Experimental and Numerical study of Freezing Water around a cylindrical tube: application to desalination

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ABSTRACT

To face the shortage in fresh water, many techniques are used nowadays for brackish and seawater desalination. One of them which consume the less energy is freezing. This process allows the separation of the different salt water's components and gives rise to a saltier liquid phase called brine and a solid phase of ice becoming fresh water after melting.
The quantity and the quality of the products depend, among other, on the geometry of the surface of the exchanger on which will occur the freezing.
In this paper, we present experimental and numerical results of fresh and seawater freezing around a circular Cu cylindrical tube immersed into a cavity filled with water to freeze. The tube is fed by a refrigerant coming from a cryostat. A data logger was used to register temperature at different times. Shadowgraphs allowed to visualize the birth and growth of ice. Numerical simulations were based on Navier- stokes, energy and species equations in transient flow. FLUENT software was used to solve theses partial differential equations using a bi-dimensional formulation and an appropriate mesh. Thus temperature, velocity, concentration and flow visualization were investigated and compared to experimental ones. It was found that:
1) Vertical tube produced more ice than the horizontal one.
2) Less the water is salty, more is the production of ice.
3) Dendrites may appear and delay heat and mass transfer.

KEY WORDS

Desalination, Freezing, Numerical simulation, Navier/Stokes equations

INTRODUCTION

Nowadays word is facing a shortage of fresh water [1], unfortunately, any water production process consume much energy. Consequently seawater and renewable energies should much together for a sustainable solution. It was shown [2] that freezing desalination is more competitive for two reasons: using latent heat allows to consume less energy and generated brine is less corrosive. This process was tested since the 50th, and most of the literature on the subject dated back to the 1950s, '60s, and '70s [3-6] deals with feasibility of the desalination and not with the mechanisms of solidification and the dynamic of the freezing front.
A better understanding of mass and heat transfer in liquid mixture have been investigated later theoretically [7-8] and experimentally [9] and results were applied in freezing desalination as well as in metal alloys melting-solidification [10], in metallurgy, pharmacy and food industry.
In this paper we focus on the feasibility of freezing desalination the effect of the geometry and on the mechanisms of heat, and species transfer.

MODELLING AND NUMERICAL SIMULATION

Since seawater is considered as binary mixture, a mushy zone where the phase change process occurs during solidification appears. The model used in this study has been used for modeling binary alloy solidification [11] where the mushy zone was considered as a porous medium [12]. Instead considering separately the three phases: solid, liquid and the mushy layer, we used the approach of a single domain including both phases. Transition from one phase to an other is based on the physical properties depending on the liquid fraction.
The finite volume method was used to discretize the governing equations of the two dimensional model. The grid was staggered and distributed uniformly in the x and y directions. The SIMPLE algorithm was used to handle the coupling of the pressure and the velocity. The second-order upwind scheme was used to handle the coupling of convection and diffusion terms in the momentum, energy and species equations. The enthalpy-porosity method was used to simulate the solidification process. The implemented convergence criterion required that at the end of each time step the residuals of the momentum equation be lower than 10^{-5}, whereas for energy and species equations this value was 10^{-7}. The time step was set to 0.01s. The computational fluid dynamics software FLUENT was used to implement the details of the numerical model. Special user-defined functions were developed to handle the variation of the thermal conductivity and transport properties. For this study a grid independence study was conducted using the grid arrangements of 0*375 giving 112500 cells so fine to follow the ice/brine interface evolution.

RESULTS AND DISCUSSION

Fresh water freezing

Fresh water whose solidus temperature is 0°C was taken as benchmark. The numerical conditions were set as following: initially, water was at rest at 10°C, and freezing temperature was fixed at -7°C. The numerical simulation results are expressed in terms of isotherms and liquid fraction contours evolution during 1h and are illustrated by Figure1-2.
We can notice that:
- These contours evolve in the same manner expressing the spreading of cold from the surface to the water and from the top to the bottom during all the process.

- A vertical stratification takes place against the surface of the tube expressing that diffusion transfer is predominant.
-An ice layer appeared against the external gold surface and grows with time to reach 2.5 cm thick after 1h30 running simulation.
-A distortion of isotherms occurs after a long time therefore a convective movement may appear at the bottom.

