23rd National Heat and Mass Transfer Conference and 1st International ISHMT-ASTFE Heat and Mass Transfer Conference, 17-20 December, 2015, Thiruvananthapuram, India, paper no -IHMTC2015-1583

Experimental and numerical studies of phase change phenomena at cryogenic temperature

Vishnu Rajpuriya and Amitesh Kumar
Department of Mechanical Engineering
National Institute of Technology Rourkela, Odisha, India,769008.

January 7, 2016

Abstract

The solidification and melting phenomena of a phase changing material (PCM) are studied both experimentally and numerically. For this purpose, water is considered as the phase changing material. The phase change phenomenon is initiated by dipping a cryocooled steel sphere into a tank full of water. The results are presented in the form of variation of ice thickness at different angular locations with time, the solidification time, the melting time, and the average thickness of ice. The solidification of water and melting of ice showed an axisymmetric nature indicating the flow condition to be laminar for the studied cases. However, it has been observed that the convection effect plays a major role during the melting process which results in an uneven melting of ice over the sphere.

***Keywords*:** Solidification, Melting, Experimental, Numerical, Phase change material

INTRODUCTION

In Industries, PCM (Phase Change Material) is an important topic, which is also very essential for different devices like refrigerators, condensers, evaporators, ice storage tanks, LHTES (Latent Heat Thermal Energy Storage) systems. These PCMs are also used for conservation and transportation of temperature sensitive materials. These are required to be used efficiently such that its maximum energy storing capacity can be utilized. They act as working fluid, so they must be kept or used with geometries providing better efficiency for heat transfer. Water is the most common and very widely used PCM. The PCM used now a days are stored inside cylindrical tanks, rectangular tanks, plates or spherical capsules. Recently, spherical encapsulation is preferred over other structures because of its higher heat transfer area in relation with the volume.

The ice formation through natural convection was first studied by Riley et al. [1]. They studied solidification of PCMs inside the sphere and cylinder. The solidification was started by sudden chilling of these containers. Cheng et al.[2] experimentally studied the ice formation around cylinder in cross-flow and it was performed under temperature range of 6.3^oC to 75.8^oC. Moore and Bayazitoglu [3] prepared a mathematical model and found the energy storage characteristics and convective effects due to melting within spherical enclosed cavity. Hartnett and Minkowycz [4] did experiment of freezing of super-heated water around isothermal horizontal cylinder and used shadow graph technique to visualize plume development and photographically recorded the contour formed. In an another study, Cheng et al. [5] studied the ice formation around horizontal cylinder by dipping it inside a steady water bath at ambient temperature and found the Nusselt number, Local heat transfer coefficient and average Nusselt number behavior at stagnation point. Chen et al. [6] provided the correlation between Nusselt number and Modified Grashoff number. Fukusako and Yamada [7] did lot of studies on varieties of water freezing and ice melting problems and represented effects like decrements in flow rate, hydraulic pressure loss, and damage caused by blockage due to ice formation in pipes. These experiments were further carried out on immiscible fluids. Yamada et al. [8, 9] immersed cylinders inside immiscible fluid, i.e. vegetable oil. The experiment was carried out with hot and cold tube which had respective temperatures of 8.0^oC

to 30^oC and-5.0^oC to-13.0^oC and, later, they did the experiment by immersing vertical ice cylinder. Chen and his group [10, 11] studied about supercooling and freezing inside a cylinder placed horizontally. They studied the effect of cooling rate and internal diameters of cylinders. Further, they carried out experiment on different types of nucleation agents that are silver iodide (AgI), lead iodide (PbI_2) and concluded that nucleation was increased by Silver Iodide more than any other material. Few of the recent studies on cylindrical and spherical geometries include that of Yoon et al. [12], Habeebullah [13], Buyruk et al. [14], Ezan et al. [15] and Khodadadi and Zhang [16], Tan et al. [17] respectively.

