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An Investigation of Ice Formation around Cylinders in Cooling Storage Tank

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In the present study, it is proposed to investigate ice formation of natural convection and variously located cylinder arrangements in a cooling storage rectangular tank with filled water. For this purpose a Fluent package program was used to solve a flow domain with unsteady state conditions. Ice formation shapes and temperature distributions were shown. Water temperature in the tank and surface temperature of cylinders were taken as 4 oC and -10 °C respectively. Staggered and inline cylinder geometries were investigated for temperature distribution, velocity vectors and ratio of $A_{ice}/A_{cylinder}$ (ice area/cylinder cross sectional area) by changing transversal and longitudinal spacing.

Istraživanje formiranja ledenog sloja oko cijevi u spremniku rashladnog sredstva

Izvornoznanstveni članak

Cilj ovog rada je istraživanje formiranja ledenog sloja prirodnom konvekcijom pri raličitim rasporedima cilindara u rashladnom spremniku punjenim vodom. Za tu je svrhu korišten programski paket FLUENT za rješavanje domene strujanja pri nestacionarnim uvjetima. Pokazani su oblici formiranja ledenog sloja i temperaturne raspodjele. Temperatura vode u spremniku i površinska temperatura cilindara bile su 4, odnosno -10 °C. Za šahovski i linijski raspored cilindara istraživan je raspored temperature, vektori brzina i omjer $A_{ice}/A_{cylinder}$ (površina leda/površina poprečnog presjeka cijevi) u uzdužnom i poprečnom smjeru

1. Introduction

For the past few decades, the world's energy supply has not been keeping up with increasing demand. Burgeoning countries undergoing industrial reform are consuming an increasing amount of crude oil, coal and electricity, which has increased overall energy prices to an unprecedented level. As a result, energy conservation has been on the rise lately, and new sources to feed the human energy hunger are sought continually. Moreover, the search for more efficient, ecologically friendly and cost effective ways to capture and store energy for later use is always a popular topic [10]. Cool thermal energy storage (CTES) plays a significant role in conserving available energy and improving its utilization, such as shifting on-peak demand to off-peak period. Many applications have been employed, for example, cool storage systems for air-conditioning, natural cooling of energy-efficient building. CTES is classified as sensible, latent heat and the combined storage systems. The advantages of the latent heat system in comparison with sensible storage are high heat storage density, small size of the system and a small temperature change during charging and discharging processes [5].

Ice cool thermal energy storage systems are often classified as static or dynamic, according to the way ice is delivered to the storage tank. In dynamic systems, ice is produced outside the storage tank and removed from the ice-making surface continuously [4]. In static systems, an ice-making pipe is installed in the storage tank where ice is formed and later melted. Ice-on-coil systems produce ice outside a coil. The ice may be melted using either an external melting system, which melts ice from the outer side, or an internal melting system [4].

Understanding of the solid-liquid phase change heat transfer phenomena around cylindrical tubes is needed for design of efficient ice-on-coil cool thermal energy storage systems. Habeebullah [8] investigated growth rate of ice on the outside of cooled copper tubes. Ice

Symbols/Oznake

A_c	- cross-sctional area of cylinder, m^2 - površina poprečnog presjeka cijevi
A_i	- solidified areas, m^2 - skrutnuta površina
c	- specific heat capacity, J/(kg·K) - specifični toplinski kapacitet
d	- diameter of cylinder, m - promjer cijevi, m
h	- sensible specific enthalpy, J/kg - osjetna specifična entalpija
k	- thermal conductivity, W/(m·K) - toplinska provodnost
K	- permeability, m^2 - pemeabilnost
K_o	- empirical constant in Kozeny-Carman equation - emperijka konstanta u Koeny-Carmanovoj jednadžbi
L	- specific latent heat, J/kg - specifična latentna toplina
P	- Pressure, Pa - tlak
t	- time, s - vrijeme
T	- temperature, K - temperatura
u	- velocity component in x direction, m/s - komponenta brzine u smjeru osi x
L	- velocity vector, m/s - vector brzine
x, y	- Cartesian coordinates, m - Kartezijeve coordinate
β	- liquid volume fraction - volumni udio kapljevine
μ	- dynamic viscosity, Ns/m^2 - dinamička viskoznost
ρ	- density, kg/m^3 - gustoća
υ	- velocity component in y direction, m/s - komponenta brzine u smjeru osi y

Indices / Indeksi

f	- fusion state - stanje taljevine
l	- liquid phase - kapljevita faza
ref	- reference value - referentna vrijednost
s	- solid phase - kruto stanje