Seawater freezing

In this case, the water to freeze is sea water. The same initial and boundary conditions as in the case of fresh water were used. The results illustrated by Figure 3-4 show a similar flow in the beginning: transfer by diffusion phenomena and vertical stratification in temperature and density take place. Since t=25min, this stratification is distorted in the bottom surface and a mixture phenomena appears . Since the gradient brine increases, a dendritic lattice appears leading to a salt pocket inclusion in the ice. Note that at t=1h many salt pockets are included in the lattice ice matrix. The relative thermal gradient to the salt one gives birth to a convective movement which affects the quality of the product. To overcome this phenomena, a critical value between the temperature and the concentration is to find.

EXPERIMENTAL STUDY

In a precedent study[12], we tested freezing using plane geometries and we concluded that cylindrical tubes allow better production.
Figure.5 shows the experimental setup we used. It consists of a copper tube immersed within a rectangular Plexiglas tank filled with water to freeze . This tube is a heat exchanger in which a refrigerant fluid circulates from a cryostat LAUDA 120 at -7°C. Thermocouples nickel / chrome type K of 0.2mm diameter and ±5°C resolution were located at the entrance and the exit of the tube, and connected to an acquisition Agilent 34970A data Logger to record temperature every minute. Shadowgraph Technique was used to locate the interface solid-liquid overtime and the appearance of the dendtrites.

Figure 5 Experimental setup

The tube was tested in horizontal and vertical positions using the same operating conditions: the solution to freeze is a synthetic sea water at an initial temperature of 10'C and the freezing liquid was set at -7'C.A layer of transparent ice appeared respectively at 15min and 20min around the vertical and the horizontal cylinders and continue growing to reach, after 90 min, 2.5 cm on the vertical tube and 1.5cm on the horizontal one (Figure 6). Note that the same thick was found numerically. Consequently vertical position is advantageous. At the same time dendrites covered all the vertical tube surface. Obtained water had a conductity of: ms/cm
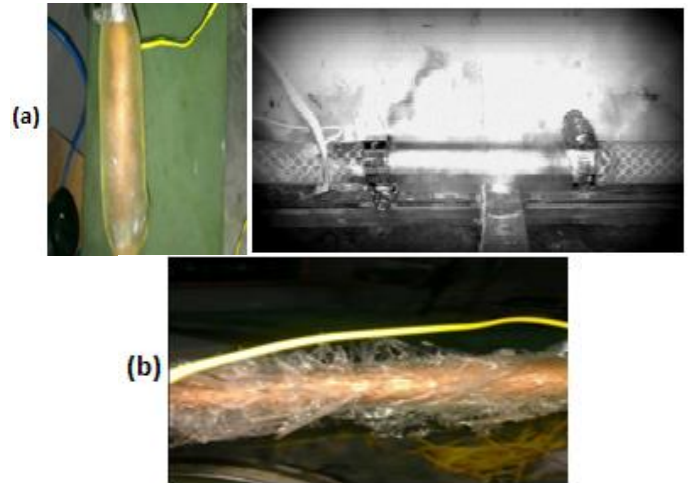

Figure 6 (a) Vertical and horizontal tube coverd with ice after 90min freezing
(b)Dendrites around the vertical tube

CONCLUSION

A numerical simulation and experimental study of freezing water were investigated. This work shows that:
- Separation of brine and fresh water for desalination process is possible,
- Using vertical tube than an horizontal one has the advantage to be faster, so more efficient .
- Beyond a critical value of the concentration gradient, dendrites appear in the mushy layer and delays the transfer. Therefore it is necessary to restart, after some time, the freezing cycle with the obtained brine.

Since freezing by using solar energy is feasible and cheaper than using electricity, freezing desalination may compete , in few years, with the standard desalination processes. However some improvements of our knowledge is still necessary and more technical achievements should be encouraged.

