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A PIV and CFD Analysis of Natural Convection Ice Melting

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Abstract

An experimental (PIV) and numerical (CFD) analysis of the melting of a vertical cylindrical ice cube in water at different temperatures has been carried out. The objective was to examine the effects of the density inversion of water, which occurs at 4°C approximately. In this experiment a PIV analysis was carried out and vector maps of the flow field were be obtained. These results were then compared with a numerical model of the ice melting process.

Key-words : Ice melting, natural convection, phase change, density inversion, PIV, CFD.

1. Introduction

The analysis of convective heat transfer with solid-liquid phase change is important in a broad range of scientific and engineering fields. These may be found in the solidification and melting phenomena commonly encountered in metallurgical processes, latent heat thermal energy storage, oceanography and nuclear reactor safety. Such a case involving heat transfer with phase change coupled with a moving solid-fluid boundary is often referred to as a *Stefan* problem.

In this paper an experimental (PIV) and numerical (CFD) analysis has been carried out in order to better understand and predict the thermodynamic and transport processes involved in the *Stefan* problem by considering melting of a vertical ice cylinder in a surrounding water environment. A literature review has highlighted that general work in this field has been relatively extensive, however, little or no studies appear to have been carried out on vertical ice cylinders particularly with regard to PIV analysis and numerical simulation of natural convection heat transfer involving a moving boundary with coupled phase change. The problem is also an interesting one as it covers the range over which the density extremum in water occurs (maximum density at approximately 4^{o}C) which influences the natural convection process.

Experimental investigations have been carried out on vertical ice surfaces melting into water. In these studies, water at temperatures in the vicinity of the density extremum was considered. Bendell and Gebhart [1] used thermocouples to indicate whether the natural convection flow was up or down. In the experimental work of Van P. Carey and Gebhart [2], flow patterns were visualised by seeding the water and illuminating the flow field with a sheet of laser light. Wilson and Vyas [3] applied the thymol-blue technique in order to visualise the velocity profile occurring in the natural convection boundary layer.

Experimental studies for melting problems with other geometries have been considered. Oosthuizen and Xu [4] presented evidence that the flow around a horizontal melting ice cylinder is three-dimensional in nature. Gebhart, Bendell and Shaukatullah [5] were the first to analyse natural convection flows adjacent to horizontal surfaces in cold water. Gebhart and Wang [6] melted short vertical ice cylinders into cold fresh water in order to visualise the melting and resulting convective motions.

Fukasako and Yamada [7] have presented an extensive summary of the work carried out on water freezing and ice melting problems. Subject areas such as analytical and numerical methods for freezing and melting problems, freezing of water with and without convective flow and atmospheric and marine icings have been considered.

In relation to the numerical side of melting problems, various problem geometries and solution methods have been considered. Wilson and Lee [8] presented a finite difference analysis for the leading portion of a vertical ice sheet as it melted into fresh water. Wang [9] conducted a numerical study into the buoyancy-induced flows next to a vertical wall of ice melting in porous media that was saturated with water. In the paper of Van P. Carey, Gebhart, and Mollendorf [10] numerical results for laminar, buoyancy induced flow adjacent to a vertical isothermal surface in cold, pure or saline water were presented.

In [11], Sparrow, Patankar and Ramadhyani used a finite difference scheme to analyse the melt region created by a heated vertical tube embedded in a solid, which was at fusion temperature. Ng, Gong, and Mujumdar [12] used a streamline-upwind / Petrov-Galerkin finite element method to simulate the melting of a phase change material in a cylindrical, horizontal annulus heated isothermally from the inside wall. Wu and Lacroix [13] used a stream function-vorticity-temperature formulation to track the position of the solid-liquid interface for an ice cylinder melting.

2. Experimental analysis

The experiment consists of an ice-cylinder of dimensions 20 cm height and 5 cm diameter which is immersed in water that has been cooled to different temperatures. The top of the cylinder was effectively insulated with a layer of polystyrene. As the problem is axisymmetric, the flow field was studied only on a single plane of the cylinder axis.

The instrumentation used for the PIV analysis consisted of a 5W Argon-ion laser with a continuous wave output to illuminate the flow. Its beam became a thin sheet of light of approximately 1 mm thickness when passed through the cylindrical lens. The flow was recorded using a CCD camera connected to a Kodak Motioncorder Analyser Model 1000 and a video recorder. Also, in order to reduce the effect of diffraction of the laser light through the glass, the cylinder of water was placed in a tank of water, as shown in Figure 1 below:

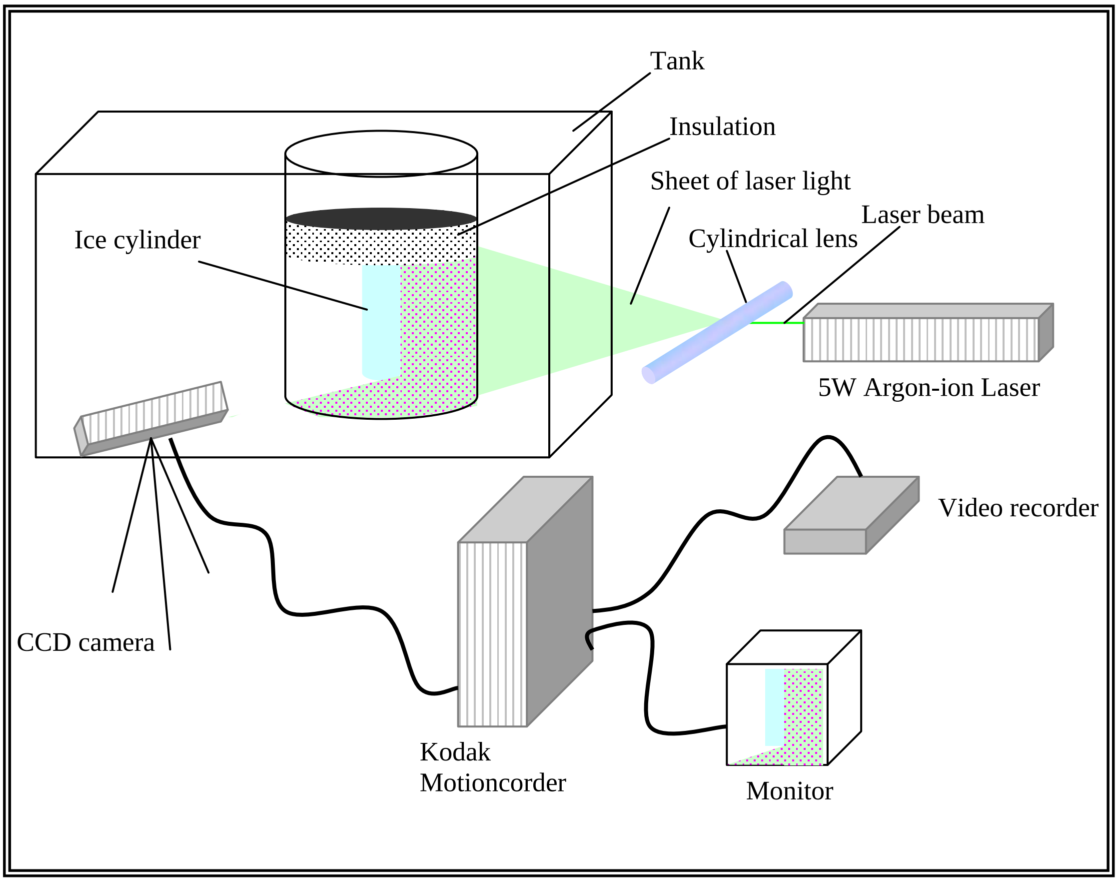


Figure 1 *Experimental set up for the PIV analysis*

Fluorescent seeding particles of diameters between 20 and 40μm were incorporated into the water and were assumed to be effectively neutrally buoyant. Since these particles only reflect light at the same frequency as the laser this helped greatly to reduce the glare from the laser light reflected on the air bubbles present in the ice cylinder. The presence of air bubbles in the ice crystal was minimized by using water which had been treated using a vacuum pump and ultrasonic bath prior to freezing.

At the beginning of each experiment, it was necessary to record a few sample frames in order to obtain the experiment reference scale. Then the ice crystal was then immersed immediately in the water when its temperature had achieved -10°C. This was found to be the minimum freezing temperature that would prevent the ice from thermal stress cracking when introduced into the water.

The flow was then recorded using the Kodak Motioncorder Analyser. It records short spells (3 seconds) with a rate of 30 frames per second. Thus, approximately 100 frames of the flow field were stored during each analysis. These frames were then captured using software Adobe Premiere® and then modified into greyscale pictures with software Picture Publisher®. The software VidPIV™ was the applied to produce the vector maps associated with the frames. This software performed a cross-correlation between two successive frames to obtain vector maps.

