EXPERIMENTAL STUDY OF FUSION OF PCM IN SPHERICAL GEOMETRY

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Abstract. *The main objective of this study is to experimentally investigate the fusion process of PCM in a spherical geometry subject to constant wall temperature and obtain experimental correlations for the time for complete fusion and the involved parameters of the process. These correlations are important for discharge models development for PCM fixed bed storage. In the experimental treatment, four spherical shells of 35, 76, 106 and 131 mm diameter were used at four initial temperatures ranging from -20°C to -5°C and under constant external wall temperature of 10°C, 18°C, 25°C. Water and mixtures of water and polyethylene glycol in percentages ranging from 10% to 50% were used as PCM. The results show that the increase of the diameter of the spherical shell increases the time for complete fusion, the increase of the initial PCM temperature and the external wall temperature reduce this time. The increase of the percentage of the polyethylene glycol in the mixture reduces the time for complete fusion. A correlation for the time for complete fusion as function of these parameters was developed and compared with the experimental results indicating satisfactory agreement.*
Keywords: *Fusion, Spherical shell, PCM, Storage system, Fusion correlations.*

1. INTRODUCTION

Thermal energy storage system provides advantageous solutions to time gap that often occurs between supply and energy demand. The technology of thermal storage is used to satisfy the requirements of large power consumption during low energy offer periods. Thermal energy can be stored as a change in internal energy of certain materials. The most commonly used method of thermal energy storage is the sensible heat method. Other method that have been studied for over 25 years, is storing energy in the form of latent heat in adequate phase change materials, PCM, of adequate storage characteristics as high latent heat, thermal and chemical stability, relatively high thermal conductivity and not chemically aggressive.

The use of phase change material in the development and construction of sustainable energy systems is crucial to the efficacy of these because of the capacity of PCM to bridge the gap between energy release and energy demand in an efficient way way.

Different theories and experimental investigations were developed to model the thermal performance of the storage units and PCM phase change materials, investigations into new geometries, new concepts for energy storage and improvement of technologic viability.

"Saeed, *et al*., 2014" analyzed the melting characteristics of a phase change material (PCM) in different geometry and configurations. The paraffin wax was selected as the phase change material. The different geometries studied are rectangular block, sphere and cylinder. Also the effect of configuration on melting rate was studied. A simplified 3-dimensional pressure-based CFD model was used in Fluent to simulate the melting process. "Tan, *et al*., 2009" studied the role of buoyancy-driven convection during constrained melting of phase change materials (PCM) inside a spherical capsule. The melting phase front and melting fraction of the PCM were analyzed and compared with numerical solution obtained from the CFD code Fluent. Following a short period of symmetric melting due to prominence of diffusion, expedited phase change in the top region of the sphere and a wavy surface at the bottom of the PCM are observed. The computational predictions pointed to the strong thermal stratification in the upper half of the sphere as a result from rising the molten liquid along the inner surface of the sphere and thus displacing the colder fluid. The waviness and excessive melting of the bottom of the PCM was shown, by the experimental observation, to be underestimated. "ElGhnam, *et al.*, 2012" has investigated heat transfer during freezing (charging) and melting (discharging) of water inside a spherical capsule of the type often found in thermal (ice) storage systems used for the building air conditioning systems. Spherical capsules of different diameters and materials were tested. The aqueous solution of 35-wt% ethylene glycol is used as the heat transfer fluid (HTF). The principal studied parameters are the size and material of the spherical capsule, the volume flow rate and temperature of the heat transfer fluid (HTF). The experimental results showed that the energy recovery ratio is becoming better when using metallic capsules, increasing the capsule size and reducing the HTF volume flow rates.

"Eames and Adref (2002)" evaluated the results of an experimental study for the characterization of the freezing and melting processes of water contained in spherical elements. The results include semi empirical equations that allow the mass of ice within a sphere to be predicted at any time during the freezing or melting processes. "Ismail and Henriquez (2003)" presented a transient simplified one-dimensional numerical model to simulate a storage system consisting of PCM-filled spherical capsules placed inside a cylindrical tank filled with a circulating working fluid. "Roy and Sengupta (1989)" has analyzed the melting process within a spherical enclosure. When the wall temperature is raised above the melting temperature of the solid, the core rapidly melts. This molten material is of lower density than the solid and the weight of the solid thus forces the molten material towards the top of the enclosure. This process takes place in a very thin layer between the solid and the wall of the enclosure. Heat transfer to the solid is assumed to take place only by conduction through this thin layer. A mathematical model has been developed using these assumptions and results have been compared with experimental data.