Beside all these studies, the literature survey reveals that most of the studies are limited to cylindrical geometries. However, very few authors have considered the spherical geometries. As we know that sphere is more effective than cylinders and any other geometries so in this study, freezing of water is considered over the surface of an isothermally cryocooled sphere. The study is performed through experiments and numerical modeling. The results are presented in terms of time of solidification, time of melting and the thickness of ice formed at different axial locations. Overall solidification of water and melting of ice are discussed in detail. Also, the numerical results are compared with the experimental results and are presented in the following section.

Experimental Work and Methodology

Setup and Materials required

In this experimental setup, as shown in Figure 1, water tank of $30cm \times 30cm \times 30cm$ dimension was made by Acyrilic Sheet (Poly methyl methacrylate) or PMMA which is having very high transparency and is $5mm$ thick. Steel sphere of three different standard diameters, i.e $4.14cm$, $3.18cm$ and $2.72cm$ is used.

[Figure 1 about here.]

For lifting up the spherical ball and dipping it inside the liquid nitrogen container, a net made of high density polyethylene (HDPE) is used which was tied by string made up of high-modulus Vectran fiber. A wooden ply is used for carving out frame which supports the water tank as well as for hanging the steel sphere and a pin has been hooked to top-center of wooden frame, where string can be tied easily within 2 seconds. A high resolution camera, Sony Cybershot WX 350, is used for visualization of solidification and remelting processes. An LED light is also fixed for proper visualization. All the experiments were performed under normal room temperature at 20^oC.

Procedure

In this experiment, first of all the solid steel sphere is dipped inside the liquid nitrogen container. Usually 8 to 10 minutes are required for steel sphere to reach the liquid nitrogen temperature. During this time there is boiling of liquid nitrogen. Ultimately, the boiling stops once the steel sphere acquired the liquid nitrogen temperature. After this, the ball is lifted up by the string tied with the net and it is dipped inside the water tank gently to avoid any possible vibration. The freezing and thawing processes take place and as the meting process is completed, the ball is again lifted up and is allowed to dry and attain the room temperature. In this way, a single experiment is completed and the same procedure is repeated with other sizes. Video and images of the solidification and remelting processes have been captured at different time instants.

Numerical Modeling

Because of the symmetry of the problem, axisymmetric Navier-Stokes equations along with the energy equation incorporating the phase change phenomenon are solved using finite volume approach. To solve the energy equation, single region (or continuum) enthalpy formulation is implemented. A Darcy law type porous medium formulation, due to Voller and Prakash [18], is utilized to account for the effect of phase change on convection.

The two-dimensional axisymmetric Navier-Stokes equation along with energy equation have been discretized on a structured collocated, non-orthogonal multiblock grid system using finite volume approach. The grid with two structured blocks used for this simulation is shown in figure 2.

[Figure 2 about here.]

The governing equations were solved using SIMPLE algorithm of Patankar [19]. A multiblock grid system having two blocks of 80 × 80 and 80 × 200 was found to be sufficient to resolve the details of flow, temperature fields and the liquid-solid interface positions. The first block corresponds to the grid system used for steel ball while second one is used for meshing the entire water domain. The temporal discretization was done using implicit three time level scheme. Detailed discussion about the structured multiblock system adopted here can be found in Ferziger and Peric [20].

RESULTS AND DISCUSSION

Experimental Results

The experiment is performed a number of times with three different sizes of steel balls and the picture is taken at different time instants during solidification of water and melting of ice. As steel ball is cooled to the liquid nitrogen temperature and then dipped inside the water tank, freezing of water starts instantly. More or less the solidification is mostly governed by the diffusion process in the beginning which is reflected in almost spherical layer of ice thickness over the steel sphere; as can be seen in Figure 3(a).

[Figure 3 about here.]

Thereafter, the convection plays some role which results in thicker ice layers towards the bottom. This figure presents the solidification of water over a cryocooled sphere of 4.14 cm diameter. When solidification starts, the water in contact with sphere starts loosing its sensible heat and latent heat within fraction of seconds and starts freezing. Due to convective effect uneven solidification starts, this unevenness can be seen in Figure 3(a) which is taken at 30s of the solidification process. With the passage of time ice thickness increases as we can see in the Figure 3(b). The ice thickness keeps on increasing during solidification process as it can be seen in Figure 3(c) and 3(d).

