Applied Thermal Engineering 75 (2015) 839–855

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Numerical simulations of water freezing processes in cavities and cylindrical enclosures

A.C. Bourdillon, P.G. Verdin*, C.P. Thompson

School of Energy, Environment and Agrifood, Cranfield University, Bedfordshire MK43 0AL, United Kingdom

HIGHLIGHTS

- Two solidification models have been implemented in OpenFOAM.
- The liquid/solid mixture is either considered as a mushy or a slurry–mushy region.
- Published models have been combined to create these models.
- Physical phenomena could be reproduced with high accuracy using either model.
- The slurry model slightly under predicts the temperature field.

ARTICLE INFO

Article history:
Received 10 May 2014
Accepted 9 October 2014
Available online 22 October 2014

Keywords:
Convection
Freezing
Simulation
Mushy
Slurry

ABSTRACT

Convection and enthalpy-porosity based solidification solvers have been implemented in the Open source CFD code OpenFOAM to study water freezing phenomena in internal geometries. A polynomial water density variation has been used for the gravity related terms. Liquid to solid phase changes have been accounted for in both energy and momentum equations and the water volume fraction has been modelled with a temperature function in the domain. The models described in this paper have been compared with numerical results obtained with commercial or in-house CFD codes for a squared shape cavity and inside a cylindrical enclosure. When possible, results have also been compared to experimental measurements. This solidification solver has finally been extended and modified to create a novel formulation to account for slurry and mushy regions. It appeared clearly that physical phenomena observed in experiments could be reproduced with high accuracy when using either the solidification solver or the new slurry–mushy solidification solver. For the latter model, a distinction is made between the newly formed ice particles not interacting with each other (slurry region) and the mixture of compact ice and liquid (mushy region). The correct modelling of these two distinct regions is necessary for hydrocarbon industries for instance, where cooling oil can form wax gels.

1. Introduction

Solidification phenomena are commonly encountered in the foundry industry, food conservation and oil engineering for instance [1]. The numerical modelling of solidification processes remains a challenging field of study for engineers and researchers. Prescribing the moving solid–liquid interface and dealing with variable fluid properties induced by thermal evolution, constitute the main difficulties of this research area. Several researchers have focused on moving grid techniques for the treatment of the liquid–solid front [2,3]. However, the use of deforming mesh can often become complex and therefore considerable efforts have been made over the past few years to track the solid/liquid moving boundary on a fixed Eulerian grid. Many numerical models used to tackle solidification problems are described in detail in Ref. [4]. Among available models, the enthalpy based models have been widely investigated [5–11]. Particular attention on modelling the sink of velocity from liquid to solid phases is, however, required when using fixed grid methods. To numerically represent the phenomenon, common procedures consist of adding viscosity to the flow in the solid zone [12] or reducing the velocity into the momentum equations directly by adding sink terms.

The enthalpy-porosity method, first proposed by Voller and Prakash [13], combines the enthalpy approach with sink terms to account for the null velocity condition in the solid zone. This method has been successfully validated over the past few years in

* Corresponding author. Tel.: +44 (0)1234 750111 x5214.
E-mail address: p.verdin@cranfield.ac.uk (P.G. Verdin).

http://dx.doi.org/10.1016/j.applthermaleng.2014.10.021
1359-4311/

Nomenclature

Dimensionless numbers

CFL	Courant Friedrichs and Lewy condition [−]
erf	error function [−]
P_r	Prandtl number [−]
R_a	Rayleigh number [−]

Greek letters

α	volume fraction [−]
β	thermal expansion coefficient [1/K]
Δt	time step [s]
γ	thermal diffusivity [m^2/s]
λ	thermal conductivity [W/m K]
μ	dynamic viscosity [kg/m s]
ν	kinematic viscosity [m^2/s]
$\rho(T)$	polynomial density variation [kg/m^3]
ρ	density [kg/m^3]
ε	small constant [−]

Operators

Δ	Laplacian operator $\Delta a = \partial^2 a/\partial x^2 + \partial^2 a/\partial y^2$