"Assis, *et al*., 2006" explored numerically and experimentally the process of melting of a phase-change material (PCM) in spherical geometry. The PCM properties used in the simulations, including the melting temperature, latent and sensible specific heat, thermal conductivity and density in solid and liquid states, are based on a commercially available paraffin wax, which is manufactured to be used mainly in latent-heat-based heat storage systems. A detailed parametric investigation was performed for melting in spherical shells of 40, 60, and 80 mm in diameter, when the wall-temperature is uniform and varies from 2°C to 20°C above the mean melting temperature of the PCM. Dimensional analysis of the results was performed and presented as the mean Nusselt numbers and PCM melt fractions vs. an appropriate combination of the Fourier, Stefan, and Grashof numbers. "Sakr, *et al*., 2008" conducted experimental and theoretical study on freezing and melting of PCM in capsules with different configurations, five different copper capsules (sphere, cylinder, pyramid, cone, and cuboids) having the same internal volume. They used water as a phase change material (PCM). The effect of geometrical configuration on the characterization of the freezing and melting processes was investigated. The spherical capsule showed the best thermal energy storage performance among the five tested configurations.

"Kalaiselvam, *et al*., 2008" has analyzed Phase change materials encapsulated inside cylindrical enclosures for solidification and melting process. Analytical solutions for finding the interface locations at various time steps were obtained. Transient interface positions and complete phase change time was predicted by two models for solidification and by three models for melting. The agreement was found to be good for model with conduction and heat generation in solidification process, but in melting the model with conduction, convection and heat generation gives a better prediction. Validated analytical model was extended to study the phase change behavior and heat transfer characteristics inside PCM. Presence of heat generation increases the total solidification time of the cylinder, though it accelerates melting. Total solidification time depends on Stefan number and heat generation parameter β, whereas complete melting time depends on equivalent thermal conductivity. "Moraes and Ismail (2007)" evaluated the complete solidification time of commercial spherical shells available in the domestic market for use in fixed bed type storage units.

In the present study four spherical shells of 35, 76, 106 and 131 mm diameter were used at four initial temperatures ranging from -20°C to -5°C and under constant external wall temperature of 10°C, 18°C, 25°C. Water and mixtures of polyethylene glycol and water in percentages ranging from 10% to 50% were used as PCM. The results show that the increase of the diameter of the spherical shell, the increase of the initial PCM temperature and the external wall temperature and the increase of the percentage of the polyethylene glycol in the mixture reduce the time for complete fusion. A correlation for the time for complete fusion as function of these parameters was developed and compared with the experimental results indicating satisfactory agreement.

2. ANALISYS EXPERIMENTAL

The main objective of the present study is to investigate experimentally the effect of the size of the spherical shell (storage element), wall temperature, and initial PCM temperature on the time for complete fusion and develop correlation between the time for complete fusion and the above parameters.

The test equipment used in this study is shown schematically in Fig. 1. It is composed of test tank (1), spherical capsule (2), heating section of the tank with temperature control (4), system for circulation of working fluid (5) (centrifugal pump, piping system, globe valves). These components are described below:

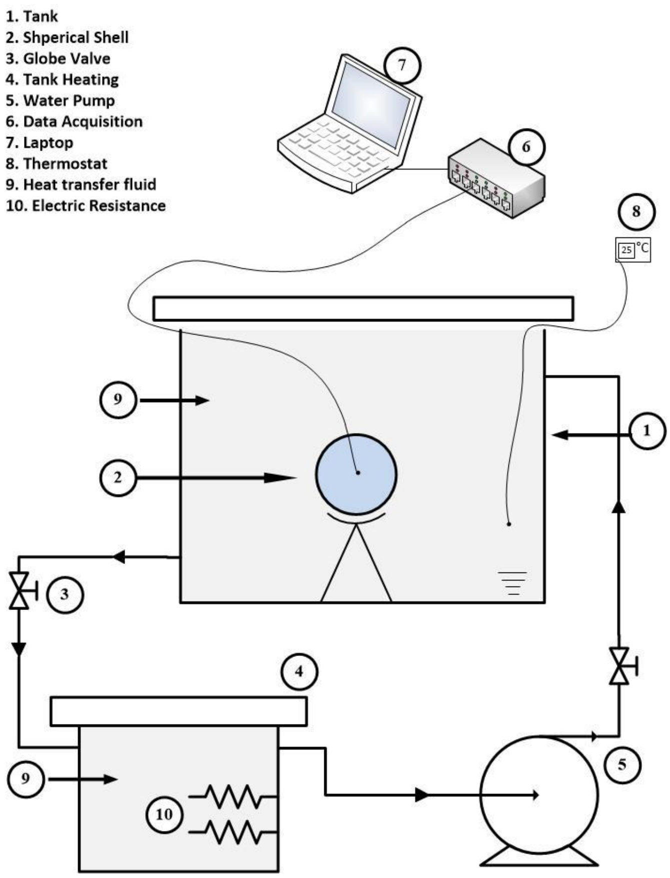

Figure 1. Diagram of Test Device.

2.1 Test Tank

The test tank is of asbestos and is thermally insulated with 50 mm polystyrene sheets. The dimensions of the tank are 350x 330x 280 mm.

2.2 Spherical Shell

The test section is equipped with plastic seat to suspend the spherical shell under test. The spherical shell has a T type calibrated thermocouple allocated at the center for monitoring the temperature at the center of the shell. Calibrated thermocouples of the T type are placed in the tank to ensure uniform temperature distribution Thermocouple were calibrated against precision thermometers and have accuracy of ± 1°C. The four spherical shells used have diameters of 35, 76, 106 and 131 mm diameter and are filled with phase change material (water or polyethylene glycol) according to the testing procedure.

2.3 Heating section

The main objective of the electric heating section is to heat water to a specified temperature to meet the requirements of the discharge process. The heating section is composed of a tank with two electric resistances of heating capacity of 300W connected to voltage of 110 volts.

A digital temperature controller (electronic thermostat) is used to control the desired temperature inside the tank with a set point differential of ± 1 ° C.

A centrifugal pump and globe valves are used to circulate and control the heat transfer fluid through the piping system.

2.4 Measuring instruments

Appropriate measuring instruments are used for monitoring the temperature. Temperatures measured at the center of the spherical shells were captured by a calibrated thermocouple copper-constantan (Type T) for which the uncertainties are found to be in the range of ± 0.505°C. They are then connected to data acquisition system that has response delay of up to 20 ms after the command is received, at a sampling rate of 30 s. As can be seen the uncertainty in the time for complete phase change is too small and hence we decided not to include it in the graphical data. A digital temperature controller (electronic thermostat) is used to control the desired temperature inside the tank during test experiments. The thermostat specifications are ICT-17RGTi, accuracy of 0.5%, set-point difference ±1°C.

2.5 Experimental procedure

The fusion tests were realized following the procedure below. The spherical shell is filled with the required PCM and placed in the freezing compartment of a freezer and monitored until the thermocouple placed at the center indicates the required test temperature. The spherical shell is rapidly placed in the test section and all thermocouples are connected to the data acquisition system. Adjust the circulating water flow rate, the heating system to the required test condition. Measurements of the temperatures of PCM within the spherical shell and the circulating fluid temperature are digitized and recorded every thirty seconds by the data acquisition system. The fusion experiment is terminated when the temperature of the PCM at the center of the spherical shell begins to approach the bath temperature to ensure that the solid PCM is completely melted. The electric heater and the pump are then switched off to prepare the system for a new test.

The fusion experiments were realized under different working conditions as presented in Table 1.

Table 1. Experimental parameters.

Initial temperature inside spherical shell	-5°C, -10°C, -15°C, -20°C
Temperature (during the discharge process)	10°C,18°C, 25°C
Volume flow rate	3 Lpm
Size of spherical shell	0.131, 0.106, 0.076, 0.035 m
Spherical shell material	Plastic

The experimental measurements of temperature and time were repeated three times and an average value was considered as representative of the specific measurement. The test parameters, percentage of polyethylene glycol (0.1% ≤ W ≤ 0.5%), initial temperature (-20°C≤ T_{ini} ≤ -5°C), wall temperature (10°C ≤ T_{wall} ≤ 25°C) were varied for each spherical shell totalizing 480 trials. To derive the correlation equation the predictive model was used showing a significant regression at a confidence level of 95%, and high correlation coefficient R2.