[Figure 4 about here.]

At t = 120s the solidification process is almost completed. After this the melting starts. Due to natural convection heat transfer, melting process starts unevenly which is reflected by spheroidal shape of the frozen ice. For this case, the buoyancy takes place from top to bottom, causing top surface to melt faster compared to the bottom surface. That is why bottom surface of sphere is having more ice thickness as we can see in Figure4(b) and at this time the melting is more pronounced near the top part of sphere; this is due to buoyancy-driven convection. This also can be observed in Figures 4(c), (d) and (e). Similar observations have also been noticed for other spheres with only difference in total time of melting.
The ice thickness at different angular locations, viz. 0^0, 90^0, and 180^0 is also found out for the studied cases at different time instants. Figure 5 shows the evolution and destruction of ice layer with time during solidification and remelting processes for all the studied cases.

[Figure 5 about here.]

This figure also presents the numerical results obtained by solving the axisymmetric Navier-Stokes equations along with the energy equation. It is quite clear that in the beginning of the solidification process, diffusion is dominating. Later on, buoyancy effect plays a role which results in longer time in remelting of the bottom ice layer as compared to the other locations.

Comparison of Experimental and Numerical Results

The overall process of solidification of water and melting of ice for 3.18 cm sphere is compared in Figure 6.

[Figure 6 about here.]

The left part of figure shows experimental result and the right side shows numerical result at different time instances. In this figure, the shaded portion indicates the portion of sphere which is below 0^oC. The ice thickness formed at different time instances are almost similar for both the cases. The ice layer formed in both the cases can be clearly seen. It can be noticed that during the solidification and remelting processes, the growth and the decrement of ice layer are almost symmetric. The melting takes place unevenly because of the natural convection effect. That is why, the top part melts much earlier than the bottom part. Similar observations have been noticed for other steel balls having diameters of 4.14 cm and 2.72 cm.

CONCLUSION

The experimental and numerical analysis is performed for solidification of water and melting of ice around cryocooled sphere. The following conclusions are drawn:

1. Solidification of water and melting of ice follow similar trend irrespective of the size of spheres.
2. Melting time is more compared to the respective solidification time irrespective of the size of spheres.
3. The thickness of ice formed at the bottom is always more compared to other portion irrespective of the size of sphere. This is due to Buoyancy-driven natural convection effect.
4. The ice thickness at any angular locations always increases with increase in the radius of sphere.

References

[1] Riley, D. S., Smith, F. T., and Poot, G., 1974. “The inward solidification of spheres and circular cylinders”. *International Journal of Heat Mass Transfer,* ***17***, pp. 1507–1516.

[2] Cheng, K. C., Inaba, H., and Gilpin, R. R., 1981. “An experimental investigation of ice formation around an isothermally cooled cylinder in crossflow”. *Heat Transfer,* ***103:4***, november 1, pp. 733–738.

[3] Moore, F. E., and Bayazitoglu, Y., 1982. “Melting within a spherical enclosure”. *Journal of Heat Transfer,* ***104:1***, Feb, pp. 19–23.

[4] Hartnett, J., and Minkowycz, W., 1984. “Effect of natural convection on freezing of water around an isothermal horizontal cylinder”. *International Communications in Heat and Mass Transfer,* ***11:4***, July‘, pp. 301–310.

[5] Cheng, K. C., Inaba, H., and Gilpin, R. R., 1988. “Effects of natural convection on ice formation around an isothermally cooled horizontal cylinder”. *Heat Transfer,* ***110:4a***, nov 1, pp. 931–937.

[6] Chen, S. L., Liang, S. S., and Hong, J. T., 1992. “Effects of natural convection on ice formation inside a horizontal cylinder”. *Experimental Heat Transfer An International Journal,* ***5***, April, pp. 131–145.

