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Numerical investigation of freezing process with forced convection in channel flow

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Abstract
In the present study, the laminar flow with forced convection has been investigated in two dimensional channel for food freezing. The governing equations, continuity, momentums and energy equations have been solved numerically. The control volume method with staggered grid has been used to achieve the dicretized form of governing equations. The thermophysical properties of air are assumed to be constant while the thermalphysical properties of food vary with temperature during the freezing process. According to phase change in food, the apparent specific heat model has been used. Comparison of these numerical results with experimental ones shows good accuracy of predictions.
Keywords: freezing, forced convection, channel flow, food

Introduction
Freezing process and its rate have industrial importance. Keeping of freezing food cause to decrease bacteria, viruses and microscopical components grow, which are exist in food and its surrounding air.

Theory and solution model: The physical situation and boundary conditions have been shown in Figure 1, Air with uniform velocity and temperature enters the channel to freeze the solid food. The top and bottom walls of channel are assumed to be isolated [1]. The Reynolds number is 5650 in the basis of entrance diameter of the channel and air temperature is -30 ℃. No gradient conditions on the outlet of the channel and no slip condition on to the walls are imposed as boundary conditions of the governing equations. The transient governing equations in the fluid and solid phases have been solved simultaneously. SIMPLE algorithm [2] has been used to solve the transient Navier-Stocks equations in fluid. Also the transient energy equation in fluid and food are solved. A staggered grid has been applied to solve the velocities [3]. The solution of fluid flow is transient that achieved the steady conditions in which just energy equation is solved. The model used for phase change is enthalpy method in which the specific heat is substituted by a specific apparent heat that varies with temperature. It includes the specific heat of food, water and ice, and the latent heat of water [1]. A complete model which is related to time dependent coefficients is approximated with fifth polynomial functions in terms of temperature by least squares fitting [4] in different temperature range. Mass transfer has been ignored in this study, because it confines to regions close to the external surfaces. The main objective of this work is direct solution of Navier-Stocks equations in fluid and energy equation in fluid and solid phases.

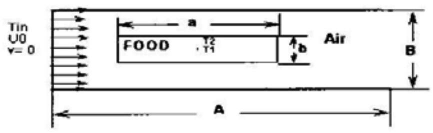


Figure 1- Physical situation of problem

Discussion: Dependency of results to grid size and time step was analyzed. It has been found out the grid 80×28 and time step 0.01 s are appropriate in terms of running time and accuracy, these values remove sensibility of model to grid size and time step. The numerical results related to central temperature of food and the point between center and top bound of food were compared to experimental published results [4] and observed good agreement between them.

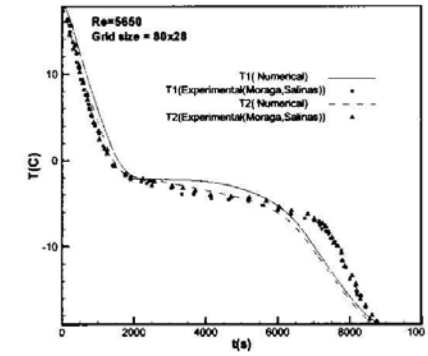


Figure 2-Temperature distribution in the food at points 1 and 2

The variation of temperature versus of time inside of the food in two mentioned points (Figure 1) has been shown in Figure 2.The temperature different of the food and fluid in the first 2000 seconds is high, that is caused to decrease temperature of food more fast than after freezing process. The temperature variation of the food versus time due to change phases is small in the freezing process. The maximum error of the temperatures between the presented solution and experimental data after freezing is 29%. Heat transfer on the top and bottom faces has been shown in Figure 3 that is symmetric and this confirms the symmetry of the problem domain. Figure 3 shows the heat transfer on the top face of the food decreases along the flow direction in each time due to the growth of the boundary layer in the direction of flow. This means the heat transfer coefficient through the top surface of the food decreases along the flow direction. Also the pass of time causes to reduce the temperature difference in the fluid and food and hence the heat exchange between those materials decreases with respect of time. According to Figure 3 the heat transfer rate about 6000s in the leading edge of the food is zero because the difference of temperature at the interface of the food and fluid is equal zero. This process occurs from the leading to trailing edge of the food as time passes. The variation of heat transfer in the bottom face is similar to the cited top face but its direction is opposite of it.

