Modeling of heat transfer for an ice rink track using finite elements

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Abstract: The paper describes a model for heat transfer and ice formation around the pipes of an artificial skating rink using finite element method. For pipe classifier ice rinks, temperature distribution during ice formation cannot be modeled using analytical methods. The paper presents a method for computing the temperature distribution around the pipes. Heat transfer in ice rink track is unsteady and involves phase change.

Key-Words: Solidification, ice, skating rink, heat transfer, phase change.

1 Introduction

The problem of melting and solidification of substances, regarded from the point of finding the temperature distribution within solid and liquid phases and of the movement of the solid – liquid interface, is very interesting (both from theoretical and practical point of view), because conduction heat transfer accompanied by phase change occurs in many applications, such as ingots solidification, directional solidification of alloys in order to obtain a certain metallographic structure, freezing of foods, soil freezing and thawing, phase change thermal storage, etc. Mathematical modeling of this phenomenon and especially mathematical solving of this problem are aggravated by the fact that general solutions refers to unsteady 3D temperature distribution for bodies whose thermo-physical properties depend on temperature [1, 2].

2 Problem Formulation

Numerical modeling was accomplished using Fluent 6.3, software for two different constructive types of the ice rink track: track with pipes immersed in water and pipes embedded in sand. For symmetry reasons, the study was performed using a plane discretization grid, bounded as follows: to the left and to the right by two vertical axis in the middle of the distance between the two adjacent pipes, on top, a horizontal line representing the water (or ice) surface, and another one the bottom for the foundation plate (Fig 1).

For water immersed pipe, the boundary of the computing domain are the same as shown above, with the remark that the entire surface around the pipe was considered as liquid. For this case the grid contains 13563 mesh point, and 12952 tetrahedral elements and for the second case 11243 mesh points and 10896 de elements. Due to the multi-block structure gridding which use tetrahedral elements, the grid has a relatively small number of elements, fact that has a positive influence on computational time, on solution convergence and one result accuracy.

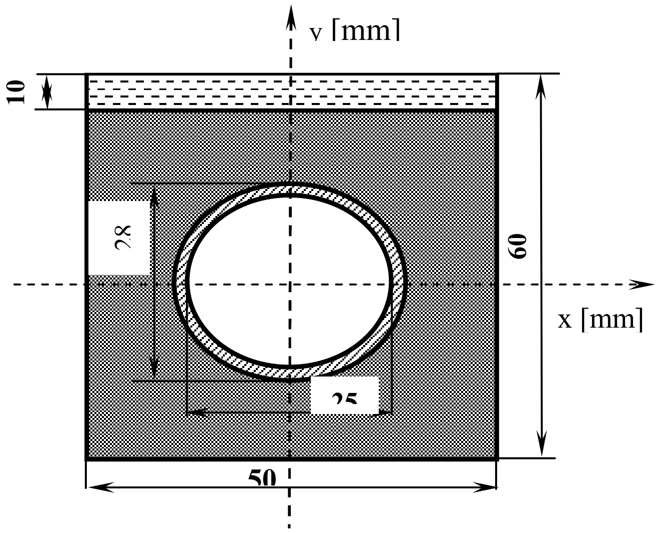

Fig.1 Sand embedded pipe domain

Fluent software has an impressive library with properties of various solid and fluid substances [6]. Numerical modeling of phase change heat transfer using this software is consistent with the real solidification process around cylindrical surfaces. The transport properties of the substances are now temperature dependent, and the phase change is non isothermal.

The chosen mathematical model is *Pressure Based*, considering that heat transfer occurs in incompressible fluids. The model is considered implicit that makes the solver stable and convergent, although the number of equations increases and therefore the complexity of computations. The implicit scheme is recommended for phase change heat transfer, for the reason that offers the liberty of choosing the time step in a large range.

