Study of Solidification at Intense Low Temperature in a Spherical Container

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Abstract- The objective of the present paper is to provide the experimental data for the study of solidification of phase change material (PCM) in the cylindrical container. The pure water was considered as a PCM, copper was chosen for the cylindrical container and the liquid nitrogen was taken as the cooling fluid. The experiments were done for different sizes of cylindrical cavities, whose dimensions were 20×20, 20×30, 30×30, 30×40 and 40 × 40 (diameter in mm× height in mm). The PCM was taken initially at room temperature for all the cavities. The temperature variation is presented at different time steps during the solidification of PCM. The result shows that the convection from the atmosphere has a significant effect on upper surface. As the diameter of the cavity changes, for the same height, then notable change in solidification time is observed while as the height is changed, for the same internal diameter, the change in solidification time is observed to be less significant. It is also found that when the depth increases from 20mm to 30mm for the same internal diameter (20mm), the solidification time increases by only 3.78% and when the depth increases from 30mm to 40mm, the solidification time increases by 2.69%. But when the internal diameter increases for the same height, there is more change.

Keywords: PCM, solidification, conduction and convection, ice track.

I. INTRODUCTION

Liquid nitrogen is a cryogen whose boiling point is around -196^{o}C. It is colorless, nonflammable and inert gas. Nitrogen is freely and abundantly available. So the best source for producing liquid nitrogen is the atmosphere. Liquid nitrogen is prepared from the Linde cryo-plant by separating the nitrogen from the air and then by condensing the nitrogen gas.

The solidification or melting is related to Stefan problem. Stefan has done the study of melting of the polar ice. The phase change problem is also called moving boundary problem (MBP) as the interface of ice and water moves with time as solidification or melting takes place. The moving boundary problems are nonlinear in nature and more complex.

Hence, the exact solution of such problems is difficult to obtain for 2 or 3 dimensional problems. But for 1-D problems, Crank obtained results which are more accurate. In actual practice, most of the solidification and melting problems are 2 dimensional or 3 dimensional, only few of them can be simplified enough to be one dimensional. Boundary conditions are also complex and physical properties change with respect to time. The other ways to solve this problem are numerical and experimental solutions.

The analytical method can be used for some simplified problem of solidification. If the problem is one dimensional and the boundary conditions are simple then analytical methods can be used. For example a solidification problem for one phase and derived a non dimensional number

$$\text{STEFAN NO.} = [C(TS-Tm)] / LH$$

Where LH = Latent heat

It gives the relationship between sensible heat and latent heat of PCM. Stefan gave the analytical solution only for the one phase (1989-91) related to melting of polar ice cap. After that, many studies were reported on the analytical study of solidification and melting, but all of those problems were considered to have simple boundary conditions.

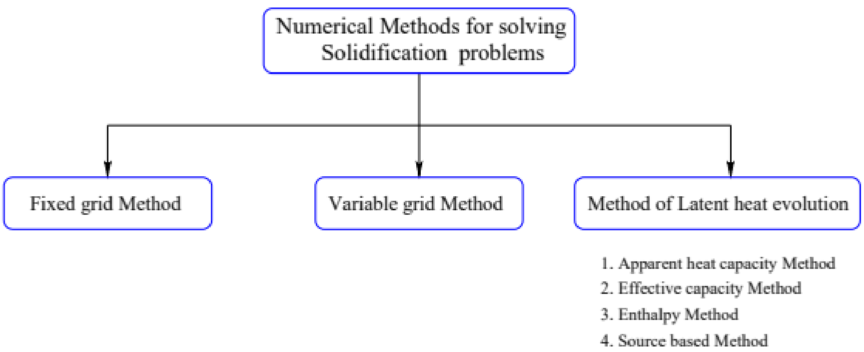

Figure 1: Various numerical method for solving solidification and melting problems

Table 1: Boundary Condition

Boundary	Boundary condition	Range
$r = 0$	$\frac{\partial T}{\partial r} = 0$	for $z = 0$ to $z = H$
$r = R$	$T = T_{LN}$	for $z = 0$ to $z = H/2$ from the base
$r = R$	$T = T_{VN}$	for $z = 0$ to $z = H/2$ from the top
$z = 0$	$Q = 0$	for $r = 0$ to $r = R$
$z = H$	$h_a(T - T_a) = k\frac{\partial T}{\partial Z}$	for $r = 0$ to $r = R$

Numerical solution as an analytical method has some limitations; researchers are giving more preference to the alternate solution, i.e. Numerical solution. Numerical methods are used to solve complex problems. There are various numerical methods to solve moving boundary problem. The numerical method can be classified into three groups, i.e. fixed grid methods, variable grid methods and method of latent heat evolution. The detailed classification of numerical methods for solidification and melting problem. Finite volume method, finite element method and finite difference methods are the various methods used for the discrimination of the governing equation.

