Experimental Study of Fusion and Solidification of Phase Change Material (PCM) in Spherical Geometry

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ABSTRACT

The objective of this work is to investigate the parameters affecting the time for complete solidification and fusion in spherical capsules and develop correlations between this time and the investigated parameters. These correlations will be used in the numerical simulations of latent heat storage systems of the fixed bed type having the phase change material, PCM encapsulated in spherical containers. Four spherical shells of 35, 76, 106 and 131 mm diameter were used at temperatures ranging from -20°C to -5°C for solidification process and temperature of 10°C, 18°C, 25°C for the melting process. Water and mixtures of water and polyethylene glycol in percentages ranging from 7.5% to 50% were used as PCM. Based on the experimental results correlations of the time for complete solidification and complete fusion were developed and compared with the experimental measurements showing good agreement and confirming the suitability of using these correlations to predict the complete phase change times. These correlations are applicable in the ranges: 0.076 m ≤ Diameter of spherical capsule ≤ 0.131m, 0.1% ≤ concentration of polyethylene glycol ≤ 0.5%, -20°C ≤ Initial temperature of PCM ≤ -5°C, 10°C ≤ Thermal bath temperature≤ 25°C. The differences between the values predicted by the correlation and the experimental measurements are below 10%.

NOMENCLATURE

A	[-]	Constant of Correlations
W	[%]	Percentage of polyethylene glicol
D	[m]	Diameter of the spherical shell
T_{ini}	[°C]	Initial temperature on the center of the sphere
T_{wall}	[°C]	Wall temperature
$\tau_{completesolidification}$	[s]	Time complete solidification
$\tau_{completefusion}$	[s]	Time complete fusion

INTRODUCTION

Energy storage systems are essential elements for conventional and non-conventional intermittent heat generation and energy conservation systems. There are many alternative systems for thermal energy storage, which can be broadly divided as sensible heat systems, latent heat systems, and hybrid storage systems. Sensible heat systems are well dominated technologically with many projects in real operation. Latent heat storage systems are struggling its way in some applications but still needs additional research of theoretical and applied nature to highlight its numerous benefits and strengthen its acceptability in real full-scale applications.

Latent heat storage is a very promising technique for thermal energy storage because of the high storage density, nearly isothermal charging and discharging processes but its major drawbacks are the low thermal conductivity and the degree of super cooling.

To use the concept of latent heat of phase change materials (PCM), it is important to have a simple, cheap and thermally efficient method of containment. Many studies were devoted to investigate techniques for containment of PCM without degrading its physical and thermal properties and be able to absorb and release thermal energy as efficient as possible. The containment geometries include cylinders, spherical shells, and tubes with and without fins, flat sheets and annular geometries. The materials used in most of these cases are cupper, steel and aluminium, which usually are expansive but good heat conductors. Plastics in the form of tubes cylinders and spherical shells are cheaper but have lower thermal conductivities.

One of the methods of PCM containment uses spherical plastic shells. Saeed et al. [1] analyzed the melting characteristics of a phase change material (PCM) in different geometry and configurations such as rectangular blocks, spheres and cylinders. A simplified 3-dimensional pressure-based CFD model was used in Fluent to simulate the melting process. Tan et al. [2] studied the role of buoyancy-driven convection during constrained melting of phase change materials (PCM) inside a spherical capsule

El Ghnam et al. [3] investigated heat transfer during freezing (charging) and melting (discharging) of water inside spherical capsules. The experimental results showed that the energy recovery ratio is better when using metallic capsules.

Eames and Adref [4] evaluated the results of an experimental study for the characterization of the freezing and melting processes of water contained in spherical elements. They developed semi empirical equations which allow the mass of ice within a sphere to be predicted at any time during the freezing or melting processes. Ismail et al. [5] presented the

results of a parametric study on ice formation inside spherical capsules while Roy and Sengupta [6] analyzed the melting process within a spherical enclosure. Assis et al. [7] explored numerically and experimentally the process of melting of a phase-change material (PCM) in spherical geometry. A detailed parametric investigation was performed for melting in spherical shells of 40, 60, and 80 mm in diameter and wall-temperature varying from 2°C to 20°C above the mean melting temperature of the PCM. Sakr, et al., 2008 [8] conducted experimental and theoretical study on freezing and melting of PCM in capsules with different configurations including sphere, cylinder, pyramid, cone, and cuboids and all having the same internal volume. They used water as a phase change material (PCM). The spherical capsule showed the best thermal energy storage performance among the five tested configurations.