The chosen solver type was *Solidification and melting*, solver that is intended for this type of problems. For a better analysis of temperature distribution, in certain areas were added some points and contours in which was tracked the temperature variation during the process (Fig. 2). At the same time, the temperature variation was also tracked on several important surfaces such as: water surface, foundation slab and pipe inner/outer surface.
The equations of the mathematical model [3] and initial and boundary conditions are [4], [7]:

$$\frac{\partial\rho}{\partial\tau}+\nabla(\rho V)=0 \tag{1}$$

$$\frac{\partial(\rho u)}{\partial\tau}+\nabla(\rho u V)=-\frac{\partial p}{\partial x}-\frac{\mu}{k}u+\nabla(\mu\nabla u) \tag{2}$$

$$\frac{\partial(\rho v)}{\partial\tau}+\nabla(\rho v V)=-\frac{\partial p}{\partial y}-\frac{\mu}{k}v+\nabla(\mu\nabla v)+(\rho_m-\rho)g \tag{3}$$

$$\frac{\partial(\rho h)}{\partial\tau}+\nabla(\rho h V)=\nabla\left(\frac{k}{c}\nabla h\right)-\frac{\partial(\rho\beta L)}{\partial t}-\nabla(\rho\beta L V) \tag{4}$$

$$K=K_0\left(\frac{\beta^3}{(1-\beta)^2}\right) \tag{5}$$

where:
τ - time, ρ - density, p - pressure, V - velocity vector, u, v - velocity components on x and y axes, μ - dynamic viscosity, β - liquid fraction, L - latent heat, K - permeability, K_0 - Kozeny-Carman constant.

$$h=\begin{Bmatrix} C_s T & T<T_f \\ C_l T & T\geq T_f \end{Bmatrix} \tag{6}$$

$$h=h_{ref}+\int_{T_{ref}}^{T} c_p dT \tag{7}$$

where:
T_f - solidification temperature, C_s, C_l -specific heat of solid and liquid phase, h - enthalpy, T_{ref} - reference temperature, h_{ref} - reference enthalpy, c_p - constant pressure specific heat.

3 Problem Solution

For the numerical simulation of ice formation around water immersed pipe, were performed 25210 iterations using a time step τ = 10 seconds. The total time for the solidification process was 7 hours, and the process was considered ended when free surface of ice reached a temperature of -5.55 °C.
For the sand embedded pipe were performed 18000 iterations using a time step of 10 s. The total time for the solidification process was 5 hours, and the process was considered ended when free surface of ice reached a temperature of -4.62 °C.
Parameters of the mathematical model were [5]:

- initial water temperature t_{water} = 10 °C
- surrounding air temperature t_{air} = 10 °C
- refrigerant temperature inside the pipe t_r = -10 °C
- refrigerant flow rate m, $\dot{\ }$ = 0.185 kg/s
- refrigerant convection coefficient inside the pipe α_{agent} = 550 W/m^{2}K
- air convection coefficient at the water surface α_{aer}= 15W/m^{2}K
- heat flow rate for the base plate q = 10W/m^2.

