradient is higher at the first window; consequently the heat transfer rate, the interface position and the interface velocity are higher as can be seen in fig. 6.

Figure 7 shows that the decrease of the temperature of the working fluid increases the solidified mass thickness which can be attributed to the temperature difference between the working fluid and the PCM.

One can observe that the lower the temperature of the working fluid the higher the interface velocity. A low working fluid temperature results in a high temperature gradient which increases the heat removal rate from the liquid PCM and consequently increases the interface velocity as can be observed in fig. 8.

Figure 9 shows the effect of varying the working fluid flow rate on the position of the interface. The increase of the flow rate of the working fluid increases the Reynolds number, and increases the film coefficient on the internal side of the tube. This increases the overall heat transfer coefficient and the heat removal rate leading to more solidified mass. As can be seen the effect of varying the flow rate of the working fluid on the interface position is extremely small.

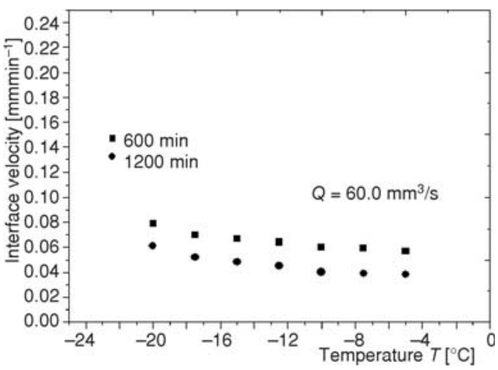

Figure 8. Variation of the interface velocity as function of the secondary fluid temperature

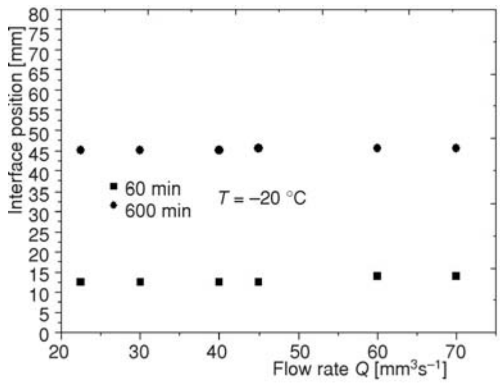

Figure 9. Variation of the interface position with the secondary fluid flow rate

Figure 10 shows the effects of the variation of the secondary fluid flow rate on the interface velocity. Again as mentioned above this effect is relatively small.

To investigate the effects of the turbulence promoter on the solidified mass, the position and velocity of the interface, a helical coil is tightly inserted into the copper tube.

Figure 11 shows the effect of the turbulence promoter on the position of the interface. As can be seen the promoter enhances the position of the interface. This increase is due to the local agitation and turbulence which increase the heat transfer coefficient and consequently the heat removal rate between the liquid PCM and the circulating secondary fluid.

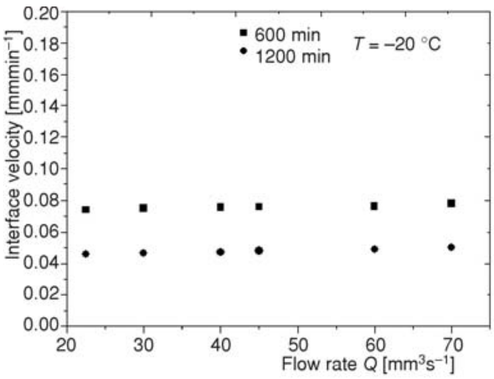

Figure 10. Variation of the interface velocity with the secondary fluid flow rate

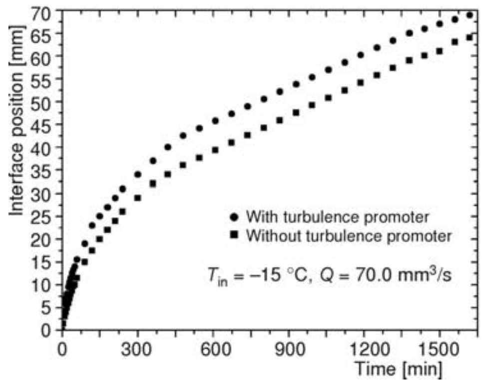

Figure 11. Effect of the turbulence promoter on interface position

Figure 12 shows the beneficial effect of the turbulence promoter on increasing the interface velocity. This increase is due to the increase of the heat transfer coefficient and consequently the increase of the rate of heat transfer between the liquid PCM and the circulating secondary fluid flow.

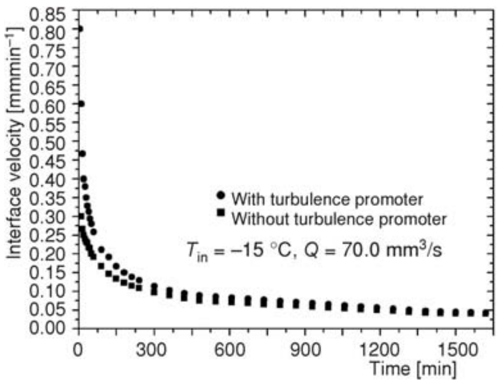

Figure 12. Effect of the turbulence promoter on interface velocity

Conclusions

Based upon the results of the present investigation, it is possible to make the following conclusions.

- The decrease of the temperature of the secondary fluid increases the interface position, the solidified mass and the interface velocity.
- The increase of the mass flow rate increases moderately the interface position and the interface velocity.
- The turbulence promoter is found to increase the local interface position due to the increased turbulence, which increases the local heat transfer coefficient and consequently the rate of heat removal from the liquid PCM.

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