Kalaiselvam, et al. [9] 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. Moraes and Ismail [10] evaluated the time for complete solidification using commercial spherical shells available in the domestic market.

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 solidification and develop correlation between the time for complete fusion, solidification and the above parameters.

DESCRIPTION OF THE EXPERIMENTAL RIG

The test equipment used in this study is shown schematically in Fig. 1. It is composed of test tank, spherical capsule, heating section of the tank with temperature control, refrigeration unit and system for circulation of working fluid (centrifugal pump, piping system, globe valves).

The test tank (thermal bath) is of asbestos and is thermally insulated with 50 mm polystyrene sheet. The dimensions of the tank are 350x 330x 280 mm. 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 its 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. The thermocouples were calibrated against a certified precision thermometers and have accuracy of ± 0.5°C. The four spherical shells used have diameters of 35, 76, 106 and 131 mm diameter and are filled with phase change material (pure water or a mixture of polyethylene glycol and water) according to the testing procedure.

The electric heating section is used to heat water to the specified temperature to meet the requirements of the discharge process. It is composed of a tank with two electric resistances of 300W. A digital temperature controller 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.

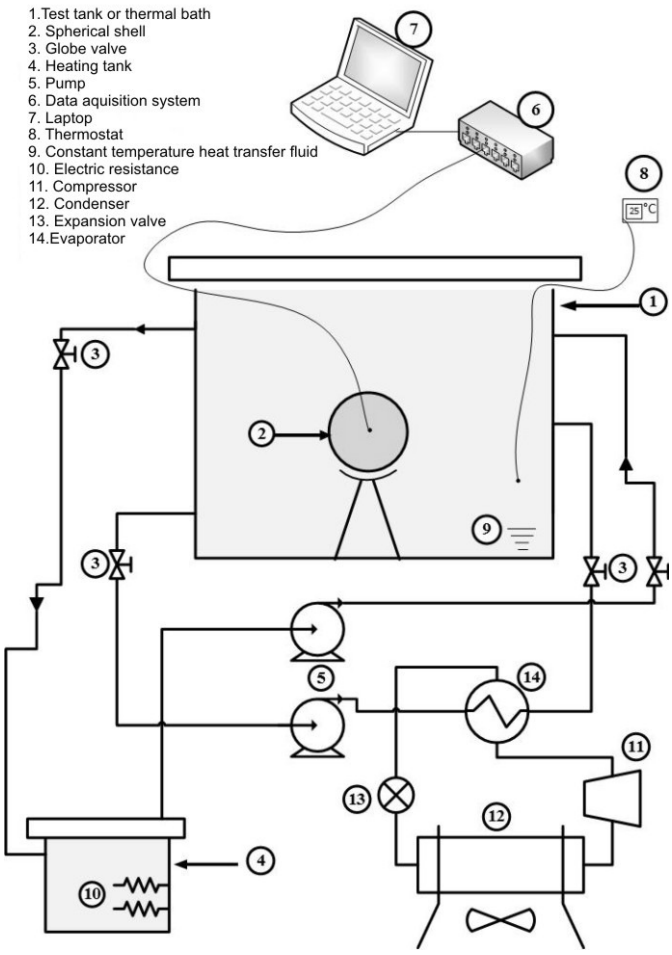

Figure 1 Experimental rig

The refrigeration unit is a commercial vapor compression unit operated with R22. It includes a semi-hermetic compressor, condenser, filter, liquid separator, liquid accumulator, expansion valve, and an evaporator. The refrigeration unit is used to cool the alcohol to the specified temperature to achieve the requirements of the charging process. A digital temperature controller is used to control the desired temperature inside the tank.