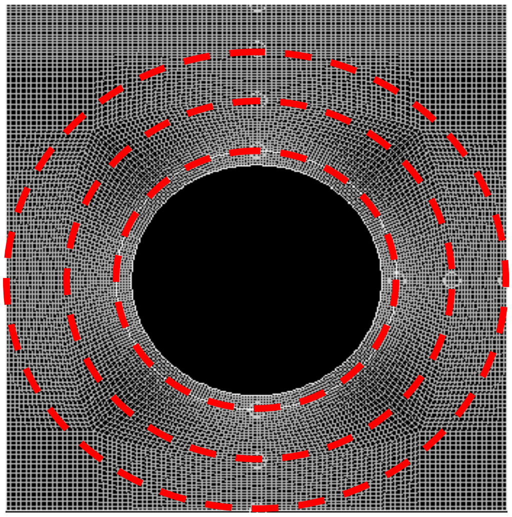

Fig.2 The grid of the analyzed domain

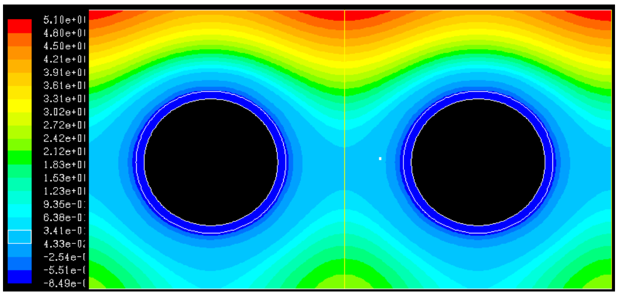

Fig.3 Temperature distribution at τ = 30min

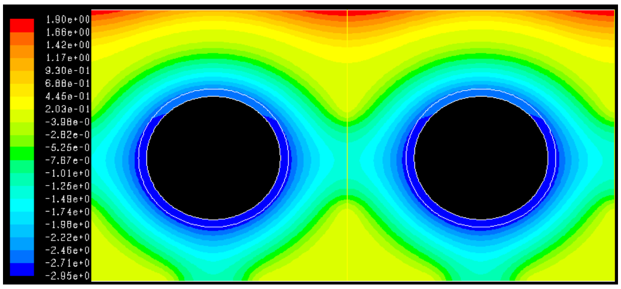

Fig. 4 Temperature distribution at τ = 150 min

In Fig. 3 and Fig. 4 are shown pictures of temperature distribution over time for the water immersed pipe. It can be noticed the different distribution over the 2 axis, due to different boundary conditions and also due to external influences. Thus, for the *X* and *–Y* directions we have a swift temperature decrease, and on *Y* direction a slower decrease due to the water surface convective heat flow. A special importance for ice formation on the outer surface of the pipe process is time variation of the solidification rate.

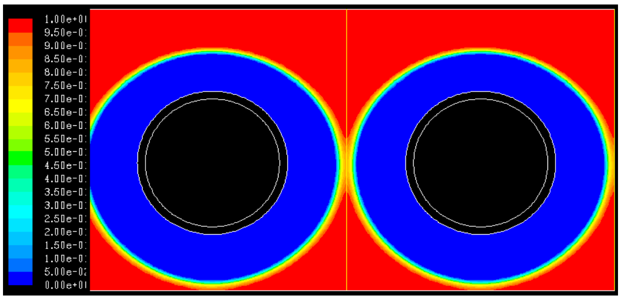

Fig.5 Liquid fraction distribution for τ = 120 minutes

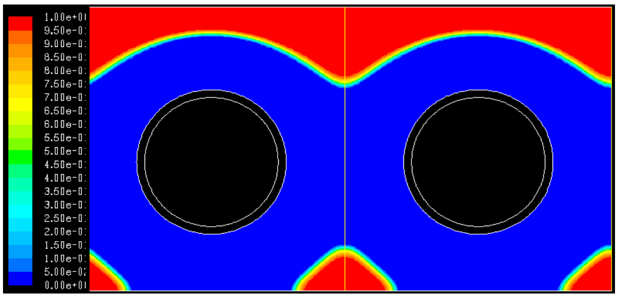

Fig.6 Liquid fraction distribution for τ = 180 minutes

In Fig. 5 and Fig. 6 are shown pictures of the solidification front for some moments in time.

Ice formation process around the pipes ends at τ = 296 minutes, moment at which the liquid fraction for the entire domain becomes zero, and the solid one becomes one.

During solidification it can be noticed a differential increase of solidification rate around the pipe: a rapid increase on the sides and on the bottom of the pipe (τ = 180 minute) and a slow increase on the top.

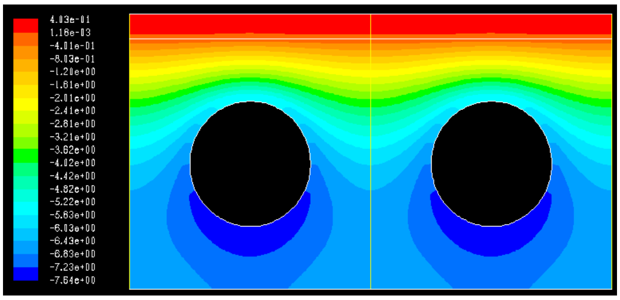

Fig.7 Temperature distribution at τ = 30min

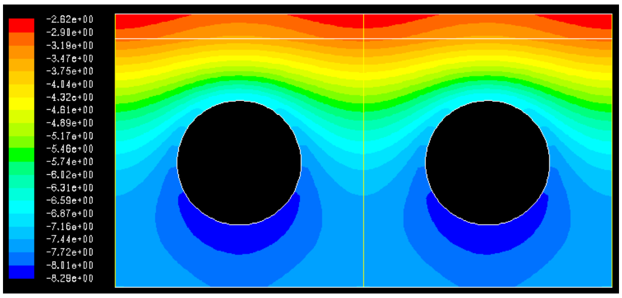

Fig.8 Temperature distribution at τ = 120min

Fig. 7 and Fig. 8 show images of temperature distribution for the sand embedded pipe for some moments in time.

