International Journal of Heat and Fluid Flow 000 (2016) 1–11

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

journal homepage: www.elsevier.com/locate/ijheatfluidflow

Numerical investigation of transient natural convection heat transfer of freezing water in a square cavity

Mehmet Akif Ezan*, Mustafa Kalfa

Dokuz Eylül University, Faculty of Engineering, Department of Mechanical Engineering, Buca, İzmir, Turkey

ARTICLE INFO

Article history:
Received 29 November 2015
Revised 24 March 2016
Accepted 6 June 2016
Available online xxx

Keywords:
Transient model
Effectiveness
Solidification
Phase change

ABSTRACT

In this study, a transient heat transfer process of freezing water inside a two-dimensional square cavity has been investigated numerically. Water was used as a phase-change medium, and the numerical model has been created with control volume approach by using C++ programming language. To be able to accelerate the numerical calculations, CUT (Consistent-Update-Technique) algorithm has been implemented in the numerical code. Span-wise variations of the vertical component of the velocity have been represented in comparison with the experimental measurements from the literature at various vertical positions to examine the accuracy of the numerical scheme. The influence of natural convection has been considered by comparing the conduction and convection dominated solidification under same boundary conditions. Comparative results have been obtained regarding time-wise variations of the cold wall temperature and the dimensionless effectiveness. Moreover, the streamlines and isotherms have been represented to understand the differences between the conduction and convection driven phase change processes.

Results indicate that natural convection becomes remarkable and has different forms at the initial periods of the phase change process. Increasing the effect of natural convection in the cavity increases the cooling rate of water. Near the density inversion temperature of water (4°C), temperature variations fluctuate and counter currents observed in the domain.

1. Introduction

Natural convection in cavities is a problem of interest because of numerous applications in many natural and engineering processes. Solidification is relevant to the growth of crystals from liquids and solutions for the semiconductor industry, metallurgy, convection in magma chambers, oceanography, nuclear reactor safety and elsewhere. The process of freezing of water in enclosures is also common in many engineering applications. When temperature gradients exist in the liquid phase during a solidification process, they initiate a buoyancy-driven flow that may affect the shape of the ice/water interface as well as the progress of the solidification, significantly.

Temperature variations inside the fluid cause the density differences so that natural fluid motion occurs. Boussinesq approximation can be validly used to investigate the natural convection of the fluids that have linear density variations with respect to the temperature. Several fluids (i.e. *tellurium, gallium, antimony*, and *bismuth*) exhibit an extremum in their densities at specific temperatures. Water, on the other hand, is the most significant fluid where this kind of maximum in density occurs. As an instance, the density of water increases with the temperature range of 0°C to 4°C. Beyond 4°C, its density decreases in a nonlinear manner as the temperature passes through the critical value. Hence, 4°C is known as "*density inversion*" point in the literature (Lin & Nansteel, 1987). The effect of density inversion is also known to be important for convective heat transfer in the vicinity of the temperature where this maximum density occurs. During solidification of this type of fluid, the free convection driven by buoyancy develops in a complicated manner and controls the growth of the solid phase.

Transient natural convection in cavities has been studied both numerically and experimentally by numerous investigators. Some authors have simulated the behavior of the fluid under steady-state or transient natural convection conditions. All investigators have found that the density inversion strongly influences flow structure and heat transfer. Inaba and Fukuda (1984) investigated the flow in an inclined rectangular cavity where the temperature of one wall was maintained at 0°C while the temperature of the opposite wall was varied from 2 to 20°C. Lankford and Bejan (1986) conducted experiments in a vertical enclosure where a constant heat flux boundary condition was imposed on the vertical hot wall while the opposite wall was cooled. Seki et al. (1978) reported on

* Corresponding author. Tel.: +90 (232) 301 92 67; fax: +90 (232) 301 92 04.
E-mail address: mehmet.ezan@deu.edu.tr, mehmetezan@gmail.com (M.A. Ezan).

http://dx.doi.org/10.1016/j.ijheatfluidflow.2016.06.004
0142-727X/

Nomenclature

c	specific heat (Jkg^{-1}K^{-1})
C	heat capacity (Jm^{-3})
g	gravitational acceleration (ms^{-2})
h	convective heat transfer coefficient (Wm^{-2}K^{-1})
H	height of cavity (m), enthalpy (Jkg^{-1})
k	thermal conductivity (Wm^{-1}K^{-1})
p	pressure (Pa)
t	time (s)
T	temperature (°C, K)
u, v	velocity components (ms^{-1} / mm s^{-1})
U	overall heat transfer coefficient (Wm^{-2}K^{-1})
x, y	coordinates (m)
W	width of the cavity (m)
X	dimensionless horizontal coordinate (x/H)
Y	dimensionless vertical coordinate (y/H)
S	source term (Jm^{-3})
Greek letters	
ε	effectiveness (–)
δT	mushy range temperature (°C)
ϕ	variable
ρ	density (kgm^{-3})
μ	dynamic viscosity (kgm^{-1}s^{-1})
Subscripts	
c	cold
in	initial
l	liquid
m	maximum density, melting, mushy
ref	reference
s	solid
sf	solid-liquid
∞	ambient