Appropriate measuring instruments are used for monitoring the temperature. Temperatures measured at the center of the spherical shells were captured by a calibrated copper-constantan thermocouple (Type T) for which the uncertainty is ± 0.505°C. The thermocouples are connected to data acquisition system which has a 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 was neglected in the calculations. A digital temperature controller is used to control the desired temperature inside the tank during the tests. The thermostat specifications are ICT-17RGTi, accuracy of 0.5%, set-point difference ±1°C.

EXPERIMENTAL PROCEDURE

The solidification and melting experiments were realized under different working conditions as presented in Table 1. The spherical capsules are filled with PCM and placed in the test tank. The globe valves incorporated into the pipe system are adjusted to the charging mode and the refrigeration unit is switched on to cool the heat transfer fluid (alcohol). The digital temperature controller is initially set at the test temperatures shown in Table 1. Measurements of PCM temperatures within the test capsules and the bath temperature are registered every thirty seconds by the data acquisition system. The charging experiment is terminated when the temperature of the PCM within the test capsule is equal to the thermal bath temperature. This indicates that the PCM is completely solidified. The cooling unit and the pump of the charging process are then switched off, and the solidified capsule is maintained within the tank to maintain its temperature to complete the preparation of the discharge experiment (which takes a few minutes).

With the valves positioned for the discharge mode, the digital thermostat is set at temperature for the discharge process. The heating section and the pump are switched on to heat the circulating transfer fluid (water). The experiment is terminated when the temperature inside the spherical capsules reaches the thermal bath temperature. This indicates that the ice is completely melted. The electric heater and the pump are then switched off.

Table 1 Experimental parameters

Temperature (during the charge process)	-5°C, -10°C, -15°C, -20°C, -25°C
Temperature (during the discharge process)	10°C,18°C, 25°C
Volume flow rate	0.003m^3/minute
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 for each run and an average value was considered. The test parameters, percentage of polyethylene glycol ($0.075\% \leq W \leq 0.5\%$), charging temperature ($-20°C \leq T_{ini} \leq -5°C$), discharge temperature ($10°C \leq T_{wall} \leq 25°C$) were varied for each spherical shell totalizing 480 tests. To develop the correlation equations the predictive model was used showing a significant regression at a confidence level of 95%, and high correlation coefficient R^2.

RESULTS AND DISCUSSION

Solidification process

Determination of the time for complete solidification

Figure 2 shows as an example the solidification curve for PCM (water) in a spherical capsule of 106mm diameter at initial temperature of 23 °C and wall temperature (temperature of the heat transfer fluid) of -18 °C. As can be seen the temperature at the center of the spherical shell drops slowly due to conduction and convection in the liquid PCM in the spherical shell until it reaches the solidification temperature of 0 °C. At this point the temperature remains constant until all the PCM is solidified and then the temperature of the solid PCM starts to decrease due to thermal conduction and starts the super cooling phase. The time interval between the start and end of the constant temperature range is the time for complete solidification.

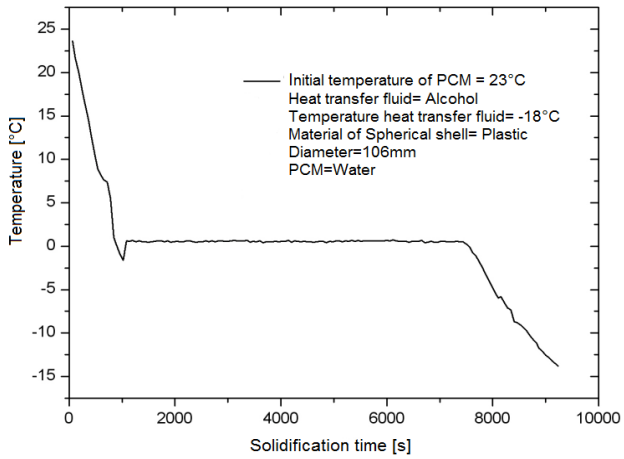

Figure 2 Effect of temperature variation on the center of the sphere with a temperature of -18°C fluid

Effect of PCM and wall temperature on the time for complete solidification

The materials used as PCM in the tests were pure water and mixtures of water and polyethylene glycol of 7.5; 15; 30 and 50% polyethylene glycol. Figure 3 shows that the increase of the polyethylene glycol concentration in the mixture causes increase of the time for complete solidification. Also, It was observed that the reduction of the wall temperature reduced the time for complete solidification. This result is expected since decreasing the wall temperature increases the temperature gradient which enhances the heat transfer rate from the PCM in the spherical shell to the working fluid and hence reduces the time for complete solidification.

