Introduction:

Freezing and melting in enclosures of various shapes are important phenomena with applications in solar energy, food and chemical processing industries. In the case of energy storage systems, it is necessary to know accurate rate of phase change and total time for complete freezing/melting to accurately design the systems. In the literature, studies pertaining to freezing/melting of pure materials and binary mixtures are available [1-14]. We consider freezing of pure materials in cylindrical enclosures. The early work of Sparrow et-al [5] gave a correlation for frozen mass with time and temperature drop across the frozen layer of data of freezing n-eicosane on a cooled tube with and without fins. Such a correlation is expected from the mathematical analysis of freezing on an isothermal cooled plate. However, the actual experimental frozen mass at any instant of time were higher than his numerical solutions by about 20%. In addition, they note that the nature of interface and uncertainty in the thermo-physical properties lead to the differences between theory and experimental data. Numerical analysis for transient freezing accounting for natural convection was also given [6-7]. In several papers different mathematical/numerical methods were used to predict transient freezing and comparison of results of improved methods were reported [9].

In the work of EL – Dessoussky et-al melting of paraffin wax on a vertical tube was studied [8]. The transient melting process was identified from the temperature – distributions in the phase change material (PCM) using thermocouples. Correlations in terms of Nusselt, Fourier and Stefan numbers were generated. A detail mathematical analysis leading to approximate solutions were given by Lin & Jiang [14]. They consider freezing in plate, cylinder and sphere with isothermal surface and conduction control freezing. The quasi-steady state analysis was improved and the accuracy of resulting solution was established by comparing it with literature solutions. The solutions of Lin & Jiang [14] are convenient to use in order to predict freezing – mass (or) freezing rate variation with time. Review of mathematical solutions using various surface conditions were given in references [9].

In this paper, we present an experimental study on freezing of two phase – change materials in vertical cylinders. The experiments were limited to conduction control freezing in order to facilitate a comparison of data with theoretical predictions.

Experimental Procedure:

Two PCM's namely n-octa decane (M.P. = 28^0 C) & Paraffin wax (58^0 – 60^0 C) were used. The experiments of freezing were conducted in copper cylinders of diameters 2.1 cm - 5.8 cm with a range of L/D. The hollow cylinders were insulated at the bottom with 1 cm thick acrylic plate. The top was capped with acrylic plate with a hole at the centre to fit PT-100 sensor. The freezing was affected by immersion of the test cylinder in isothermal water bath (accuracy 1^0C).

A weighed amount of PCM was placed in the cylinder and melted in hot water bath at 5^0C above the melting point. After complete melting of PCM, the cylinder was allowed to cool in air, to give a centre temperature of 2^0C above the melting point. The copper cylinder was then immersed in the cold water bath at a pre-fixed water temperature. The copper cylinder was removed after a specific time and the molten liquid was separated & weighed in a balance (0.1 g accuracy). The experiment was repeated for six different times for each test cylinder and water bath temperature. The temperatures were measured by PT100 sensors connected to digital meter.

In the visual observations the freezing process in all the experiments indicated uniform layer thickness; the diameter range of cylinders was (2.1 cm – 5.8 cm). The maximum length of cylinder was 15 cm for 3.5 cm diameter. The interface for n-octa decane was covered by small crystals in all experimental runs. However, Paraffin wax experiments had shown a smooth interface.

Results and Discussion:

As the initial melt temperature never exceeded 2^0C above the melting point in all experiments, the freezing mechanism was considered predominantly conduction. For comparison of data, the solution of Lin and Jiang given below was used:

$$(R/R_0)^2 . \ln(R/R_0) - \tfrac{1}{2}.[(R/R_0)^2 - 1] = [4/(1+e^{p2})].St.\tau \text{---------- (1.)}$$

Where R = Thickness of the PCM frozen

R_0 = Overall radius of the cylinder

St = Stefan Number = Cp •T/

Fo = = Fourier Number = t /R^2

Note that $M^* = 1-(R/R_0)^2$-------- (2.)