Attention was focused on obtaining good quality images of the flow. For the experiment with a water temperature of 7°C, condensation continually appeared on the walls of the tank thus cleaning them with antifreeze was often necessary. Other issues related to the quality of the pictures concerned the reflection of light on the walls of the tank. The optimum images were obtained in a darkened room, where reflections were minimised. The following figures show the melt profile results for an initial water temperature of 7 ^{o}C:

Figure 2 *Seeded flow laser illuminated image*

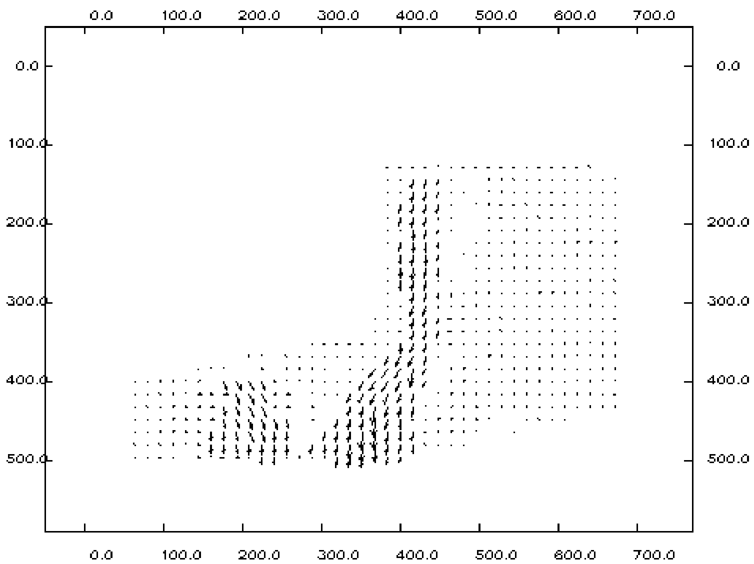


Figure 3 *Typical PIV Image of melt flow*

3 Numerical analysis

A numerical analysis of the ice cylinder configuration shown in has been carried out. The following equations have been solved using the commercially available CFD code Fluent [14]:

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla . \rho \boldsymbol{u} = 0 \tag{1}$$

Momentum equation:

$$\frac{\partial \rho \boldsymbol{u}}{\partial t} + \nabla . (\rho \boldsymbol{u}\boldsymbol{u}) = -\nabla p + \nabla . (\mu \nabla \boldsymbol{u}) + \rho \boldsymbol{g} \tag{2}$$

Energy equation:

$$\frac{\partial \rho c_p T}{\partial t} + \nabla . (\rho \boldsymbol{u} c_p T) = \nabla . (k \nabla T) \tag{3}$$

The Fluent code has been applied to solve the above equations using axisymmetric Cartesian co-ordinates. The pressure-velocity coupling is accounted for using a method based on the SIMPLE [15] algorithm. As such low velocities were encountered (typically 1.0 cm/s) and cell Peclet numbers were of the order of 1.0, numerical diffusion was not considered to be significant thus the first order upwinding [15] was adopted for convective discretisation of all transported variables. For temporal discretisation a fully implicit scheme was employed.

A computational grid of 9000 cells was employed with time steps in the order of 6 seconds. This led to calculation times typically of 8 hours on a Pentium III PC and the solution was declared converged within each time step when the global sum of the mass, momentum and thermal residuals were 0.001 times their initial values.

Equations (2) and (3) have been modified in order to account for the following features of the flow:

1) The density inversion within water between 0.01 ^{o}C to 17 ^{o}C within which the density follows a non-linear path, attaining its maximum value at approximately 4 ^{o}C. This density-temperature relationship has been formulated by Gebhart and Mollendorf [16] according to:

$$\rho = \rho_m \left(1 - w|T - T_m|^q\right) \tag{4}$$

where ρ_m is the maximum density (ρ_m = 999.972 kg/m^3) and $w = 9.2793 \times 10^{-6}$ (^{o}C)$^{-q}$, T_m = 4.0293 ^{o}C and q = 1.894816 are constant values proposed by Gebhart and Mollendorf

2) The transport properties k and ρ within the ice and k and μ within the water were set as constant values.

3) The energy and momentum equations are solved in such a manner that if the temperature falls below 0.01 °C within any iteration within any numerical time step the convection terms within these equations are switched off thus allowing only transient, diffusion and source terms to influence this '*pseudo-solidified*' region.

4) A '*mushy-zone*' is identified and this region is confined to lie within a particular temperature bandwidth ΔT, which typically has a range -0.5 °C < ΔT < 0.01 °C. It is within this bandwidth that phase change is assumed to occur and thus the variation in $c_{p(mush)}$ contained within the transient term of the energy equation may be written as $c_{p(mush)} = \Delta h_{fus} / \Delta T$ where Δh_{fus} is the latent heat of fusion (ice to water), as detailed in Figure 4 below:

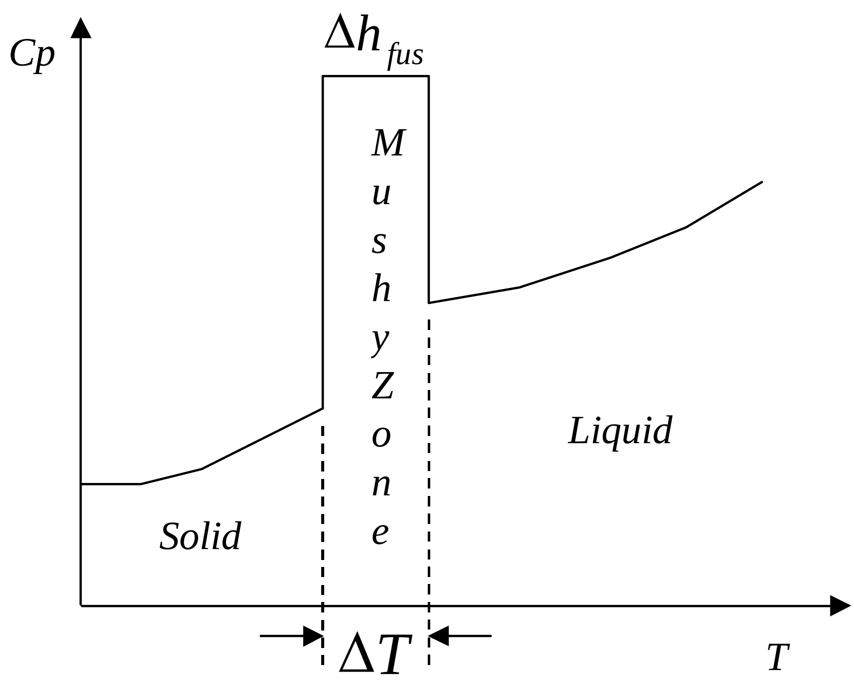
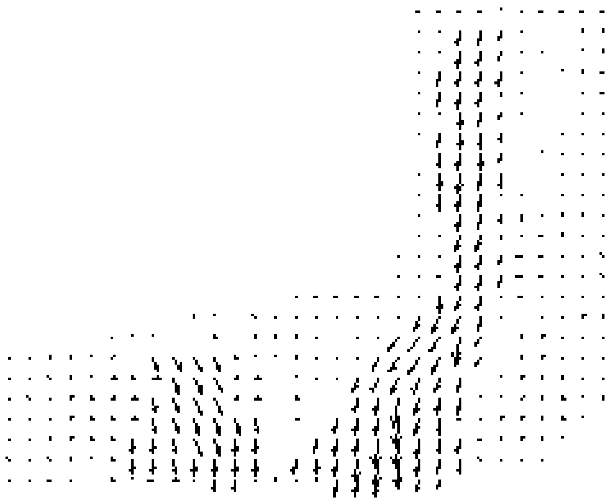


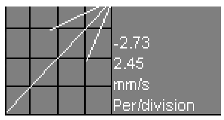
Figure 4 *Variation in specific heat capacity c_p against temperature*

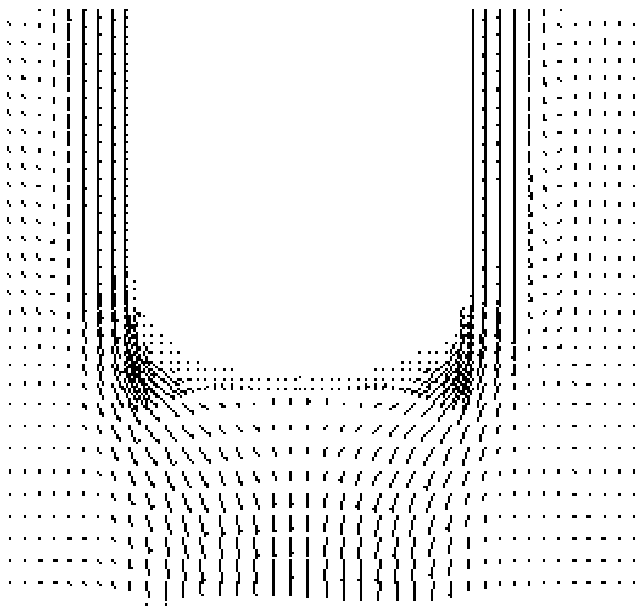
4 Results and discussion

Figure 5 below illustrates the comparison between the PIV and CFD obtained images. The results show a good concurrence between the experimental and numerical data in terms of qualitative information. The general flow patterns around the ice crystal appear to have been reasonably well captured in terms of the velocity profiles in the boundary layer and the separated flow underneath the ice cylinder.



a) PIV





b) CFD 0.01

Figure 5 *Experimental (PIV) and numerical (CFD) images of velocity distribution (Initial T_{ice} = -10^{o}C, T_{water} = 7 ^{o}C, t = 1 min)*

5 Conlcusions

An experimental (PIV) and numerical (CFD) investigation of natural convection ice melting has been carried out. The results show that this complex transient phenomenon can be qualitatively captured using computational fluid dynamics and particle image velocimetry.

Future work will include programming the influence of all transport properties as a function of temperature in the numerical model with grid adaptation also a possibility and the use of PIV for quantitative experimental work across a wider range of water temperatures.

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