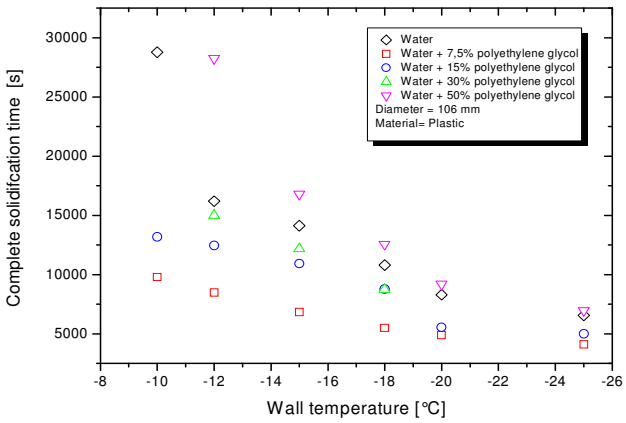

Figure 3 Effect of PCM on the time for complete fusion

Effect of the spherical shell diameter on the time for complete solification

Figure 4 shows the effect of the diameter of the spherical shell on the time for complete solidification. As can be seen the increase of the spherical shell diameter increases the time for complete solidification due to the increase of the thermal resistance between the PCM in the spherical shell and the working fluid. Also one can observe the reduction of the time for complete solidification due to the reduction of the working fluid temperature (wall temperature). This effect is caused by the increase of the temperature gradient which enhances the heat transfer rate and hence reduces the time for complete solidification.

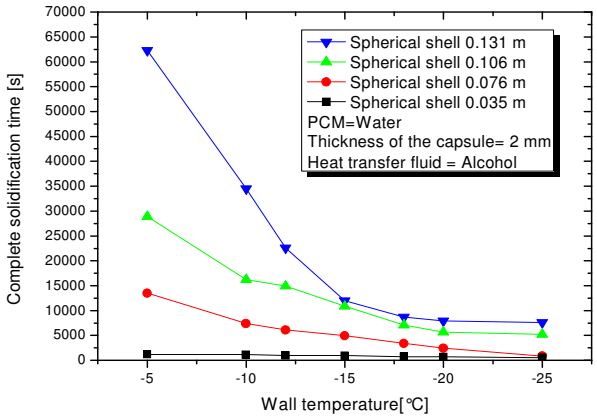

Figure 4 Effect of the spherical shell diameter on the time for complete solidification

Correlation for the time for complete solidification with PCM (Water)

To develop this correlation we considered only the spherical shell diameter and wall temperature. We considered PCM as pure water. The correlation equation was obtained based on experimental results realized in various working conditions. To obtain the coefficients of the equation, linear system of equations were constructed and solved simultaneously based on the power law, Equation (1) for the model fit to the experimental data. The predictive model shows a significant regression at a confidence level of 95%, and high correlation coefficient R^2.

$$\tau_{completesolidification} = AD^{a}T_{wall}^{\ b} \quad (1)$$

The correlation based on experimental data is calculated by equations of least squares resulting in Equation (2)

$$\tau_{completesolidification} = 2{,}5\text{x}10^{7}\text{D}^{2.074}\text{T}_{\text{wall}}^{\ -1.226} \quad (2)$$

Further, in order to test the correlation and verify its suitability for predicting the time for complete solidification, the correlation was used to predict the time for complete solidification for different sets of solidification tests of water and the predicted results are compared with the experimental measurements indicating good agreement as in Figure 5.