Where M* = (partial frozen mass)/ (total mass of PCM), and the value of p can be estimated graphically [14] for a known Stefan number. Figure 1 shows data and predictions for Paraffin wax data, the prediction of Lin & Jiang gives lower mass freezing at any instant of time. The deviations observed range from -37.2 % to -28.57 % for a •T = 17.6 (and -39.39% to -20.43% for a •T = 48.4). For n-octa decane the error is observed to be about 15%. The results of n-octa decane are comparable to the results of n-eicosane [5]. Deviations of about 20% between theory and data were noted for eicosane [5].

Possible reasons for deviations between theory and data are:

1. Uncertainty in the physical properties of PCM [14].
2. As mentioned, interface for freezing n-octa decane was covered with crystals which may influence the thermal conductivity and interface heat transfer area [14]. However, this cannot be attributed to paraffin wax data as the paraffin wax interface was smooth.
3. Theoretical models like that of Lin & Jiang [11] assume the frozen layer to completely fill the cylinder at the end of freezing process which is not true for freezing under large •T.

In order to obtain data behavior, a plot of M/A vs. (•T. time) was observed following the method of Sparrow et-al [5]. This is shown in the [figure 2]. A plot of dimensionless mass vs. (St.Fo) shows different correlations for n-octa decane and paraffin wax. N-octa decane data show a negligible scatter and an accurate correlation given by:

$$M/A\ R = 1.6749\ (St.Fo)^{0.4331.} \quad (R^2 = 0.9938)$$

is developed. However, scatter is more in paraffin wax data and the best fit representing 73 data points can be represented as

$$M/A\ R = 0.9477(St.Fo)^{0.333} \quad (R^2 = 0.8392)$$

The correlation represents within +/- 15%. It is seen that the more accurate correlation for n-octa decane may be due to its sharp melting point (M.P = 28^0 C) whereas, the paraffin wax has a range.

The variation in the correlations of –octa decane and paraffin wax are probably due to solid – liquid interface structure during freezing and the thermo- physical properties. A further study is required for quantitative analysis.

Conclusions:

Experimental data were obtained using n-octa decane and paraffin wax to understand their freezing characteristics in vertical cylinders. The experiments were conducted under conduction control freezing with variation of L/D, volume of PCM and the temperature drop across a frozen layer. The data indicate that the predictions of Lin & Jiang show lower frozen mass at any instant of time. The deviations between the theory and experimental data were higher for paraffin wax in comparison to that of n-octa decane. Two different correlations were developed as

n-octa decane:

$M/A\ R = 1.6749\ (St.Fo)^{0.4331.}$ $(R^2 = 0.9938)$

Paraffin wax:

$M/A\ R = 0.9477(St.Fo)^{0.333}$ $(R^2 = 0.8392)$

Better correlation for n-octa decane is attributed to its sharp melting point.

References:

1. Ahmet Sari and Kamil Kaygusuz , 2002, Thermal and heat transfer characteristics in a latent heat storage using lauric acid, Energy convention and management, Vol.3, ,Pg: 2493-2507.
2. Zalba, B., Martin J.M, Cabeza, L.F., Mehling, H. 2003, Review on thermal energy storage with phase change: materials, heat transfer analysis and applications, Applied Thermal Engineering, Vol 23, Pg: 251-283.
3. B.Zivkovic and I.fujii, 2001, an analysis of isothermal phase change of phase change materials with rectangular and cylindrical containers, Solar Energy Journal, Vol.70.
4. Eman – Bellah S.Mettawee and Ghazy M.R Assassa, 2007, Thermal conductivity enhancement in a latent heat storage system, Solar Energy, Vol 81, Pg: 839-845.
5. E.M.Sparrow, E.D. Larson and J.W.Ramsey, Freezing on a finned tube for either conduction controlled or natural convection controlled heat transfer, International Journal of Heat and Mass Transfer, Vol.24, Pg: 273-284.
6. E.M.Sparrow and Y. Ohkubo. Numerical Predictions of freezing in a vertical tube, Numerical Heat transfer, Part A: Applications, Volume 9, Issue 1 January 1986, pages 79-95.
7. E.M.Sparrow and Y. Ohkubo. Numerical analysis of two – dimensional transient freezing including solid – phase and tube wall conduction and liquid – phase natural convection, Numerical Heat transfer, Part A: Applications, Volume 9, Issue 1 January 1986, pages 59-77 .
8. H.T El-Dessouky, W.S.Bouhamra, H.M.Ettouney and M.Akbar, May 1999, Heat transfer in vertically aligned Phase change energy storage systems, Transactions of ASME, vol.121,pages 98-109
9. Ibrhaim Dincer and Marc A. Rosen, 2002, Thermal Energy storage, John Wiley & Sons.
10. Kamal A.R.Ismail and Maria das Gracas. E .da Silva, 2003, Numerical solution of the phase change problem around a horizontal cylinder in the presence of natural convection in the melt region, International Journal of Heat and Mass transfer, Vol :46, Pg: 1791-1799.
11. M.Pinelli and S.Piva, Solid/Liquid phase change in presence of natural convection: A thermal Energy Storage case study, Journal of Energy resources technology, September 2003, Volume 125, Issue 3, pp :190-198

12. Mohmmed M.Farid, Khudhair,A., Razackask, Al-Hakkaj,S. 2004, A review on phase change energy storage: Materials and applications, Energy conversion and management, Vol.45, PG: 1597-1615
13. S.D.Sharma and Kazunoba Sagara, 2005, latent heat storage materials and systems: A review, International Journal of Green Energy, Vol: 2, Pg: 1-56.
14. Sui Lin and Zheng Jiang, An improved Quasi Steady Analysis for solving freezing problems in a plate, a cylinder and a sphere, Journal of Heat transfer, vol.125,2003,Pg:1123-1128.

TABLE 1

PCM used:	n-octa decane(28^0 C) and paraffin wax (58^0 – 60^0 C)
Volume of the PCM:	30-250 cc.
Cylinder (diameter(cm), thickness(mm), L/D ratio):	(2.1,2.75,3.81), (2.8,2.6,2.86), (3.5,1.52,4.285), (4.8,1.33,2.396), (5,0.5,0.588), (5.8,1.55,0.7931).
•T	6^0 – 48^0 C