Experimental study is a method for solving the solidification problem. Experimental study is a way of study in which all actual conditions are considered. This thesis mainly deals with the experimental study of solidification in a copper container.

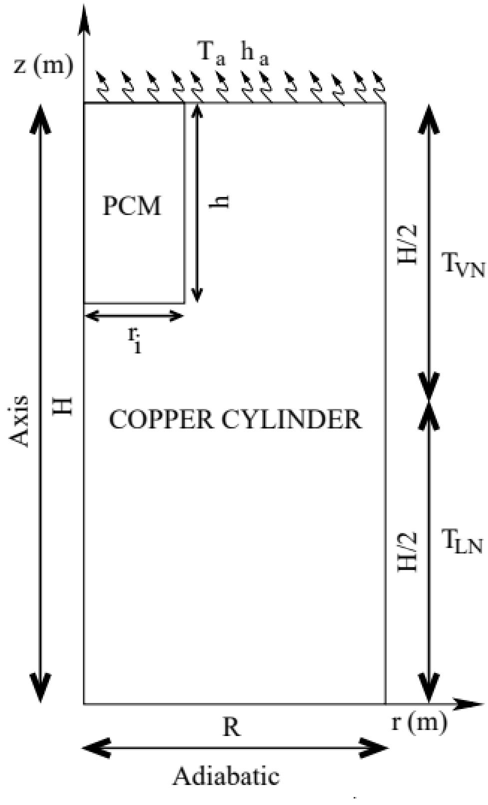

Figure 2: Schematic drawing of a 2d copper domain with boundary condition

Every problem, it may be either experimental or numerical, has some constrains. If numerical approach is adopted, the boundary condition is easy to maintain uniform throughout the study, but for the experimental study, maintaining the uniform boundary is tedious and complex task. In experimental studies initial focus is towards making the experimental setup ready because the setup should be robust and precise results are expected from the experiment. For all the experiments, the base of the copper container was kept in the cylindrical styro foam container so as to minimize the heat transfer from the base. The bottom half of the container was kept in contact with the liquid nitrogen, i.e. up to 30 mm from the base was at -196 °C. The top of the cylindrical container was in direct contact with the atmosphere and the atmospheric temperature was taken as 22 to 23 °C for each experiment. The boundary condition of the copper blocks is represented in a schematic 2D domain and in the tabular form as shown in fig.

II. LITERATURE WORK

Daabo et al. [2019] examined the effect of receiver geometry on the optical performance of a small-scale solar cavity receiver for parabolic dish applications by analyzing three different geometries viz., cylindrical, spherical and conical cavity receivers not only on the optical efficiency aspect, but also the flux distribution in respective geometries. The relation between the flux distribution and the optical efficiency of the receivers is obtained as the result from this study. The conical receiver found to have good absorption and high reflective flux energy. The shape of the receiver and receiver absorptive decides the focal point location criteria. Finally, the experimental results are compared with numerical models.

Zhao et al. [2019] studied the cyclic thermal characterization of a molten-salt packed bed TES for concentrating solar power. Molten-salt packed-bed thermo cline thermal energy storage was found to be the cost competitive thermal energy storage type concentrated solar plant. The simulations were done by a one-dimensional enthalpy method dispersed-concentric model. The thermal performance of the introduced partial charge cycles and subsequent full charge cycles are evaluated in ideal operating conditions. The partial charge effect is obtained by making variations in thermo cline development and energy storage or release capacity. Encapsulated PCMs containing configurations are of greater resistance and stronger recoverability to the variation in energy storage or release capacity. And the strong performance of the packed-bed storage depends on the thermal behavior of the storage mediums within the region.