formation around an isothermally cooled horizontal cylinder and effect of natural convection were studied by Cheng et al [3]. Fertelli et al. [5] studied analytically and experimentally the solidification around the horizontal tube by considering a fully developed velocity profile in the tube. Experiments are performed to investigate the effects of different heat transfer fluid inlet temperatures on ice formation around the tube. Sasaguchi et al. [11-12] studied the solidification around a single and two vertically space cylinders in a fixed volume. In their study, pure water was used as the working fluid and the non-Boussinesq model was utilized to simulate the buoyancy driven flow, and they investigated the effect of the initial water temperature on the transient cooling of water around a cylinder in a rectangular enclosure. Bathelt et al. [1] investigated the effects of natural convection and super-heating of PCM on solidification around a cooled horizontal cylinder. However, their analysis is basically performed on a conduction model, implementing experimental correlations for natural convection. Sparrow et al. [14] analyzed a freezing process on the surface of a cooled tube by means of the approach of transformed grids. Their numerical results revealed that the thickness of the frozen layer was related to the Biot number, but insensitive to the Stanton and Stefan numbers. Numerical study of solidification around a number of staggered cylinders in a fixed volume are investigated effects of cylinder number and water superheat on the growth of the ice layer and heat transfer characteristics during solidification. Ismail et al. [9] presented a numerical model for the solidification of phase change material around a radially finned tube with a constant inner wall temperature. In their study, numerical experiments were performed to investigate the effects of the number of fins, fin thickness, fin material, aspect ratio of tube arrangement and tube wall temperature. In this study, effects of staggered and inline cylinder geometries on ice formation were investigated numerically.

2. Materials and Methods

The effect of transversal and longitudinal spacing was carried out. Solidification around staggered and inline cylinders in a fixed volume for 4 cylinders were studied (Figure 1). All calculations were carried out under condition of transient natural convection in water with cooled tubes. The diameter of the tube was taken as d (d: 0.0254 m), and tank height was taken as $10d$. Transversal (S_L) and longitudinal spacing (S_T) were $2d$ and $3d$ for tube bundle geometry. Water temperature in the tank and cylinder surface temperature were assumed as 4 °C and -10 °C respectively.

The finite volume method [7] was used to solve solidification around cylinders placed in fixed volume as staggered and inline geometry of cooled cylinder. A quadrilateral grid was used for simulation and finer grid distribution was used near cylinder surfaces. Grid spacing increases away from cylinder surfaces, with total of 20000 to 25000 elements (Figure 2). The following assumptions were made to simulate solidification around cylinders in a fixed space: i) Flow is two dimensional, laminar and incompressible; Water as a Newtonian fluid for phase changing material; ii) Unique thermal conductivities and specific heats (k_s, k_l, C_s, C_l) are considered for solid and liquid phases; and iii) Effects of viscous dissipation and radiation are ignored.

An enthalpy formulation based fixed grid approach [13] was employed to study transport phenomena during solidification. In developing momentum equations, Darcy's law and Kozeny-Carman equation were adopted to model the flow and permeability within mushy zone, respectively. Governing equations associated with boundary and initial conditions were as follows:

Continuity,

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

X momentum,

$$\frac{\partial}{\partial t}(\rho u) + \nabla \cdot (\rho u V) = -\frac{\partial P}{\partial x} - \frac{\mu}{k} u + \nabla \cdot (\mu \nabla u), \tag{2}$$

Y momentum,

$$\frac{\partial}{\partial t}(\rho \upsilon) + \nabla \cdot (\rho \upsilon V) = -\frac{\partial P}{\partial y} - \frac{\mu}{k} \upsilon + \nabla \cdot (\mu \nabla \upsilon) + (\rho_m - \rho) g. \tag{3}$$

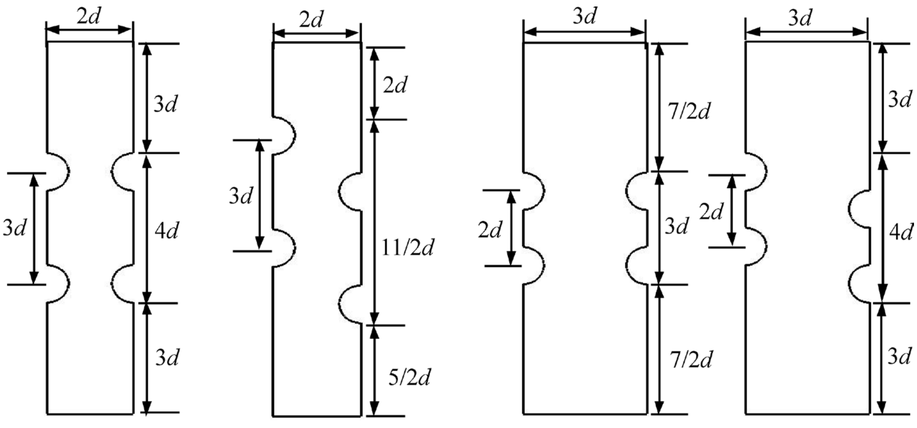

Figure 1. Physical models for several cylinders a) inline cylinder (S_L=2d; S_T=3d) b) staggered cylinder (S_L=2d; S_T=3d) ***c)*** inline cylinder (**S_L**=3d; S_T=2d) d) staggered cylinder (S_L=3d; S_T=2d)

Slika 1. Fizikalni modeli za nekoliko cijevi: a) cijevi u liniji, b) šahovske cijevi; c) cijevi u liniji i d) šahovski raspored

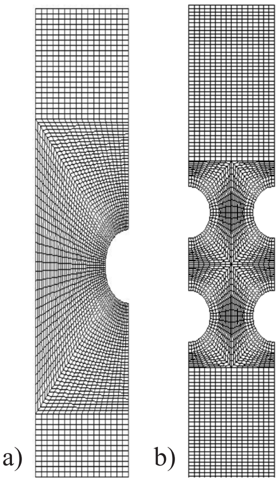

Figure 2. Grid system a) single cylinder b) four inline cylinder

Slika 2. a) jedna cijev b) četiri cijevi u liniji

Energy,

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

Kozeny-Carman equation,

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

Sensible enthalpy-temperature relation,

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

In deriving energy equation, sensible enthalpy h, is defined as

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

where, h_{ref}, reference enthalpy; T_{ref}, reference temperature; c, specific heat capacity at constant pressure [13].

