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NUMERICAL AND EXPERIMENTAL ANALYSIS OF ICE MELTING IN WATER

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Abstract. *The numerical simulation of ice melting in water considering temperature-dependent material properties and phase-change effects is proposed in this work. The governing differential equations (continuity, linear momentum and energy) are spatially discretized within the finite element method together with a implicit Euler scheme for the time derivatives. The melting of ice initially at –4.3 ºC and surrounded by water at approximately 15 ºC is particularly studied. The effects of variable properties, the incidence of natural convection and different environmental transfer conditions are analyzed with the aim of computing the temperature evolution at various points of the domain. Moreover, the model is validated by comparing the obtained predictions with experiments carried out in the context of this work.*

1 INTRODUCTION

Phase-change phenomena involving convective effects are presented in different industrial applications like refinement of metals, casting or freezing procedures. Nowadays computational simulations are recognized as a relevant tool that help to predict physical behaviors and to identify mechanisms involved during different processes. Nevertheless, physical scaled models continue being an important resource of data employed to evaluate engineering requirements. On the other hand, numerical analyses of such problems present difficulties related to mathematical and computational aspects of the models. In particular, several efforts have been devoted to develop thermally-coupled flow formulations including phase-change and to assess numerical and experimental validations of the proposed methodologies [see 1-2 and references therein]. In this work we present an experiment of ice melting in water and its simulation allowing us to evaluate the performance of the fixed-mesh finite element formulation proposed in [1-2]. The aims of this work are: to check the numerical behavior with particular material properties (inversion density phenomena and isothermal phase change), to evaluate the influence of different physical conditions in the heat-transfer process and to validate numerical predictions with laboratory measurements.

The experiments are reported in Section 2 where a brief description of the methodology used in the measurements is commented. The numerical results obtained for different situations (purely conductive and convective analyses and water-environmental heat transfer vs. adiabatic conditions) are shown in Section 3. Finally, the work concludes with a comparison between the computational predictions and the measurements.

2 EXPERIMENTAL PROCEDURE

The experiment was designed considering: a material with melting temperature in the normal environmental range, to obtain recurrently measurements and to reproduce conditions closer to two dimensional situations. To this end, a rod of ice ten times longer than the side of its transversal section is submerged in a box of glass filled with water. The dimensions of the rod and box are sketched in Figure 1. The thermocouples (type T, cupper-constantan 1.5 mm) are positioned in the middle longitudinal plane as shown in Figure 2. In what follows the thermocouples will be identified with the number depicted in such Figure. Thermocouple 11 serves as environmental temperature controller as well as measurements taken from thermocouples 1, 8, 10, 15 and 14 contribute to evaluate the influence of the heat-transfer along the water interface and the glass walls. Thermocouples initially situated in 12 and 13 where moved to positions 12’ and 13’ after the evidence that they did not provide relevant information during the analysis. All the thermocouples are calibrated with a digital thermometer where the average error in the measurements is estimated as ±0.5ºC. The ice rod is frozen during almost 5 hours at –55 ºC. Such temperature was chosen to avoid a crack due to thermal shock when the rod is submerged in water at environmental temperature (the registered rod ice temperature at that instant was –35ºC). The frozen temperature needs to be low enough to produce a uniform and complete solidification. The experience starts registering the initial air and water temperature. To obtain nearly constant initial values in all the experiences, they were carried out during the same daily period in summer. After that, the ice is fixed to the bottom in the middle of the glass box. The measurement device, that consists of a wood support for the thermocouples previously connected to the computer, is finally positioned. That instant is taken as the initial time for the experience. The temperatures are registered during 10 minutes but, considering the observations, the valid measurement range is up to the time when the ice breaks at its ends and releases the clips. A set of nearly twenty experiments were carried out but only eight were accepted considering a reasonable recurrence in the following facts: initial air and water temperatures, a square rod section (with a maximum admissible error of ±1mm that approximately corresponds to 7% of the side) and the permanence of the rod in the correct position during the test (evaluated through a visual observation confirmed by similar temperature evolutions registered by the thermocouples symmetrically located). According to that, only the measurements taken during approximately the first 4 minutes were considered. Figure 3 illustrates the experiment layout described above. One of the experiences that satisfied all the mentioned conditions is reported in the present work. The initial square section of the rod is 30 mm wide and 28 mm height, the environmental temperature is 25.9 ºC and the initial water temperature is 14.7ºC. The final rod height is 20 mm which implies a reduction of approximately 30% in its volume. The temperature measurements are presented in Figure 4. They show similar evolutions in points symmetrically located and greater temperature variations for those close to the ice in the bottom of the cavity. The unexpected temperature behavior registered by thermocouple 16 situated in the center of the ice rod denotes a localized early melting processes due to metal-ice contact effects.