3. RESULTS AND DISCUSSION

3.1 Effect of the wall temperature on the time for complete fusion

Figure 2 shows the fusion curve for PCM (water) in a spherical capsule of 35mm diameter at initial temperature of -5 ^{o}C and wall temperature of 10 ^{o}C. As can be seen the temperature at the center of the spherical shell rises slowly due to conduction in the solid PCM until it reaches the fusion temperature of about 0 ^{o}C. At this point the temperature remains constant until all the PCM is melted and then the temperature of the liquid PCM starts to increase by conduction and convection. The time interval between the initial and final constant temperature range is the time for complete fusion.

Similar behavior is found for the case of PCM in the form of mixture of water and 10% polyethylene glycol as sown in Figure 3. These curves are used to obtain the complete solidification time and its variation with the parameters varied during the tests.

3.2 Effect of PCM on the time for complete fusion

Figure 4 shows the variation of the time for complete fusion with the type of PCM (water and polyethylene glycol mixture of different concentrations). As can be seen increasing the polyethylene glycol concentration reduces the time for complete fusion. This can be explained by the effect of the long chains of the polyethylene glycol which helps heat propagation in the PCM. Figure 4 also shows that increasing the wall temperature reduces the time for complete solidification which can be explained by the fact that the increase of the wall temperature increases the temperature gradient and consequently enhances the heat transfer and reduces the complete fusion time.

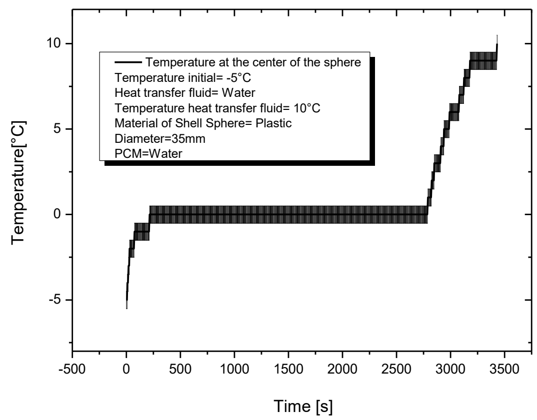

Figure 2. Effect of temperature variation on the center of the sphere with a temperature of 10°C fluid.

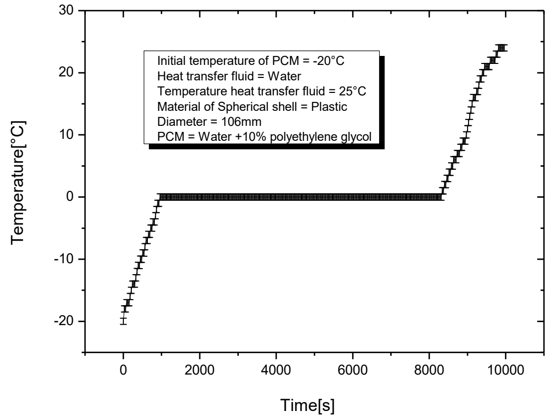

Figure 3. Effect of temperature variation on the center of the sphere with a temperature of 25°C fluid.

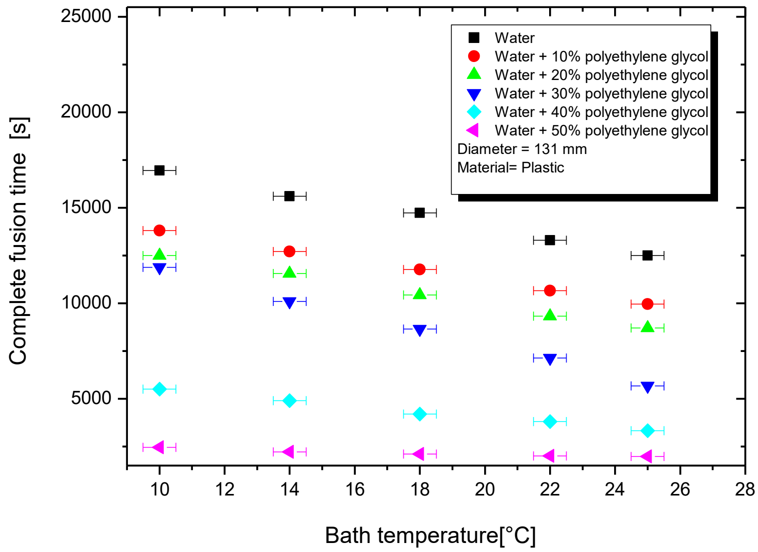

Figure 4. Effect of polyethylene glycol concentration (PCM) on the fusion time.