Roman letters

ℓ	length [mm]
A	constant [−]
c_p	specific heat capacity [J/kg K]
c_s	switching constant [−]
d	diameter [mm]
D'_c	Darcy constant in slurry model [kg/m^3 s]
D_c	Darcy constant [kg/m^3 s]
F_m	mushy switching function [−]
F_s	slurry switching function [−]
g	gravitational acceleration value [m/s^2]
H	enthalpy [J]
h	specific sensible enthalpy [J]
L	latent heat of fusion [J/kg]
p	pressure [Pa]
T	temperature [K, °C]
t	time [s]
t_h	thickness [mm]
T_{liq}	liquidus temperature [K]
T_{sol}	solidus temperature [K]
u	x-velocity [m/s]
v	y-velocity [m/s]
x	horizontal coordinate [−]
y	vertical coordinate [−]

Subscripts

ℓ	liquid phase [−]
$\sim$	dimensionless values [−]
c	coolant [−]
crit	critical value [−]
i	internal field [−]
m	max value [−]
r	reference value [−]
s	solid phase [−]
w	wall [−]
w_l	left wall [−]
w_r	right wall [−]

Source terms

S'_{m_x}	x-source term in slurry model [kg/m^3 s]
S'_{m_y}	y-source term in slurry model [kg/m^3 s]
S_{m_x}	x-source term in momentum equation [kg/m^3 s]
S_{m_y}	y-source term in momentum equation [kg/m^3 s]
S_t	source term in energy equation [J/m^3 s]

numerous studies [14–18]. It can handle problems where phase change occurs for a range of temperatures or for pure materials ($T_{\text{liq}} = T_{\text{sol}}$). The temperature is adjusted to account for the freezing process using the volume fraction and the latent heat. Depending on the value of volume fraction, the fluid can be considered as pure liquid ($\alpha_\ell = 1$), pure solid ($\alpha_\ell = 0$) or a mixture of both liquid and solid ($0 < \alpha_\ell < 1$). In the latter case, the material is regarded as a mushy region, assumed to be a solid material containing pores and holes filled by the liquid material and is treated as a porous medium. The smooth transition of the sink of velocity from liquid to solid phases is achieved through adding Darcy terms to the momentum equations. The sink of velocity is also modelled by increasing the viscosity of the fluid, which is commonly used in slurry regions, where newly formed ice particles do not interact with each other. Such effects are important in some industrial processes such as hydro-carbon industry where cooling oil can form wax gels, for example.

The sink of velocity in the flow is lower in the slurry region than in the mushy region where grains start to agglomerate and form a solid ice layer. It is therefore essential to take into account both mushy and slurry regions to be able to capture fully the physics associated with solidification processes. Numerically, small density meshes and small time steps are required to accurately capture the liquid/solid interface. To improve the computational time efficiency of such simulations, Rosler and Bruggermann [17] introduced an error function for the evaluation of the liquid volume fraction for fast distinction between liquid/mushy and solid regions.

Fluid properties changes, in particular density, also require attention during phase change processes or thermal variation. Kohlrausch [19] extrapolated a polynomial variation of water density in the liquid zone from experiments. To model changes in viscosity, specific heat or thermal conductivity, a common approach consists in considering a linear function between properties in liquid and solid phases. The purpose of the work presented in this paper is to combine and implement essential and recent advanced numerical features for solidification processes in the open source flow solver OpenFOAM: the enthalpy-porosity method, the treatment of the slurry region, the polynomial density variation and the error volume fraction function. A novel formulation for the treatment of mushy–slurry regions during water freezing processes is also discussed in this paper.

Three solvers have been developed: ConvectionFoam, a natural convection solver for the heat transfer of natural convection problems, IcingFoam for solidification problems with a mushy region and finally IcingFoamSlurryMushy, for solidification problems including both slurry and mushy regions treatment. The steady state solution from ConvectionFoam is used to initialize the two remaining solvers. Simulation results from IcingFoam and IcingFoamSlurryMushy are validated against both numerical and