To account for buoyancy-driven flow within the domain, density-temperature equation [2] is as

$$\rho = \rho_{\mathrm{m}} \left(1 - w\left|T - T_{\mathrm{m}}\right|^{q}\right), \tag{8}$$

where, ρ_{m}, max. density of water (999.972 kg/m^3); w =9.2793×10^{-6} °C^{-1}; T_{m}= 4.0293 °C; q=1.894816.

3. Results and discussion

Validation studies [11] of the present model shows that variations of area ratio ($A_{\mathrm{i}}/A_{\mathrm{c}}$) match with experimental data in entire time range for solidification around a single cylinder (Figure 3). To examine positional effect of cooled cylinder in rectangular cavity on transient natural convection in water with density inversion, calculations were carried out at four positions of cylinder for inline and staggered arrangements (S_{L}=2d; S_{T}=3d, S_{L}=3d; S_{T}=2d) for an initial water temperature (T_{i} = 4 °C). Temperature distributions at different time (t = 900 s, 1800 s, 3600 s and 7200 s) for all cylinder positions, velocity vectors and area ratios ($A_{\mathrm{i}}/A_{\mathrm{c}}$) were calculated.

Figure 4 shows temperature distributions and velocity vectors for inline geometry and S_{L}=2d; S_{T}=3d. The water which was at 4 °C temperatures in the beginning was observed to have reached different temperature values at different points of the tank at the t = 900 s.

At the end of this period, phase change was observed in the tank and the ice layer on the cylinders was reached to a specific thickness. Thermal stratified region is established by warm water placing at the bottom of the tank and cold water placing at the top of the tank This situation can also be seen from the velocity vectors at the t = 900 s. No flow was seen at the bottom of the tank, while an extensive flow upwards up was observed in the region between the cylinders. At t = 1800 s and other durations, the cold water at the top was observed to be colder when the ice thickness was increased. More temperature decrements of accumulated water at the bottom was observed to have decreased more; and a different thermal layer was seen to have appeared in the following period. When the velocity vectors are analyzed, it can be seen that flow fluctuating appears near the cylinder surfaces. It can also be observed that the tank is separated into three regions when the ice thickness increases and the flow disappear in time.

Variation of water temperature with tank heights were shown in Figure 4. While water temperature bottom section of the tank is 4 °C at the time of 900 and 1800 seconds, the temperature decreased up to phase change temperature for the whole tank from the first cylinder to the upside section of tank (Figure 5). The phase change temperature was also seen to have decreased. At the end of t = 3600 s, the distance between the cylinders was closed when the ice thickness was increased; and the temperature between both cylinder groups was decreased up to 269 K. The temperature of the ice reached the cylinder surface temperature for the same points at t = 7200 s.

Temperature distribution and velocity vectors of inline configuration of tubes in a tank were shown in Figure 6. Natural convection due to the density factor appeared at the end of the t = 900 s through the thermal stratification in the tank. The warmer water accumulated at the bottom of the tank, and the cold water accumulated at the top of the tank. At the t = 900 second, there was no flow at the bottom of the tank as seen in the velocity vectors. However, at the transportation regions between the cylinders, a higher flow movement was observed because of the effect of the cold ice surfaces which are at 0 °C. When the temperature distributions at the end of the t = 1800 s, 3600 s and 7200 s are analyzed, it can be

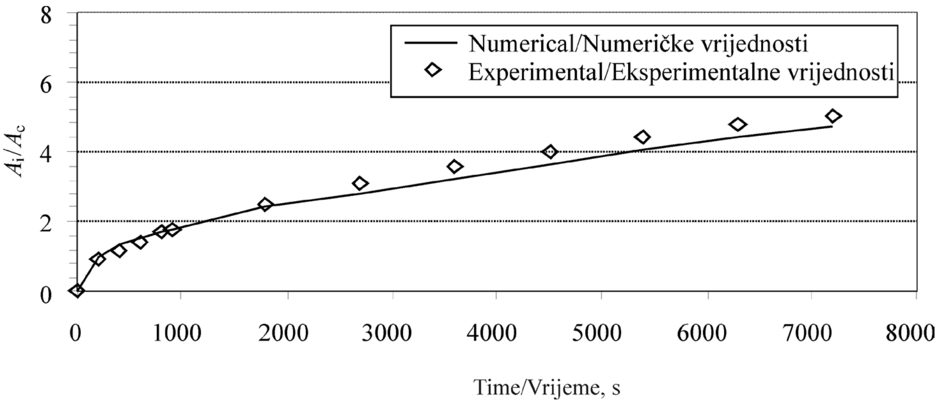

Figure 3. Comparison between numerical and experimental data for solidification around a single cylinder.