3.3 Effect of the spherical shell diameter on the fusion time for complete fusion

Figure 5 shows the effect of the diameter of the spherical shell on the time for complete fusion. One can observe that the complete fusion time increases with increase of the shell diameter. This can be explained by the fact that increasing the diameter reduces increases the thermal resistance, and reduces the heat flow to the solid PCM and consequently increases the fusion time. Again one can observe that the increase of the wall temperature reduces the complete fusion time due to the increase of the temperature gradient as mentioned before.

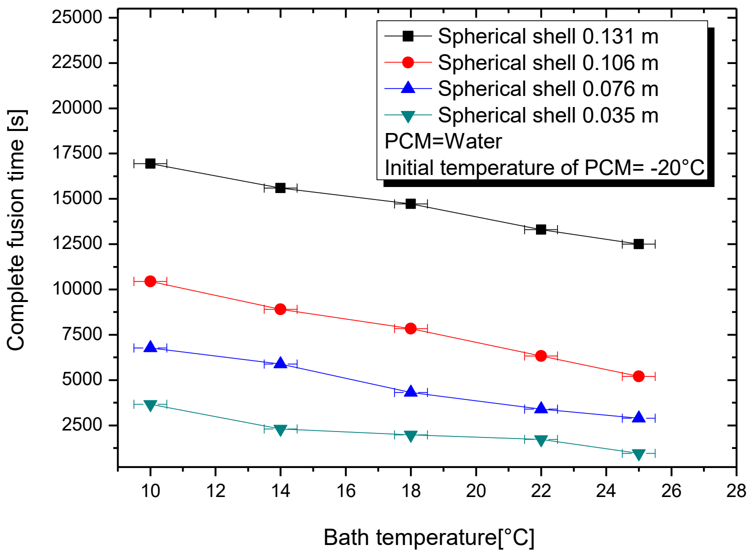

Figure 5. Effect size of the spherical shell in the fusion time.

3.4 Effect of the initial PCM temperature on the time for complete fusion

The initial temperature of PCM has a big influence on the time for complete fusion. Low initial temperature of PCM with reference to the temperature of the fluid bath leads to high temperature gradient which enhances the fase change process and hence reducing the time for complete fusion.

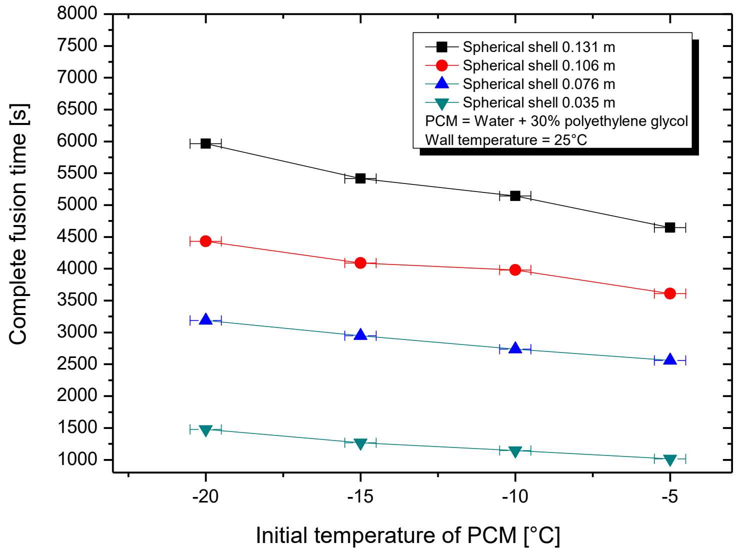

Figure 6. Effect of the initial PCM temperature on the time for complete fusion.