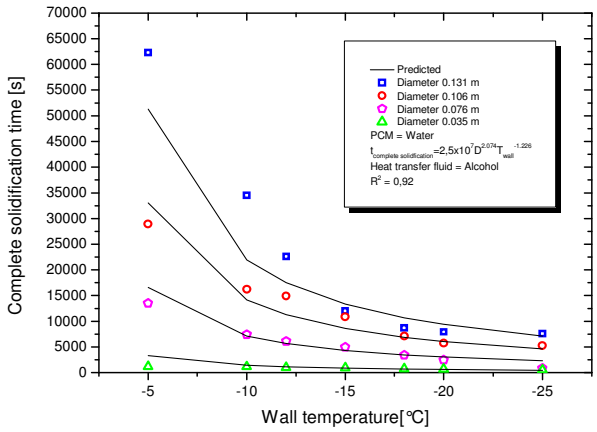

Figure 5 Validation of the correlation against solidification experimental measurements

Fusion process

Determination of the time for complete fusion

Figure 6 shows the melting curve for PCM (water) in a spherical capsule of 106mm diameter at initial temperature of -20 °C and wall temperature of 25 °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 melting temperature of 0 °C. At this point the temperature remains constant until all the PCM is completely 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.

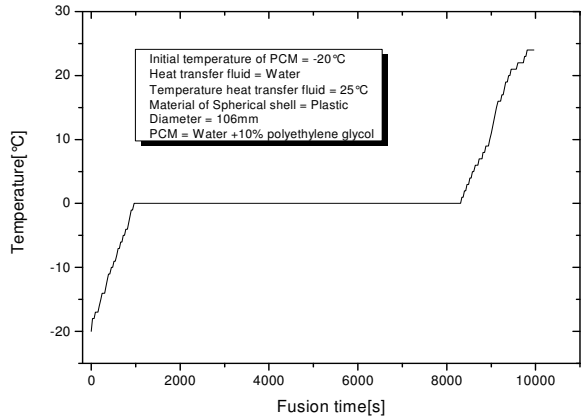

Figure 6 Variation of the temperature at the spherical shell centre with time for constant thermal bath temperature of 25°C

Effect of PCM and wall temperature on the time for complete fusion

Figure 7 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 is due to the effect of the long chains of the polyethylene glycol, which help heat propagation in the PCM. Figure 7 also shows that increasing the wall temperature reduces the time for complete fusion. This effect 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.

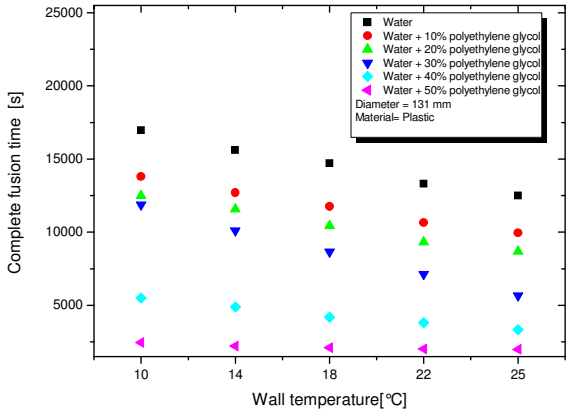

Figure 7 Effect of polyethylene glycol concentration (PCM) and wall temperature on the fusion time

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

Figure 8 shows the effect of the diameter of the spherical shell on the time for complete fusion.

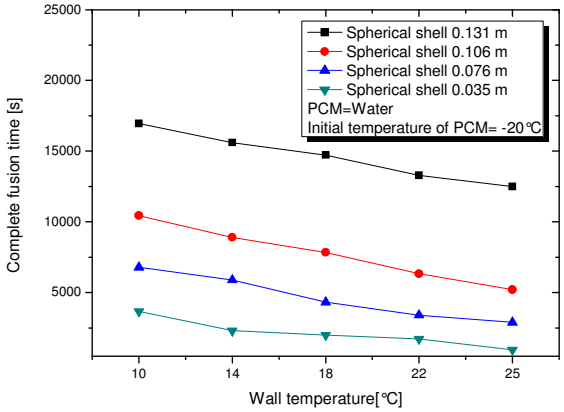

Figure 8 Effect of the diameter of the spherical shell on the time for complete fusion

One can observe that the time for complete fusion increases with increase of the shell diameter due to the fact that increasing the diameter increases the thermal resistance, 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 time for complete fusion due to the increase of the temperature gradient.