Slika 3. Usporedba numeričkih i eksperimentalnih vrijednosti skrućivanja oko jedne cijevi

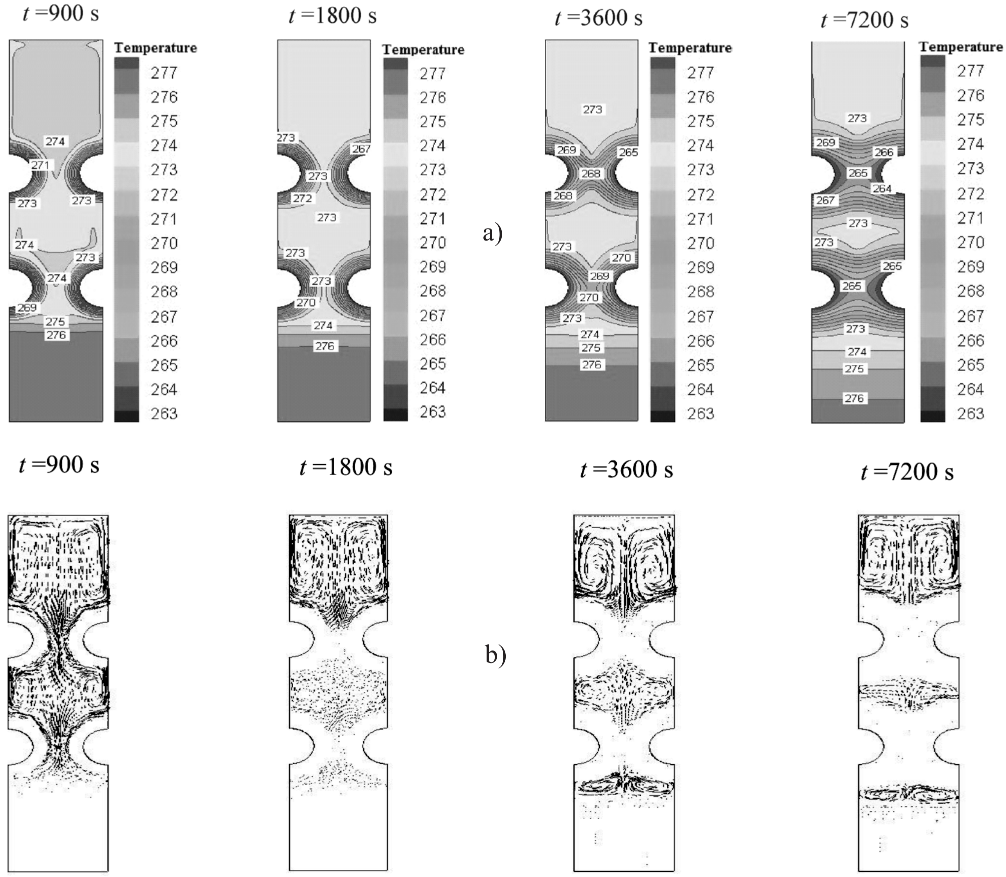

Figure 4. Timewise variation of isotherms and velocity fields for the solidification around inline cylinders (S_L=2d; S_T =3d)
a) isotherms b) velocity fields

Slika 4. Vremenska promjena temperaturnog polja i polja brzina pri skrućivanju oko četiri cijevi u liniji S_L=2d; S_T =3d)
a) izoterme b) polje brzina

seen that the water temperature has decreased up to 0 °C at the whole part of the tank except the bottom part. At t = 1800 s, the ice layers appeared on the cylinders gathered in vertical direction and started to get closer to each other in horizontal direction in time. In the whole duration, the flow in the transition region between the cylinders kept its continuity and it seemed to have decreased at t = 7200 s.

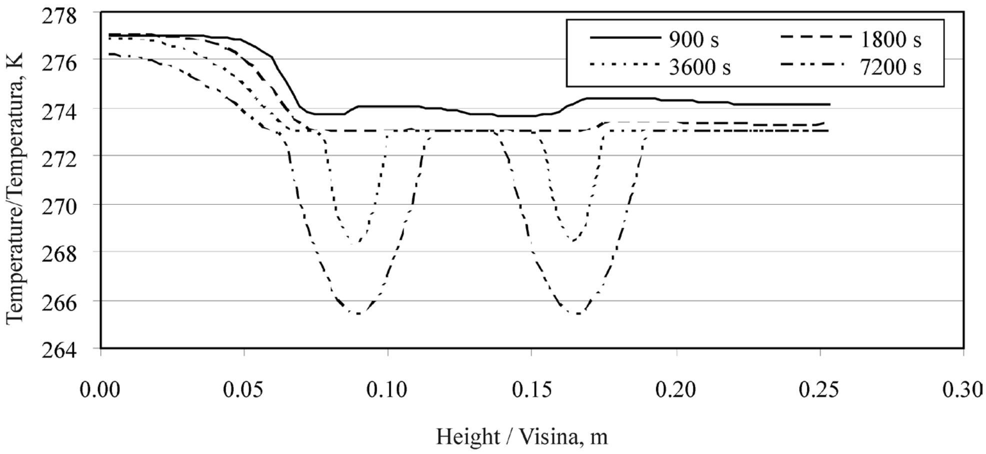

Figure 5. Variation of water temperature with axial distance for different times around inline cylinders (S_L=2d; S_T =3d)

Slika 5. Varijacija temperature vode u aksijalnim smjeru po vremenu oko četiri u liniju sloćene cijevi