In comparison to the water immersed pipes, it can be noticed a steeper temperature decrease on the domain surfaces and a more uniform distribution on the air-water contact surface.

At the end of the process, minimal temperatures on the envisaged surfaces were as follows:

- inner pipe temperature t = -8,4 ^{0}C
- bottom plate temperature t = -8,32 ^{0}C
- sand-water contact surface temperature t = -5,15 ^{0}C
- ice surface temperature t = -4,62 ^{0}C.

Fig. 9, and Fig. 10 show images of the solidification front for sand embedded pipe for some time moments.

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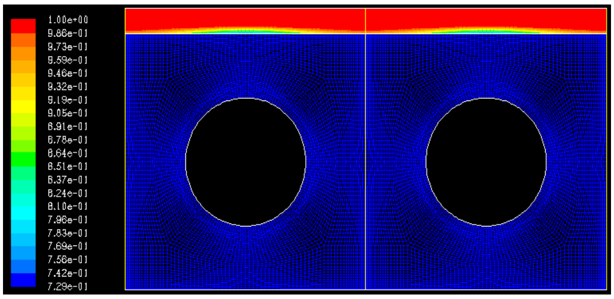

Fig. 9 Solidification front at τ = 30min

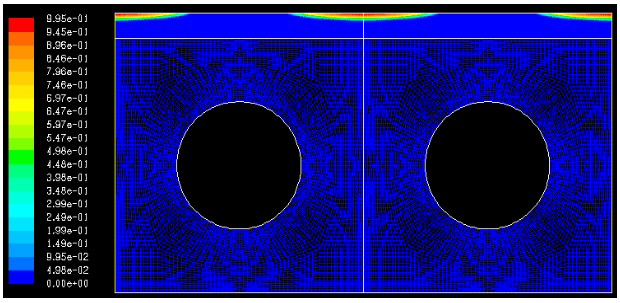

Fig.10 Solidification front at τ = 120 min

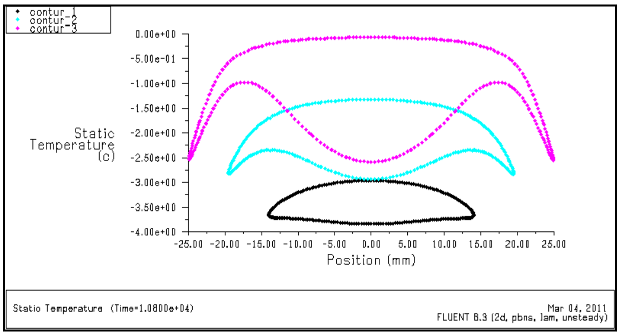

Fig.12 Temperature variation on the three envisaged contours at τ = 180 min

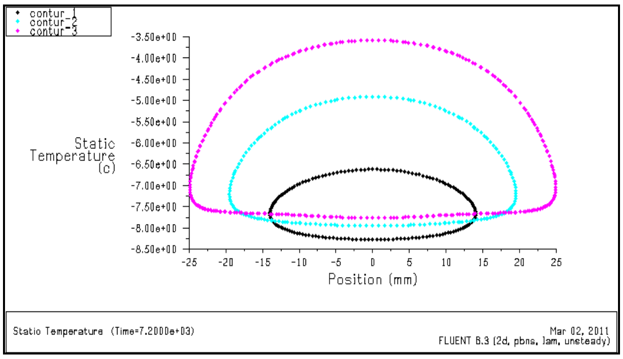

Fig.13 Temperature variation on the three envisaged contours at τ = 120 min

Fig. 11, and Fig. 12 shows temperature variation on the three envisaged contours at some time moments, for the two analyzed cases. It can be noticed a different a temperature distribution on contour surfaces depending on their position within the analyzed domain.

4 Conclusion

Analyzing the presented data it results that from heat transfer and ice quality point of view the sand embedded pipe design is preferable due to the following advantages:

- total solidification time of water is shorter;
- temperature distribution on water surface is more even, thus obtaining a higher quality of ice;
- propagation of the solidification front is swift and uniform on the entire domain;
- a more uniform temperature distribution on the pipe inner surface, i.e. an intensified heat transfer from the refrigerant to the ice rink track.

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