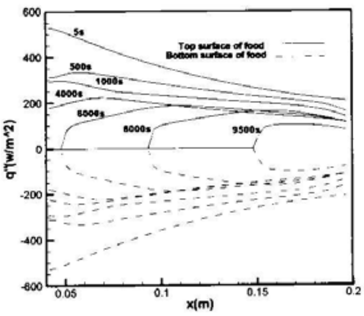


Figure 3-heat transfer rate on the top and bottom surfaces in different times

Figure 4 shows that the heat transfer on left surface of the food has reached to zero sooner than the top and bottom surfaces that occur after 9500s for them because the boundary layer grows less than the value in the top and bottom faces due to its short length, so the food temperature becomes equal to the flow temperature sooner than the two faces in top and bottom of the food. Also according to Figure 4 it has been seen the heat transfer rate in the center of left surface of food is maximum due to the boundary layer thickness that is small in the stagnation point,. This thickness increases in two side of the left surface of the food symmetrically so the heat transfer rate reduced.

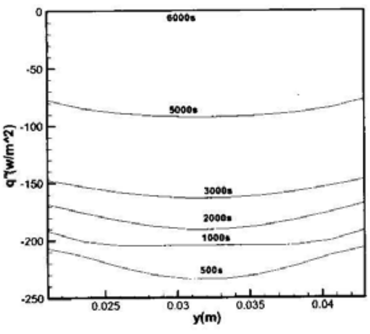
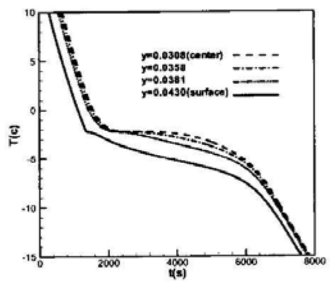


Figure 4-heat transfer rate on left surfaces of the food in different times

Variations of center to surface temperature of the food in time has been shown in figure 5. As moving from center to surface, the region of phase change lessens, because the points in the vicinity of surface transfer their latent heat quickly, while the deep points of the food take more time to remove their latent heat, therefore the phase change region becomes longer.



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[2] Patankar, S.V., 1980, "Numerical heat transfer and fluid flow", Hemisphere, Publishing corporation, Washington D.

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[4] O.Moraga,N.and Salinas,C.H., 1999, "Numerical model for heat and fluid flow in food freezing", Numerical Heat Transfer, Part A, 35:495- 517.

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Abstract
In the present study, the laminar flow with forced convection has been investigated in two dimensional channel for food freezing. The governing equations, continuity, momentums and energy equations have been solved numerically. The control volume method with staggered grid has been used to achieve the dicretized form of governing equations. The thermophysical properties of air are assumed to be constant while the thermalphysical properties of food vary with temperature during the freezing process. According to phase change in food, the apparent specific heat model has been used**.** Comparison of these numerical results with experimental ones shows good accuracy of predictions.

Keywords: freezing, forced convection, channel flow, food

Introduction

The rate of freezing process has industrial importance. Preservation of freezing food cause to decrease bacteria, viruses and microscopical components grow, which are exist in food and its surrounding air. At temperatures lower than -10°c few microorganisms can develop and chemical reactions are greatly reduced and cellular metabolic reactions are also delayed.

The freezing foods widely consumed in many countries, but they have been studied only few decades ago. Freezing process includes freezing, preservation, reservation and thawing of freezing foods, that they should be conducted properly to cause to optimal results in freezing process. The predict of cooling and freezing times is required in order to estimate the refrigeration requirements for freezing systems and to design the necessary equipment for freezing process.