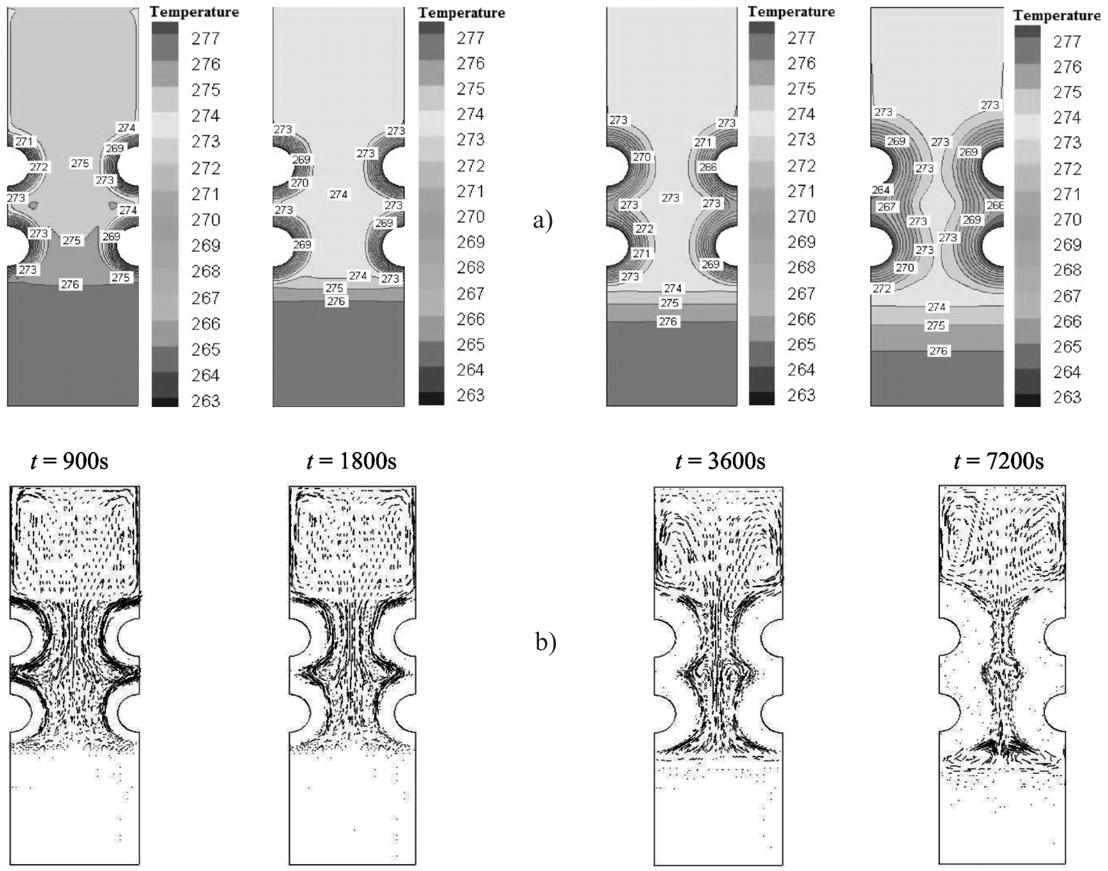

Figure 6. Timewise variation of isotherms and velocity fields for the solidification around inline cylinders (S_L=3d; S_T =2d) a) isotherms b) velocity fields

Slika 6. Vremenska promjena temperature i polja brzina pri skrućivanju oko četiri u liniju postavljene cijevi a) izoterme b) polja brzina a) izoterme, b) polje brzina

The variation of the water temperature with the tank height is seen to be parallel with the results in the temperature distributions (Figure 7). At t = 900 s, the temperature of water layer continuing towards the icy region appearing at the surface of the cylinders was found to be between 2 °C - 4 °C, while it was found to be decreasing towards to the top of the tank. When the time increased, the water temperature decreased until a phase change temperature in the whole points of the tank except the bottom region.

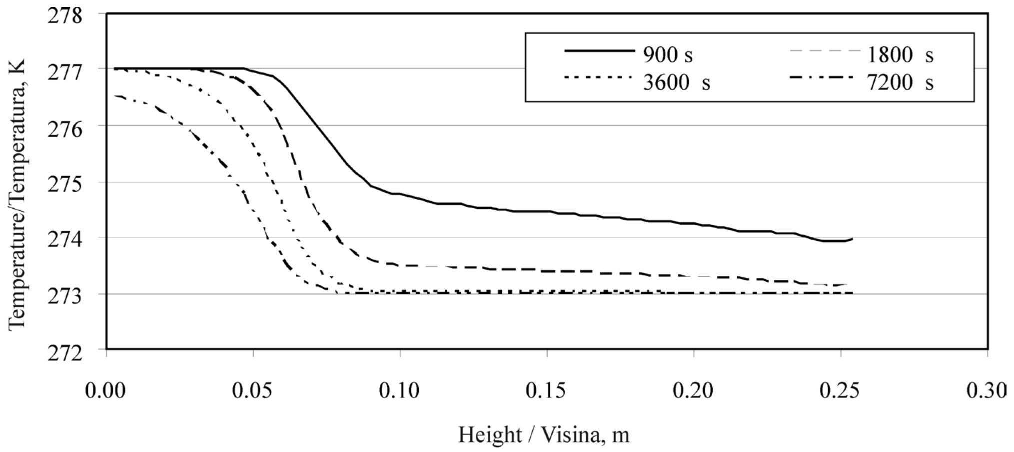

Figure 7. Variation of water temperature with axial distance for different times around inline cylinders (S_L=3d; S_T=2d)