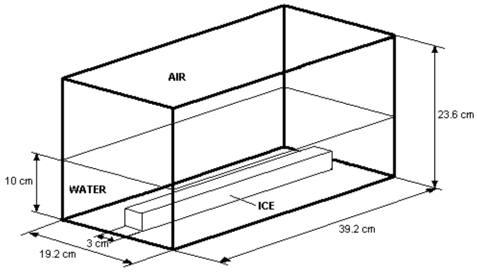

Figure 1. Experimental setup: geometry.

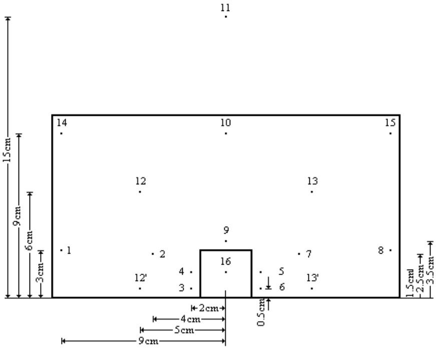

Figure 2. Experimental setup: thermocouple layout.

3 NUMERICAL RESULTS

The simulations are computed using a thermally-coupled incompressible flow analysis for a Newtonean fluid [1-2]. The buoyancy effects are described with a Boussinesq type approach that defines the thermally induced weight changes using a four order polynomial function able to deal with inversion effect. The temperature relationships for different properties (density, viscosity and thermal conductivity) are taken from [3]. A constant latent heat L=335000 J/kg and a constant heat capacity c=4182 J/kgºC are considered. The density value at 0ºC is taken as a reference value (ρ_{ref}=999.8395 kg/m^3).

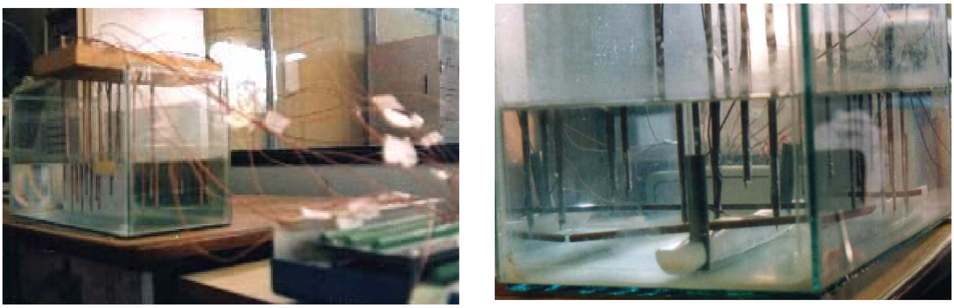

Figure 3. Experimental setup: view of the fixed ice rod and measurement device.

The initial water and environmental temperatures used in the computations are 15ºC and 26ºC, respectively. Due to the symmetry, only a half of the domain described in Figure 2 is analyzed. The finite element mesh is composed of 80x80 standard four-noded elements. The time step size used is 0.5s. Three different cases are studied: a purely conductive model (case A), a natural convection analysis with adiabatic glass walls (case B) and a natural convection system considering heat-transfer effects in the cavity walls (case C). For case C, a heat-transfer coefficient of 250 W/m^{2}ºC is chosen as a boundary condition representing the glass walls with a thickness of 4mm. The obtained temperature evolutions at different points are plotted in Figure 5 together with the experimental ones. The purely convective model exhibits practically the same temperature evolutions for points 5 and 6 showing a high reduction of their temperatures with respect to the initial ones. A constant temperature history is obtained for points 7, 8 and 13′ denoting that the heat-flux does not reach their positions during the analysis. Moreover, the temperature evolution predicted by model A exhibits a significant discrepancy with the measurements (see points 5, 6 and 13′). Model B including natural convection and adiabatic walls is proposed on the basis of the experimental fact showing a nearly constant temperature registered near the walls (e.g., point 8) denoting an insignificant heat flux through the glass. The fluid motion induced by buoyancy effects affects the temperature evolution. In particular, the temperature in points near the bottom of the cavity decreases drastically (point 13′). Moreover, point 5 shows temperatures greater than those predicted by model A while the temperature evolution of point 6 matches the results of model A after a jump experienced around 70s. Nevertheless, the results differ from the experimental ones. Due to this, the model is modified in order to evaluate the effects of the heat transfer along the glass wall (model C). The corresponding results also shown in Figure 5 agree satisfactorily with the experimental measurements. As was commented, the local melting produced in the vicinity of the thermocouple 16 is not captured by the models. The final volume of the ice is computed as 70% of the original one; this value is close to the measurements.