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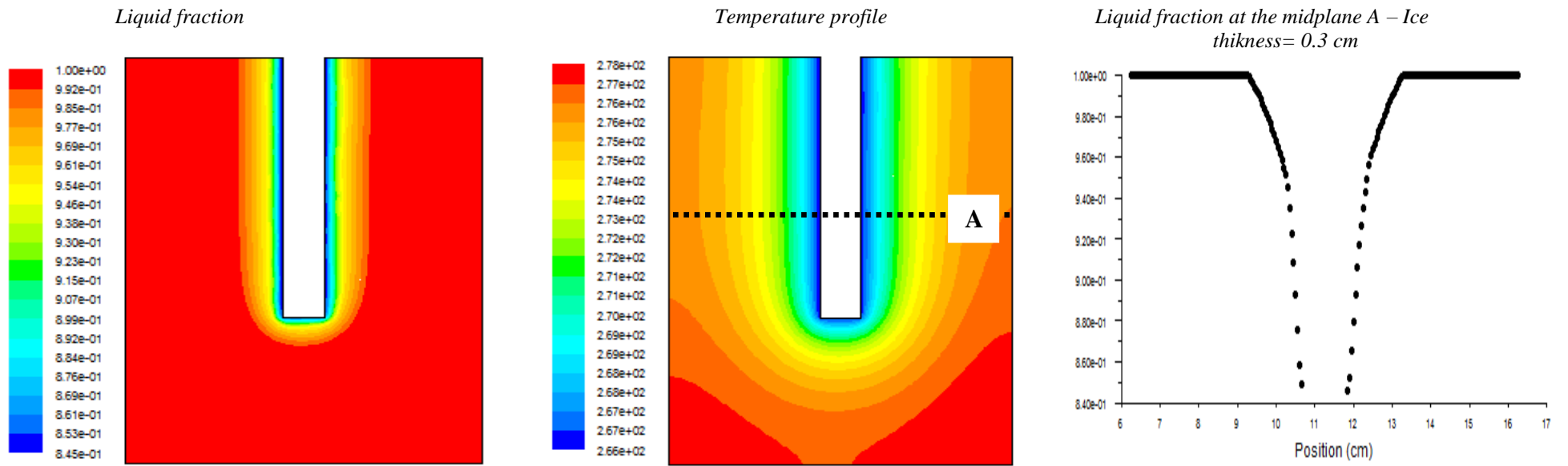
Liquid fraction

Temperature profile

Liquid fraction at the midplane A − Ice thikness= 0.3 cm

Figure 1 Starting phenomena at t=1min: apparition of ice

Liquid fraction

Temperature profile

Liquid fraction at the midplane A- Ice thikness=2 cm
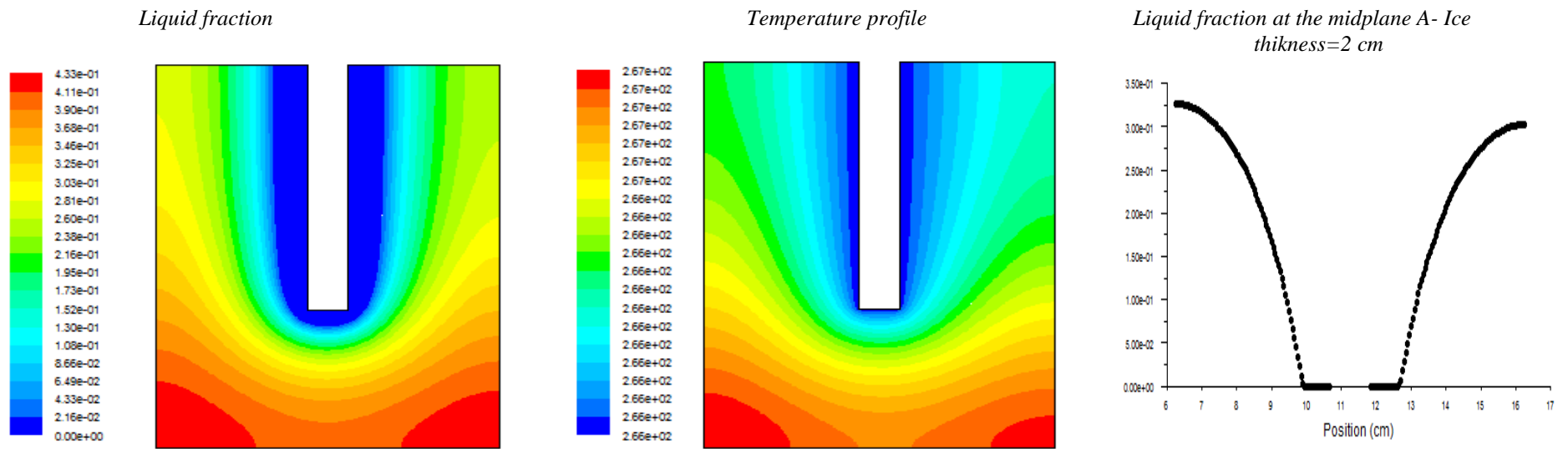
Figure 2 Phenomena at t=1h: growth of ice layer and distortion isotherms