Smith et al. [2019] studied the solidification of PCM numerically inside a thick wall cylindrical container using an alternating-direction-implicit method for solving the governing equation.A similar problem with some extra varying parameters. The enthalpy method for the numerical study of solidification in a spherical geometry and compared their results with the heat balance integral method (HBIM) for a wide range of Stefan numbers.

Tan and Leong [2018] have done an experimental study of the conjugate solidification process of n-octa decane as the phase change material inside a thick cylindrical mold considering constant base temperature for different superheated PCMs. They have considered two different materials, i.e. brass and stainless steel, for their studies and found that the solidification process is faster in brass as compared to stainless steel. They concluded that the solidification mass fraction is directly proportional to the cube root of solidification time for sub-cooled wall condition.

Lipnicki [2018] has done an experimental analysis of solidification of water with blue methylene in an annular enclosure. He compared the experimental result with the analytically result and gave a good correlation between them. Generally CFD helps to trace the solidification front, but Lipniki used a transparent cylindrical medium and a binary solution of water with methylene blue for visualization of solidification front.

Smith and Meeks [2017] have done experimental and numerical studies to provide quantitative data for a simple multidimensional solidification process of n-octadecan (PCM) in an enclosure. They presented the shape of the phase front profile.

III. PROBLEM IDENTIFICATION

The basic objections of my hypothesis work are according to the accompanying:

- Design and development of experimental setup.
- Studying the heat transfer and temperature variation in the PCM and periphery of copper

  blocks.
- Developing an idea for measuring the ice thickness in the cavity at various time steps during the solidification.

IV. OBJECTIVES

The basic objections of my hypothesis work are according to the accompanying:

- The ice thickness for the each container was recorded at the 40% and 65% of solidification.
- As the internal diameter is increased the solidification time is observed to be increased by significant value as compared to the increase in internal height.
- Atmospheric convection dominates at the upper surface. The expansion of the ice looks like a hemispherical shape.

V. PROPOSED METHODOLOGY

The copper container filled with distilled water is kept in a Styrofoam container. The distribution tank, tripod stand with thermocouples, DAQ and container are kept in a systematic manner as shown in figure. The thermocouples were connected to PC based Data acquisition system. The distribution tank is kept filled with liquid nitrogen continuously throughout the experiment.

Liquid nitrogen comes into Styrofoam main cylindrical container through the connecting pipe. The main container is always filled with liquid nitrogen up to the height of 30mm from the base and the extra liquid nitrogen is allowed to flow to the collecting container. The level of the liquid nitrogen in the main container is kept fixed till the complete solidification of the PCM. The temperature was recorded by the use of thermocouple and DAQ arrangement during the experiment.

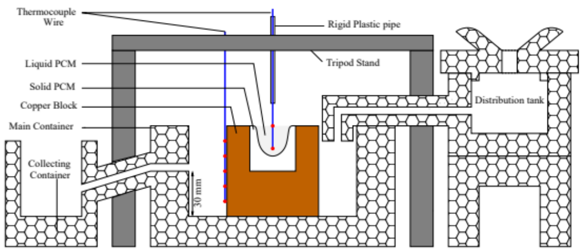

Figure 3: Schematic Setup

Figure 4: Experimental Setup

The setup arrangement was again same as for temperature measurement, but this time, the tripod stand and the thermocouples arrangement were not used. Liquid nitrogen is filled in the distribution tank similar to former one, but the experiment was done in the intermittent manner. The solidification time was noted from the temperature reading and the experiment is carried out up to 40% and 65% of the solidification time.

As soon as the solidification time reaches 40% of the total solidification time, the copper block is taken out and the remaining water is removed instantly by simply inverting the copper block. Now, the cavity created by the frozen part is filled with epoxy compound.

Because of its malleable property, the epoxy compound takes the shape of the cavity. At this time, it was not possible to take out the epoxy compound from the frozen part. The epoxy compound is only taken out when the frozen part remits completely. Similar procedure is followed for the 65% of the total solidification time experiment. The epoxy compound statue for all the cases are shown in figure.

The diameter of epoxy compound is measured at different heights, usually at an interval of 2 mm from the top by using vernier caliper. The thickness of ice at different heights was calculated by using the simple formula

$$t_{ice} = (d_i - d_e)/2$$

The procedure either for temperature measurement or for ice thickness measurement are repeated several times for each cylindrical container so that more accurate results can be obtained.