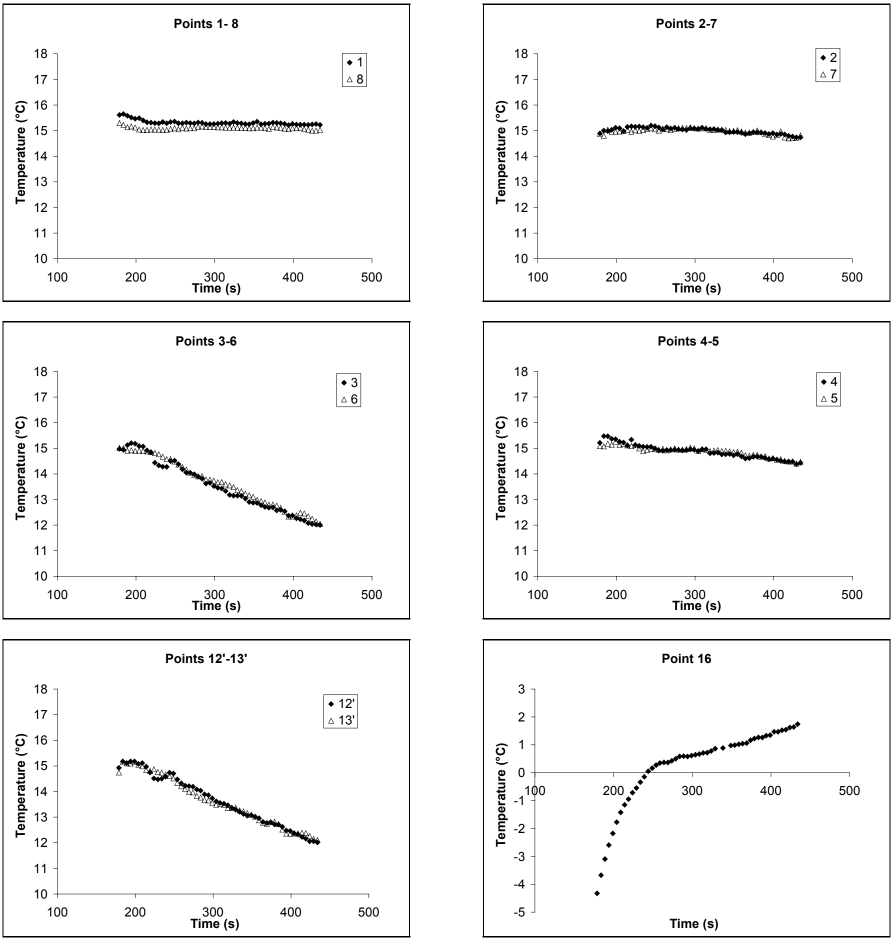

Figure 4. Experimental measurements: Temperature evolution at different points.