[7] Fukusako, S., and Yamada, M., 1993. “Recent advances in research on water-freezing and ice-melting problems”. *Experimental Thermal and Fluid Science,* ***6***, pp. 90–105.

[8] Yamada, M., Fukusako, S., and Sayed, M. E.-B., 1996. “Free convection heat transfer around a horizontal ice cylinder formed through melting within an immiscible liquid”. *Journal of Heat and Mass Transfer,* ***31:6***, August, pp. 419–426.

[9] Yamada, M., Fukusako, S., and Sayed, M. E.-B., 1997. “Experiments on melting of a vertical ice layer immersed in immiscible liquid”. *Heat and Mass Transfer,* ***32:6***, July, pp. 447–454.

[10] Chen, S. L., and Lee, T. S., 1998. “A study of supercooling phenomenon and freezing probability of water inside horizontal cylinders”. *International Journal of Heat and Mass Transfer,* ***41***(4-5), pp. 769–783.

[11] Chen, S.-L., Wang, P.-P., and Lee, T.-S., 1999. “An experimental investigation of nucleation probability of supercooled water inside cylindrical capsules”. *Experimental Thermal and Fluid Science,* ***18***, pp. 299–306.

[12] Yoon, J. I., Kwon, O. K., Moon, C. G., Son, Y. S., Kim, J. D., and Kato, T., 2000. “Numerical study on cooling phenomenon of water with supercooled region in a horizontal circular cylinder”. *Numerical Heat Transfer, Part A,* ***38:4***, pp. 357–376.

[13] Habeebullah, B. A., 2007. “An experimental study on ice formation around horizontal long tubes”. *International Journal of Refrigeration,* ***30***, pp. 789–797.

[14] Buyruk, E., Fertelli, A., and Sonmez, N., 2009. “Numerical investigation for solidification around various cylinder geometries”. *Scientific & Industrial Reasearch,* ***68***, February, pp. 122–129.

[15] Ezan, M. A., Erek, A., and Dincer, I., 2011. "A study on the importance of natural convection during solidification in rectangular geometry". *Journal of Heat Transfer,* ***133***, August.

[16] Khodadadi, J., and Zhang, Y., 2001. "Effects of buoyancy-driven convection on melting within spherical containers". *International Journal of Heat and Mass Transfer,* ***44***, pp. 1605–1618.

[17] Tan, F., Hosseinizadeh, S., Khodadadi, J., and Fan, L., 2009. "Experimental and computational study of constrained melting of phase change material (pcm) inside a spherical capsule". *International Journal of Heat and Mass Transfer,* ***52***, pp. 3464–3474.

[18] Voller, V. R., and Prakash, C., 1987. "A fixed grid numerical modelling methodology for convection-diffusion mushy region phase-change problems.". *International Journal Heat and Mass Transfer,* ***30***(8), February, pp. 1709–1719.

[19] Patankar, S. V., 1980. *Numerical Heat Transfer and Fluid Flow.* Hemisphere Publishing Corporation.

[20] H.Ferziger, J., and Peric, M., 1999. *Computational Methods for Fluid Dynamics.* Springer.

List of Figures

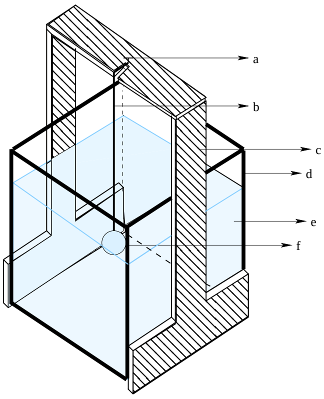


Figure 1: Experimental Setup (a) Holding pin (b) Polymer string (c) Wooden Frame (d) Acrylic tank (e) Water (f) Metal Sphere