Correlation for the time for complete fusion

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

$$\tau_{completefusion} = AD^{a}(1\text{-}W)^{b}|T_{ini}|^{c}T_{wall}{}^{d} \quad (3)$$

Where
D: diameter (m), W: percentage of polyethylene glycol (%), T_{ini}: initial temperature (°C), T_{wall}: wall temperature (°C),
τ : time for complete fusion (s).

The predictive model, based on the power law, shows a significant regression at a confidence level of 95%, and high correlation coefficient R^2.

The correlation is based on experimental data and is calculated by equations of least squares resulting in Equation 4.

$$\tau_{completefusion}=4.7x10^{5}D^{0.99}(1\text{-}W)^{2.34}|T_{ini}|^{0.033}T_{wall}{}^{-0.53} \quad (4)$$

The application range of the correlation is: 0.076 m ≤ D ≤ 0.131m, 0.1% ≤ W ≤ 0.5%, -20°C ≤ T_{ini} ≤ -5°C, 10°C ≤ T_{wall} ≤

25°C. The differences between the values predicted by the correlation and the experimental values are below 10%.

Figure 9 shows a comparison between the correlation predictions and the experimental measurements indicating a maximum difference of 10%. Figure 10 shows a comparison between predicted values and new experimental results for the case of W=0,5%. As can be seen the agreement is good.

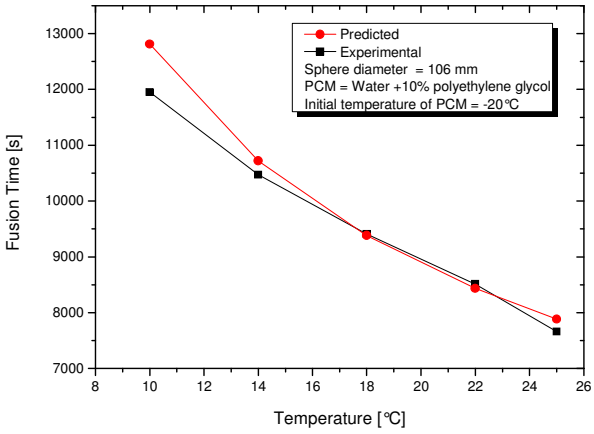

Figure 9 Comparison between predicted time for complete fusion and experimental measurements.

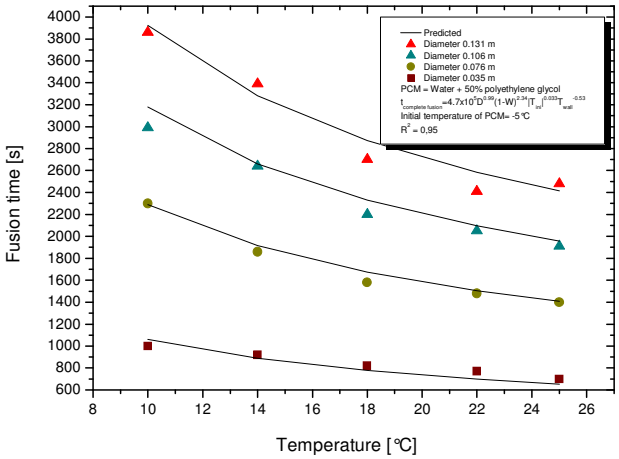

Figure 10 Comparison between predicted time for complete fusion and experimental measurements.

CONCLUSION

Based on the experimental results the correlations of the time for complete solidification and complete fusion were developed. The predictions from the correlations were compared with the experimental measurements showing good agreement and confirming their suitability to predict the complete phase change times. The application range of the correlation is: 0.076 m ≤ D ≤ 0.131m, 0.1% ≤ W ≤ 0.5%, -20°C ≤ T_{ini} ≤ -5°C, 10°C ≤ T_{wall} ≤ 25°C. The differences between the values predicted by the correlations and the experimental measurements are below 10%.

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