3.5 Correlation for the time for complete fusion

The parameters studied were the shell sphere diameter, percentage of polyethylene glycol, and wall temperature. To obtain correlation relating the parameters investigated to the time for complete fusion we assumed a relation of the form

$$\tau_{complete\ fusion}=AD^{a}(1-W)^{b}|T_{ini}|^{c}T_{wall}{}^{d} \tag{1}$$

Where:

D: diameter (m), W: percentage of polyethylene glycol (%), T_{ini}: initial temperature (°C), T_{wall}: wall temperature (°C), $\tau_{complete\ fusion}$: time (s)

The correlation is based on experimental data and is calculated by equations of least squares resulting in equation 2. The application range of the correlation is: $0.076\ m \leq D \leq 0.131m$, $0.1\% \leq W \leq 0.5\%$, $-20°C \leq T_{ini} \leq -5°C$, $10°C \leq T_{wall} \leq 25°C$. The differences between the values calculated by the correlation and the experimental values are below 10% for the correlation below:

$$\tau_{complete\ fusion}=4.7x10^5 D^{0.99}(1-W)^{2.34}|T_{ini}|^{0.033}T_{wall}^{-0.53} \quad (2)$$

Figure 7 shows a comparison between the correlation predictions and the experimental measurements indicating a maximum difference of 10%. Figure 8 shows a comparison between predicted values and experimental results for the case of W=0,5%. As can be seen the agreement is good.

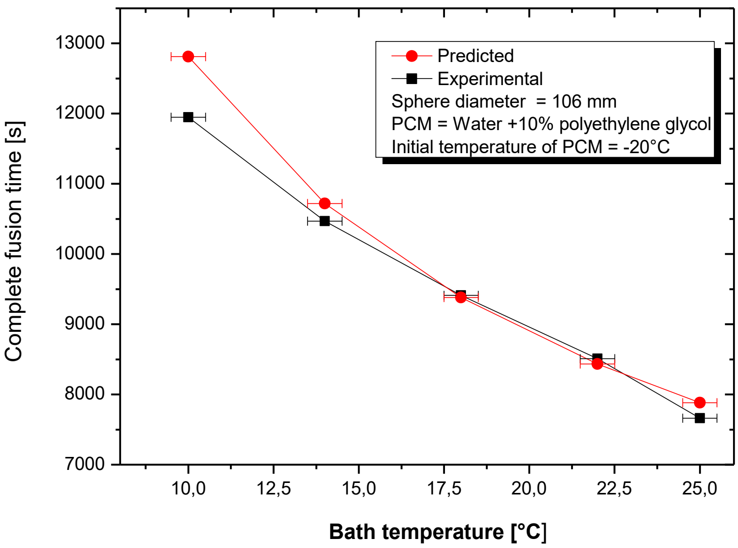

Figure 7. Fusion time against the wall temperature: D=0.106 m W=0.1% T_{ini}=-20°C.

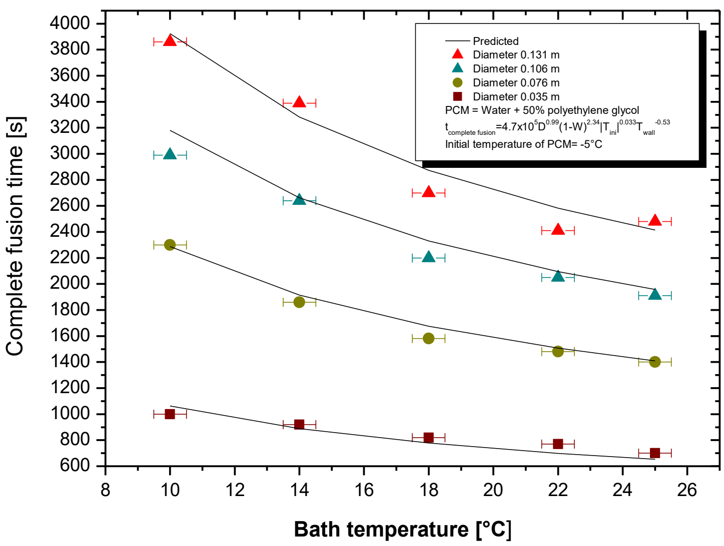

Figure 8. Comparison between predicted values and experimental results: W=0.5% T_{ini}=-5°C.

4. CONCLUSION

The complete fusion time is one of the most important parameters in the operation of the latent heat storers. In this study was investigated the effects of operating and geometric parameters on the complete fusion time, always seeking that this time may not exceed eight hours. It has been confirmed by experimental measurements that the fusion time increases with increasing diameter of the capsule, decrease in wall temperature (working temperature) and with the decrease of percentage of polyethylene glycol in water.

5. ACKNOWLEDGEMENTS

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