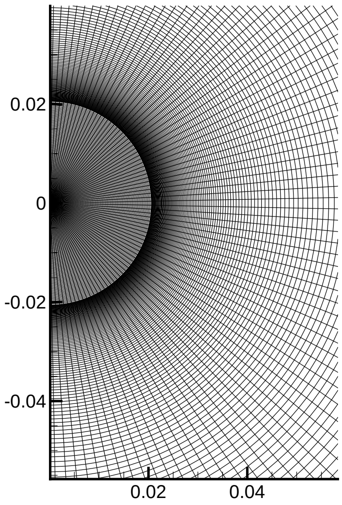
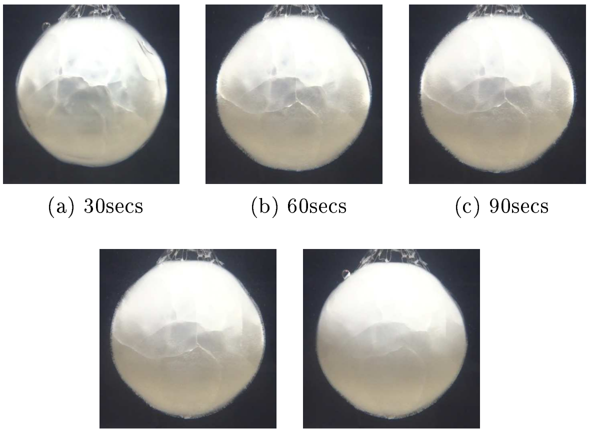


Figure 2: 2-Dimensional computational grid of sphere and water

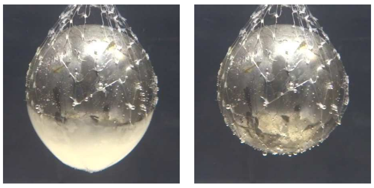


(a) 30secs (b) 60secs (c) 90secs

(d) 120secs (e) 150secs

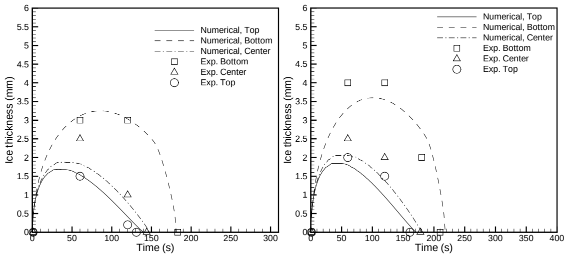
Figure 3: Solidification of Water

(a) 180secs (b) 210secs (c) 240secs

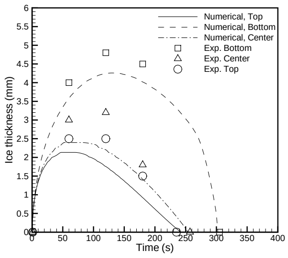


(d) 270secs (e) 300secs

Figure 4: Melting of Ice

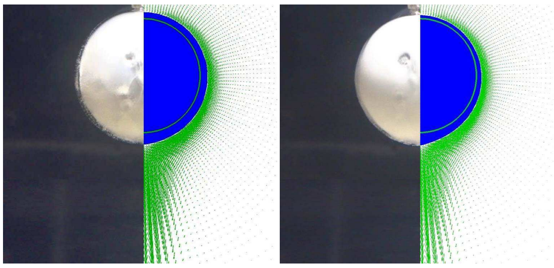


(a) 2.72cm diameter (b) 3.18cm diameter

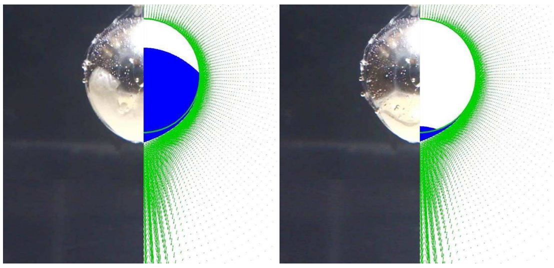


(c) 4.14 cm diameter

Figure 5: Graph showing solidification and melting patterns for different spheres



(a) 60secs (b) 120secs



(c) 180secs (d) 190secs

Figure 6: 3.18cm sphere