an experimental and analytical investigation of two-dimensional natural convection in a rectangular cavity where the cold vertical wall was kept at 0°C while the opposite hot wall was maintained at a constant temperature between 1 and 12°C. Yewell et al. (1982) investigated transient natural convection in low-aspect-ratio ($AR = 0.0625$ and $AR = 0.112$) enclosures at high Rayleigh numbers. They used water as a working fluid at temperatures between 15 and 35°C, where the density inversion does not occur. Braga and Viskanta (1992) studied both numerically and experimentally, the effects of the density inversion on transient natural convection of water in a rectangular cavity. The initially isothermal (8°C $< T_h <$ 20°C) and motionless fluid was suddenly subjected to a cold temperature ($T_c = 0$°C) imposed at a vertical wall while the opposite wall was maintained at the initial hot-wall temperature. Ho and Viskanta (1984) reported basic solid-liquid interface data during the phase change of *n*-octadecane in a two-dimensional rectangular cavity with conducting vertical walls. The heating or cooling of the cavity was accomplished through the bottom wall. They concluded that for solid-liquid phase change heat transfer, short extended surfaces are more effective than longer ones. Hale and Viskanta (1984) determined the solid-liquid interface motion during the freezing and melting from above and below of several different substances (*not including water*) in a rectangular test cell. Only a few papers were found in which the freezing of water was studied in the literature. Cheng et al. (1988) used water as the working fluid to investigate the effect of natural convection on ice formation around an isothermally cooled horizontal cylinder. The stagnation point Nusselt number, the local heat transfer coefficient, and the average Nusselt number behavior at the ice/water interface were studied. Flow inversions caused by the presence of the density extension of water at 4°C seriously affected the heat transfer at the ice/water front as well as the development of this front. Chellaiah and Viskanta (1989) studied both experimentally and numerically the transient freezing of superheated water-porous media contained in a rectangular cavity. They studied the effect of an imposed horizontal temperature difference on the two vertical walls of a cavity that was initially filled with an isothermal and motionless fluid. Also, working with a water-filled porous layer, Sugawara et al. (1988) conducted a transient experiment where the top, cooled wall was kept at −20°C while the lower, heated surface was maintained at a temperature between 0 and 30°C. Once again, it was found in these experiments that the density inversion of water influences the convective motion as well as the solidification process. Borger and Westwater (1967) measured interface velocities and temperature profiles during the freezing of water and the melting of ice in a rectangular chamber with adiabatic vertical walls and heated or cooled horizontal walls. At the highest Rayleigh number studied, oscillations in the interface velocity were reported. Zaman et al. (2013) numerically studied the natural convective flow of air in a rectangular enclosure with two discrete hot sources from below for Rayleigh numbers 10^3 and 10^7. Wu and Ching (2010) experimentally investigated the natural convection in a square cavity with a horizontal partition of two different lengths attached to the heated vertical wall in two different locations. Blaszczuk (2013) experimentally investigated natural convection for different angles of inclination and thermal conditions of heating surfaces in a converging channel. Kamkari et al. (2014), on the other hand, investigated the natural convection driven phase change inside a rectangular cavity for various inclination angles. They have compared the time-wise variations of PCM temperature with hot wall temperatures of 55, 60 and 70°C and for different inclination angles of 0°, 45° and 90°. Kamkari and Shokouhmand (2014) extended this work by implementing horizontal partial fins on the hot wall. They have compared the evolutions of melting front for the cavities with and without fins. Moreover, two correlations are developed for the liquid fraction and Nusselt number in terms of non-dimensional parameters such as Fourier and Stefan numbers.

The present work was motivated by understanding the development of the flow structure and the capacity of thermal energy storage of water under different boundary conditions during solidification. Calculations were performed in a two-dimensional square cavity to study the transient flow in an initially isothermal and motionless fluid due to a step decrease in temperature on a specified wall. In analyzes, water was used as the phase-change medium; with the cold-wall temperature was kept below the freezing temperature of water. Heat gain was defined through the other three nearly insulated walls under certain ambient temperature and convective heat transfer coefficient. During the whole freezing processes, the initial temperature of water was maintained at a constant temperature that is greater than the temperature where density extremum occurs. The growth of ice and the transient flow in the cavity were visualized by the numerical method to examine the effect of the cold wall that has different positions, and overall heat transfer coefficients. It was found that the overall heat transfer coefficient of water strongly influences both the growth of ice and convective flow in the liquid region of the cavity.

2. Material and method

2.1. Definition of problem

Current work deals with the numerical investigation of transient natural convection of freezing water in a two-dimensional