Figure 5: Epoxy compound statues at 40% solidification of total solidification time

Figure 6: Epoxy compound statues at 65% solidification of total solidification time

VI. RESULTS AND ANALYSIS

The variation of lateral thickness of ice at top and bottom locations in different containers at intermediate solidification. The horizontal ordinate represents the copper container, where 1, 2, 3, 4 and 5 represent the 20×20, 20×30, 30×30, 30×40 and 40×40 copper containers respectively. The solid line represents the condition at 40% of the solidification while dotted line represents the condition at 65% of the solidification. the minimum thickness is observed at the top from the side while the maximum is observed at the bottom. It is interesting to observe that the lateral top thickness reduces when the internal height of the copper container increases for the same internal diameter of the copper container while it increases if the internal diameter increases for the same height. But this effect is not noticed for the lateral thickness of ice at the bottom location. For this case, the thickness keeps on increasing with the increase in any one of the dimensions of the cavity.

Table 2: variation of side ice thickness in different cavity

Containers	40 % solidification		65 % solidification	
	Top ice thickness	Bottom ice thickness	Top ice thickness	Bottom ice thickness
20 × 20	2.1	2.8	5.2	7.25
20 × 30	2	3	4.5	8
30 × 30	4.6	6.2	8.5	12.2
30 × 40	4.4	6.4	7.5	12.8
40 × 40	5.05	7	12.34	15.5

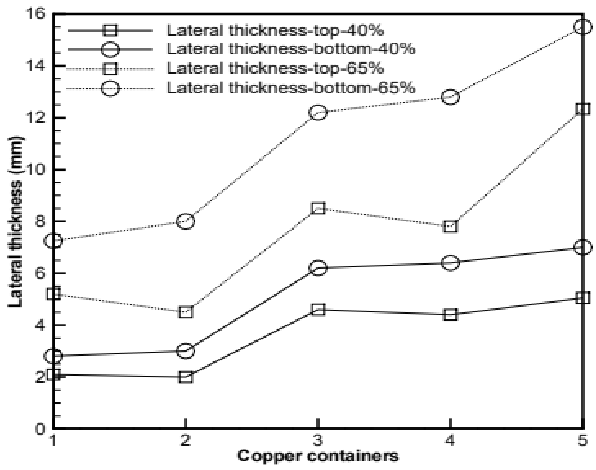

Figure 7: variation of the lateral ice thickness while increasing the cavity dimension

Similar trend of increasing ice layer thickness is also observed at the axial location. This trend is depicted on figure 4.6. In this figure also the horizontal ordinate represents the copper containers, i.e. 1, 2, 3, 4 and 5 represent the 20×20, 20×30, 30×30, 30×40 and 40×40 copper containers respectively.

VII. CONCLUSION

It is concluded that as the internal diameter is increased the solidification time is observed to be increased by significant value as compared to the increase in internal height. It is interesting to note that as the internal height is increased, for constant internal diameter, lateral top ice thickness is reduced. But on the contrary as the internal diameter is increased, for constant internal height, the ice thickness is observed to be increased.

It is also found that when the depth increases from 20mm to 30mm for the same internal diameter (20mm), the solidification time increases by only 3.78% and when the depth increases from 30mm to 40mm, the solidification time increases by 2.69%. But when the internal diameter increases for the same height, there are more change in the solidification time. For example, as the internal diameter increases from 20mm to 30mm and 30mm to 40mm for the same height of 30mm and 40mm respectively, the change in the solidification time is 35% and 15% respectively.

VIII. FUTURE SCOPE

The experiment was done with the aim that the result can be used for cryo-preservation but experiment with the tissue was not done. Now it is very difficult to say that what happens when tissue is used in the PCM. The experiment is done in the open atmosphere, but when the tissue is to be used, it has to be in a closed environment. These results are valid under the specific boundary condition.

The relation between depth and internal diameter of solidification is good when the copper container is in contact with extremely low temperature. This experiment was done with the copper container, in future it can be done with some other material. The variation of the size of the container can be studied in detail. For ice tracking, some temperature sensing instrument can be used so that experiment can be done in one step and results are more accurate.

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