Liquid fraction *Temperature profile* *Liquid fraction at the midplane-e=0.2 cm* *Velocity contours*
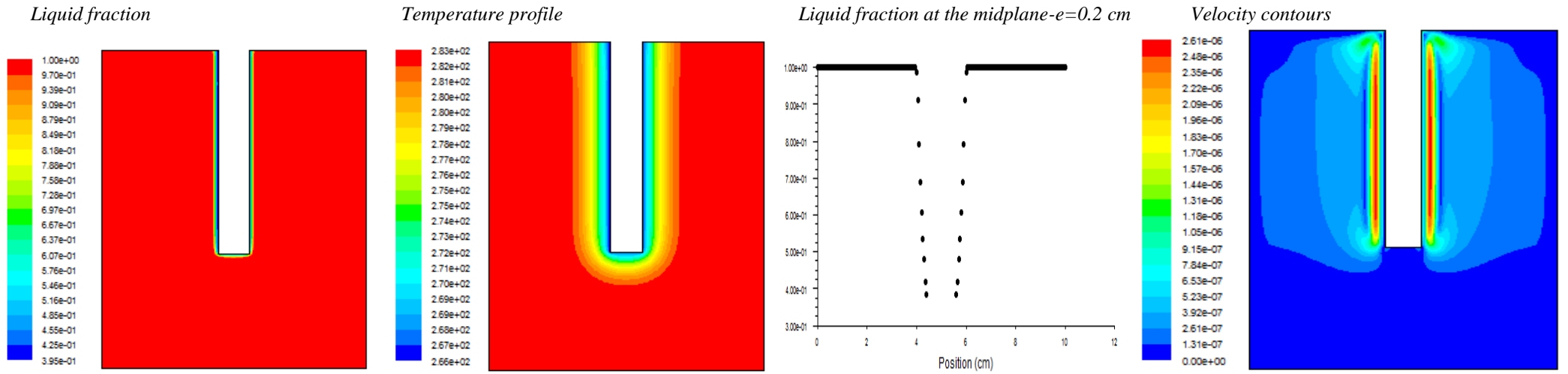
Figure 3 Starting phenomena at t=1min30 : apparition of ice

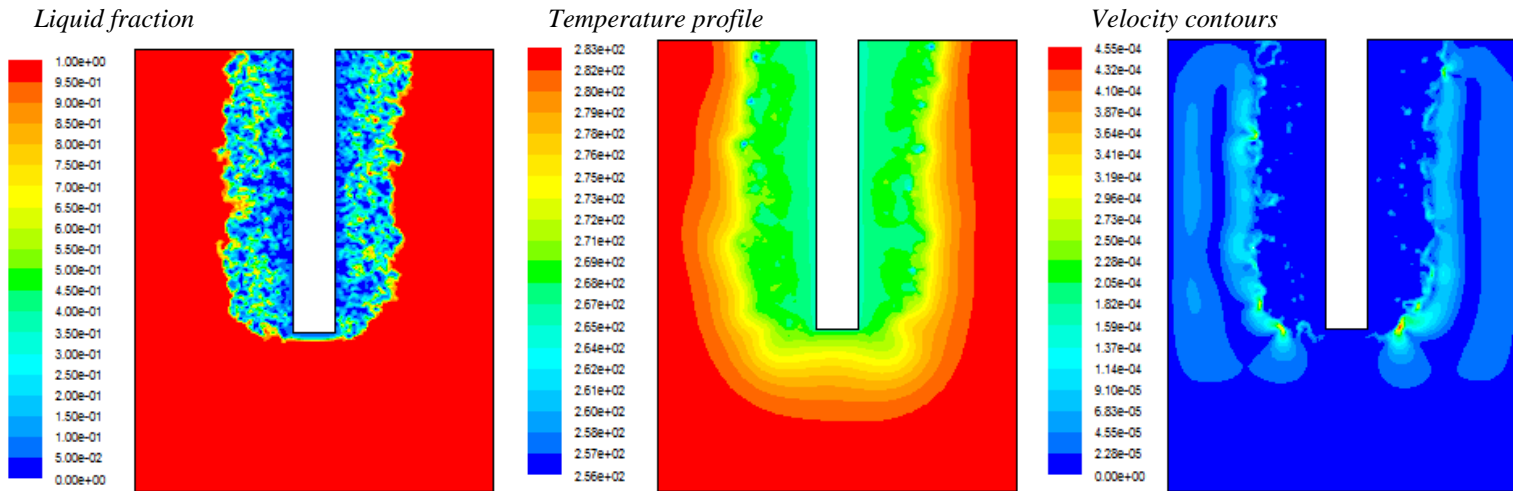*Liquid fraction* *Temperature profile* *Velocity contours*

Figure 4 Phenomena at t=1h: distortion isotherms and velocity contours (e=1.6cm)