Slika 7. Vremenska promjena temperature vode u aksijalnim smjeru i oko četiri u liniju složene cijevi

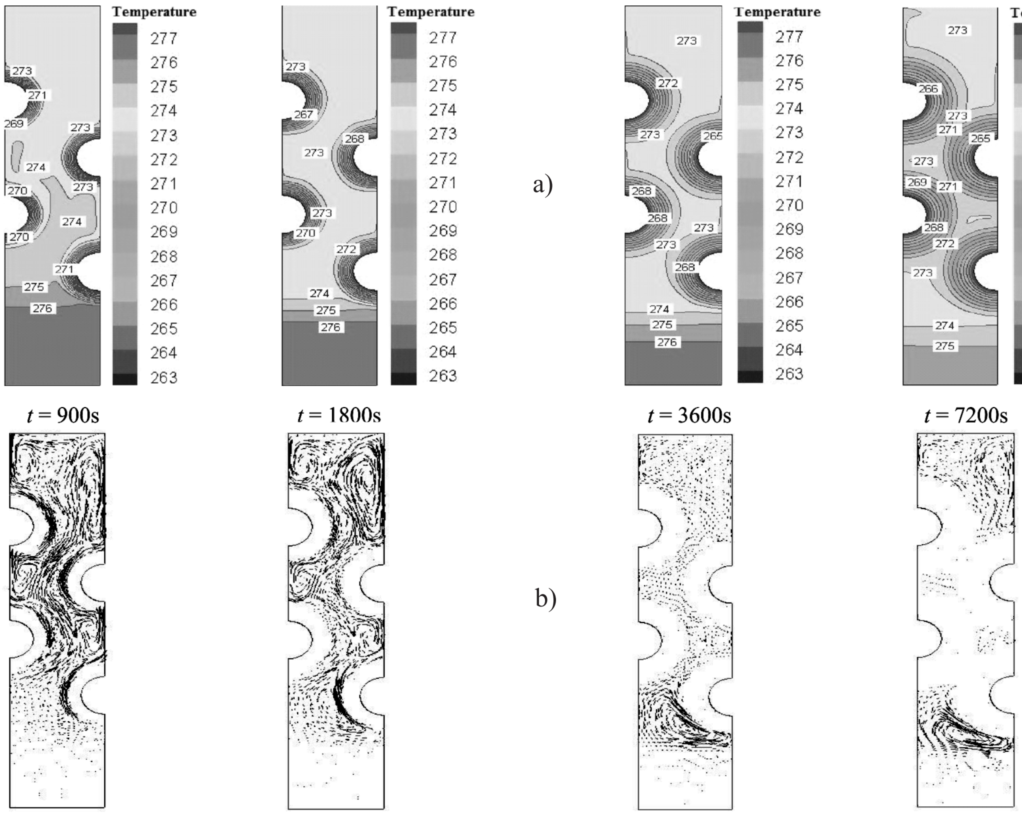

Figure 8. Timewise variation of isotherms and velocity fields for the solidification around staggered cylinders (S_L=2d; S_T =3d)
a) isotherms b) velocity fields

Slika 8. Vremenska promjena temperature i polja brzina pri skrućivanju oko četiri u liniju postavljene cijevi
a) izoterme b) polja brzina

In the case of S_L=2d; S_T=3d for staggered, the water temperature at the t = 900 s is observed to reach 273 K at the upper part of the tank (Figure 8). However, the water temperature can only reach the phase change temperature at the end of the t = 1800 s for the inline model. A higher flow fluctuating in the upward direction is seen on the surface of the cylinders and transition regions. The solidification which appeared on the cylinders whose surface temperature is -10 °C increases in time and thus, the temperature of the water both in the bottom region and in the top region starts to decrease. At t = 1800 s, in the transition regions between the cylinders, the movement density decreases and the eddy flow continues on the top part of the tank.

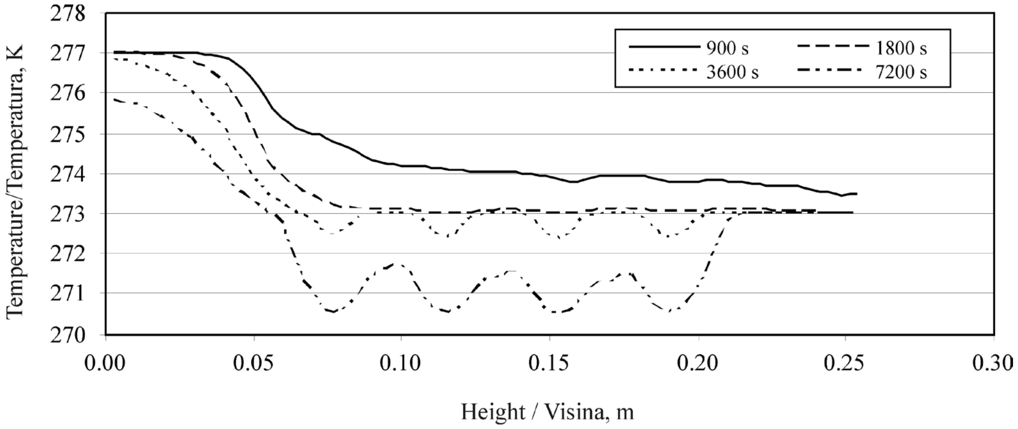

Figure 9. Variation of water temperature with axial distance for different times around staggered cylinders (S_L=2d; S_T =3d)