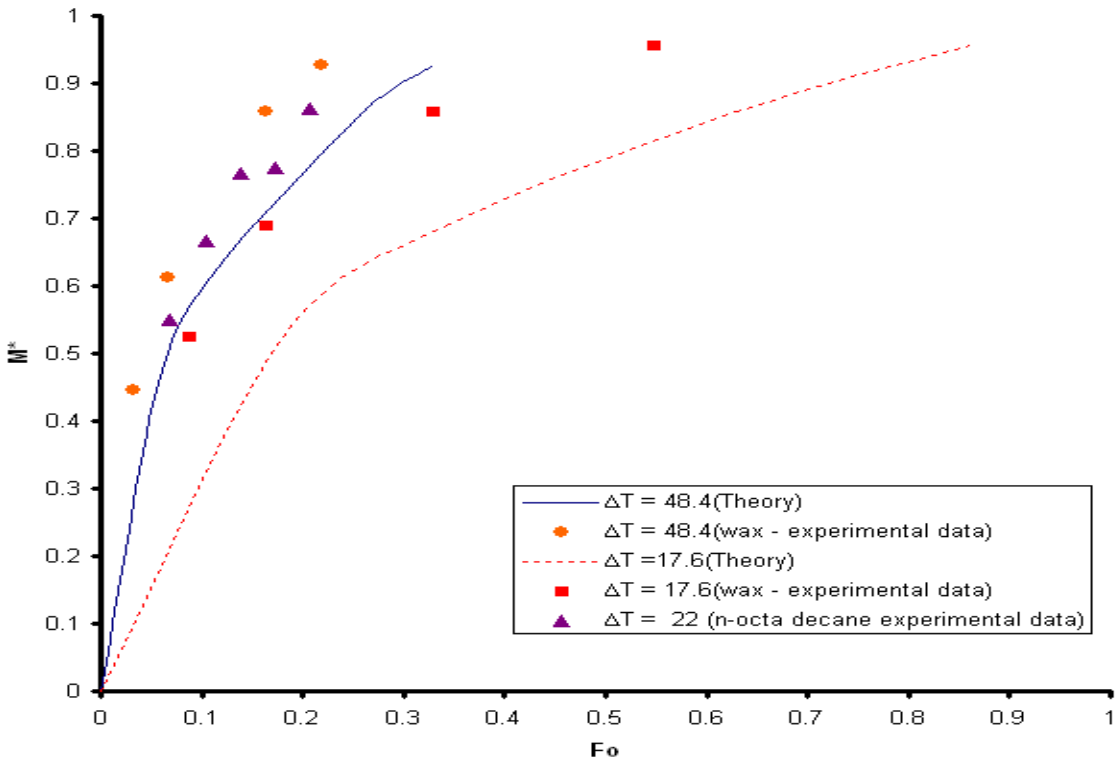

Figure 1. Comparison of data with theory

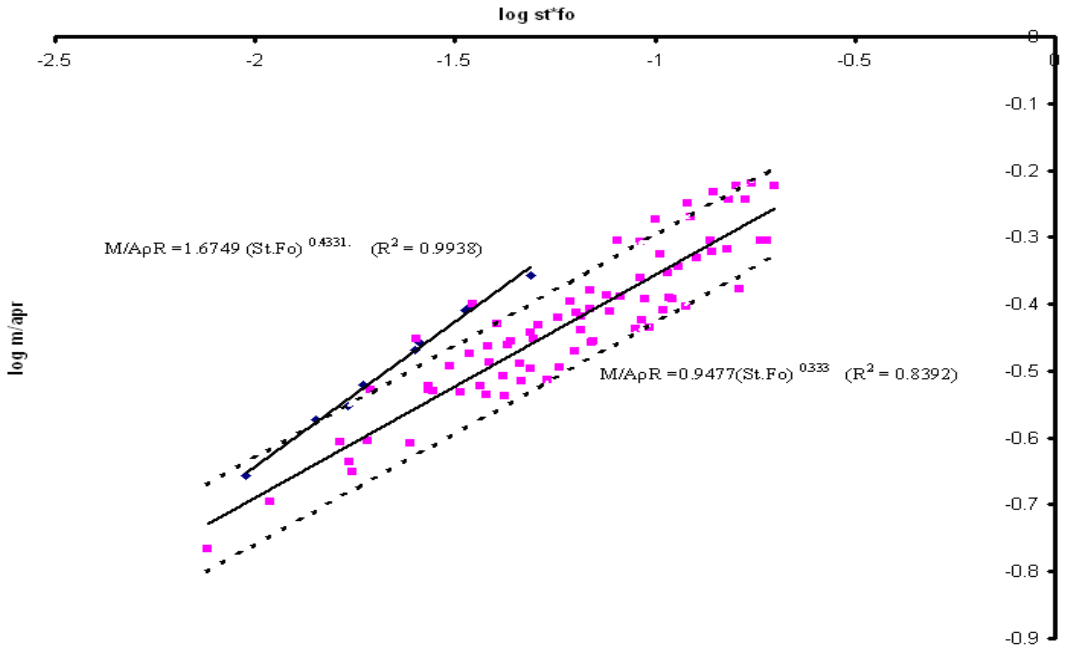

Figure 4. log M/A R vs. log St.Fo