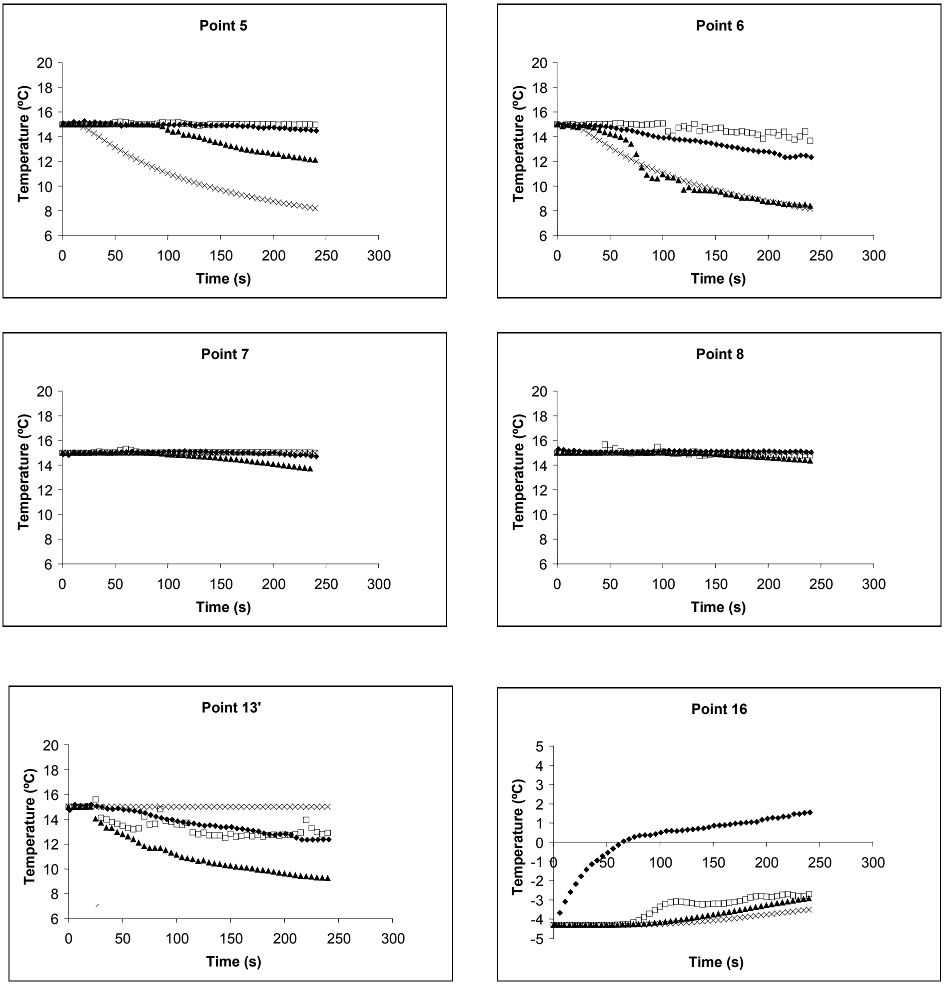

Figure 5. Simulation: Temperature histories at different points under different modeling conditions. × Case A;

▲ Case B; □ Case C; ♦Experimental.

Finally, it should be noted that some dimensionless numbers associated to this problem are the Rayleigh number ($Ra=\beta g\Delta T\rho^2 l^3/(\mu k)$) of $1.1\mathrm{x}10^7$ (based on a characteristic length l=0.1m, a temperature variation ΔT=15ºC, average values of expansion coefficient, isotropic conductivity and dynamic viscosity of $\beta=10^5$, k=0.57 and μ=0.001, respectively), a Stefan number of 0.2 ($St=c\Delta T/L$) and a Prandtl number of 7.3 ($Pr=\mu c/k$).

4 CONCLUSIONS

A physical model of ice melting in water has been developed. From the numerical simulation of the experience some remarks can be done. The heat transfer conditions along the glass walls seems to play an important role in the thermo-fluid behavior of the system studied. The numerical predictions obtained with the model including this aspect satisfactorily approach the measurements. A significant role of the buoyancy effects has been denoted in the experiments as well as in the numerical solutions. The numerical formulation has been able to deal with such effects and, in particular, with high characteristic dimensionless numbers. Nevertheless, some aspects related to the experiments, e.g. additional measurements in the ice, and also topics related to the numerical analysis, e.g. explanation of localized oscillations in the numerical response, need to be explored.

Acknowledgments

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5 REFERENCES

[1] M. Cruchaga and D. Celentano, "A finite element coupled flow formulation for phase-change problems", *Int. J. Numer. Meth. Fluids*, Vol. 34, pp. 279-305 (2000).

[2] M. Cruchaga and D. Celentano, "A fixed-mesh finite element thermally coupled flow formulation for the numerical analysis of melting processes", *Int. J. Numerical Methods in Engineering* , Vol.51, 1231-1258 (2001).

[3] M. Ishikawa, T. Hirata and S. Noda, "Numerical simulation of natural convection with density inversion in a square cavity", *Int. J. Numerical Heat Transfer*, Vol. 37, pp. 395-406 (2000).