Slika 7. Vremenska promjena temperature vode u aksijalnim smjeru i oko četiri šahovski složene cijevi

No contact of the ice layers appearing at t = 3600 s was seen in either vertical or horizontal direction, and the flow was observed to have decreased in most part of the tank. The tank height of the water temperature and its change graphic was seen to be parallel with temperature distributions and velocity vectors (Figure 9). Fluctuations are seen due to the temperature differences between ice and water appearing on the surface of the cylinder at t = 7200 s and t =3600 s.

Should tank width increase ($S_L = 3d$; $S_T = 2d$), a higher water temperature is seen in the tank in case of S_L=2d; S_T =3d. A very strong flow is observed on the ice and in the vertical and horizontal pitches between the cylinders (Figure 10). The water temperature in the tank (except in the bottom part) at t = 1800 s decreased up to the phase change temperature. The flow decreased at the bottom part of the tank though it continues at the transition region between the cylinders. Moreover, when the ice thickness increased, the contact of the ice layers was observed in the vertical direction. Although the flow at all points of the tank weakened and the ice thickness increased at the t = 3600 s and 7200 s, ice contacts with each other in the vertical distance. Similar temperature variation can be seen in Figure 11 and in the center of the tank, the water temperature continues at 0 ^{o}C for all times and ice formation continues.

The solidification rate obtained for these models was shown in Figure 12. In case the cylinders are in both inline and staggered positions, the model for the highest solidification rate is obtained in the case of S_L=2d; S_T=3d. It was found that when the horizontal distances between the cylinders are increased, the solidification is affected negatively and more formation of ice is seen for S_L=2d; S_T=3d model. When inline and staggered arrangements are compared on the same model, though more ice is seen on the inline arrangement, towards the end of the analysis solidification rates reach nearly the same value. The solidification rates are less for S_L=3d; S_T=2d model.

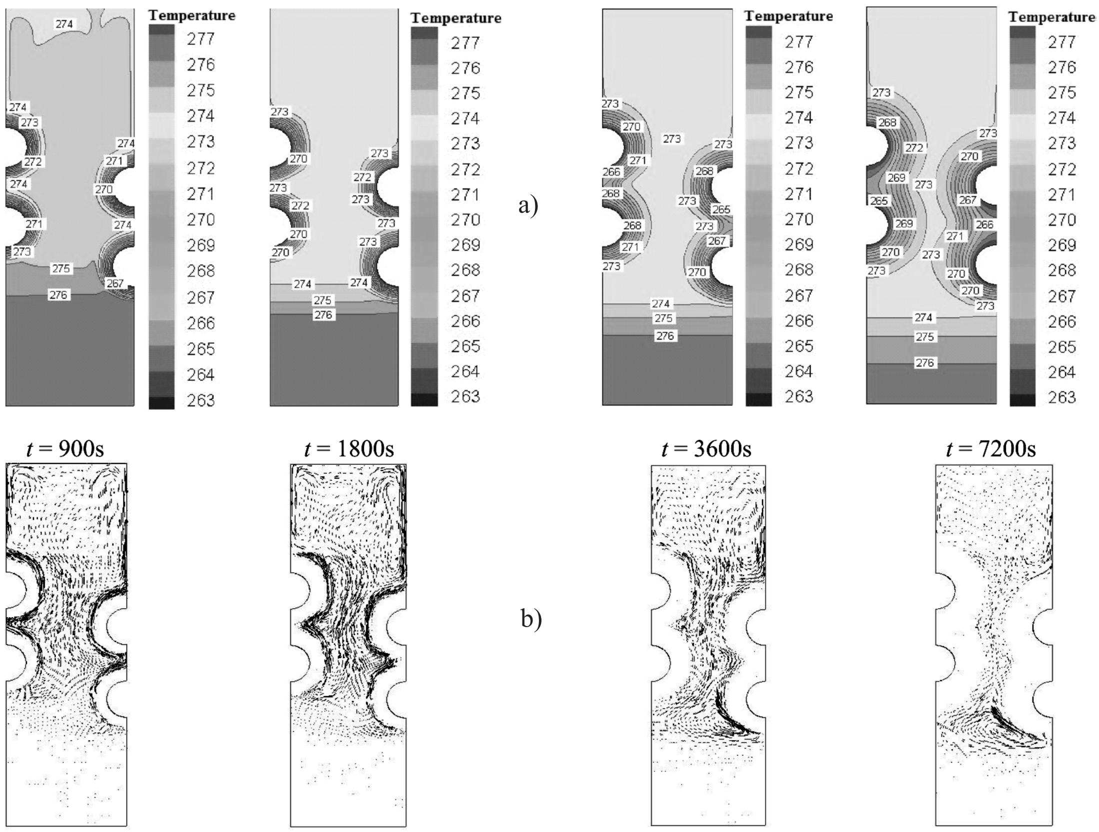

Figure 10. Timewise variation of isotherms and velocity fields for the solidification around staggered cylinders (S_L=3d; S_T =2d) a) isotherms b) velocity fields

Slika 10. Vremenska promjena temperature i polja brzina pri skrućivanju oko četiri šahovski postavljene cijevi a) izoterme b) polja brzina

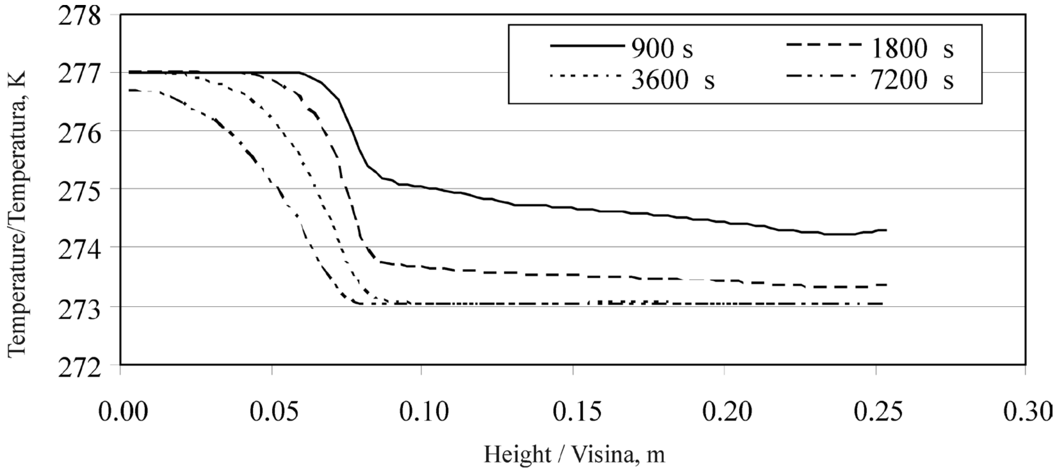

Figure 11. Variation of water temperature with axial distance for different times around staggered cylinders (S_L=3d; S_T =2d)
Slika 11. Vremenska promjena temperature vode u aksijalnim smjeru i oko četiri šahovski složene cijevi

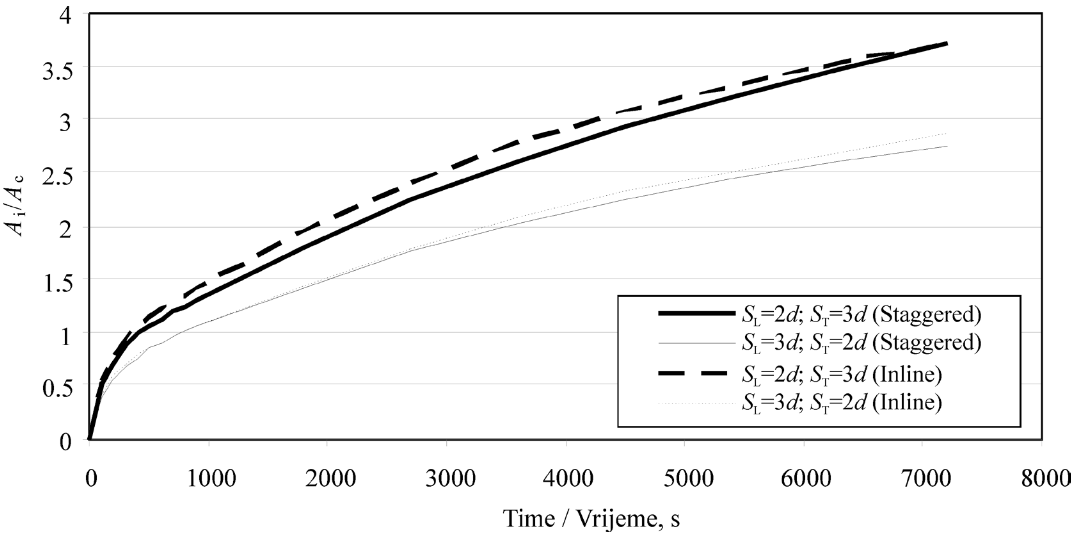

Figure 12. Effect of inline and staggered geometries cylinder position on growth of the solidified area
Slika 12. Utjecaj linijskog i šahovskog rasporeda cijevi na rast skrutnute površine

When staggered and inline arrangement is analyzed, it can be seen that the values are parallel with each other, and they have not changed a lot. The reason why change has not been observed a lot is that S_L and analysis period is are insufficient for the formation of the ice layers on the cylinder.

4. Conclusions

In this study, the values of (the vertical distance between the cylinders) S_L and (the horizontal distance between the cylinders) S_T were changed and the temperature change caused by natural convection, velocity vectors and solidification rates change depending on time, where cylinders are placed in inline and staggered positions, were obtained.

It was observed thet there was a very fluctuating flow due to the natural convection in the tank. It was also seen that flow appears in vortex in some places and sometimes in permanent flow at all times. When the vertical distance is increased between the cylinders, the volume of the tank increases, so ice formation is affected negatively.

Besides, in the case of inline and staggered positions of the cylinders, the solidification rates were observed to be very close to each other for the same S_L and S_T rates. In addition to this, the solidification rate in inline models especially for S_L=2d; S_T=3d was found to be more.

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