The mathematical formulation includes complex situation of heat transfer with simultaneous phase change. The physical model for freezing is non-linear un--steady heat conduction with variable thermal properties and surface convection cooling.

Prediction of freezing time has been the subject of many researches, Cleland [1] studied the methods of prediction of freezing and thawing times for the regular and irregular foods, he considered the data set include of 593 experiments. An analytical simple model performed by Salvadori and Mascheroni [2] that was specially prepare for practical industrial calculation and Product with regular and simple geometry. In this method freezing time can explain as a function of final temperature, dimension and physical properties of fresh foods and practical conditions.

Salvadori et al [3] expanded the application of this simple approximated method for multi-dimensional regular foods. Moraga and Medina [4] considered unsteady forced convection heat transfer and heat conduction with freezing for a two dimensional plate shape food in laminar flow in channel that thermal properties in food vary with food temperature. Moraga and Salinas [5] implemented numerical study on conjugated natural convection analyse with rectangular food freezing and considered Rayleigh and mean Nusselt number effect on freezing curves and on chamber walls and food surfaces. Hamdami et al [6] simulated the one-dimensional heat and mass transfer during freezing for a porous humid food that predict local moisture, temperature and weight loss throughout freezing process. First time Hashemi and Sliepcevich [7] presented the apparent specific heat with formulation of finite difference based on the Crank-Nicholson method. They use this method for one-dimensional problem in which phase change took place in temperature range. After that Comini et al [8] expanded this method with finite difference formulation for one-dimensional and two-dimensional problems, with the moving bound and temperature dependent thermophysical properties.

Tu and Liu [9] performed an experimental study on freezing process of cucumber. Davis and Moore [10] studied the confined flow on rectangular cylinder numerically and experimentally. Davis et al [11] implemented an experimental and numerical study for great range of Reynolds number and blockage ratio in channel flow.

Physical situation and mathematical model: A rectangular shaped portion of salmon meat with length of *a* and height of *b* has been placed in a horizontal channel. Air with uniform temperature and velocity enters into the two-dimensional channel to freeze the food. Schematic view of physical situation has been shown in figure1.

In mathematical formulation of problem following assumption are made: air is a Newtonian fluid. Density, specific heat and thermal conductivity of the food are temperature dependent.

The properties of air are assumed to be constant during the process, $\mu = 1.8224\times10^{-5}$ kg/ms; $\rho = 1.3 kg/m^3$; $k = 0.0251 W/m^\circ C$; $c_p = 1.01 kJ/kg^\circ C$. The properties of unfrozen food are $\rho = 1100 kg/m^3$; $k = 0.481 W/m^\circ C$; $c_p = 3.153 kJ/kg^\circ C$.

The governing equations are: mass conservation, Navier-Stocks and energy equations for air flow and energy equation for the food.

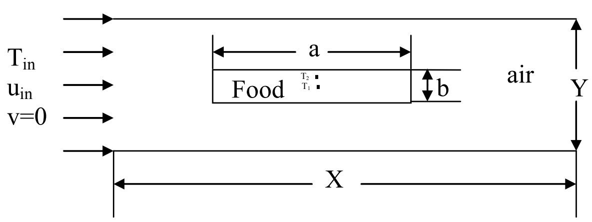


Figure 1- Physical situation of problem

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \qquad (1)$$

$$\rho_a\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = \mu_a\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) - \frac{\partial P}{\partial x} \qquad (2)$$

$$\rho_a\left(\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right) = \mu_a\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) - \frac{\partial P}{\partial y} \qquad (3)$$

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha_a\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \qquad (4)$$

$$\frac{\partial(\rho c_p T)}{\partial t} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) \qquad (5)$$

The flow is unsteady and two-dimensional, the food includes solid and water that can be either liquid or solid. The top and bottom walls of the channel are assumed to be isolated [4]. The Reynolds number is 5400 in the basis of entrance diameter of the channel and input temperature of the air is -30 ̊C. No gradient conditions on the outlet of the channel and no slip condition on the walls are imposed as boundary conditions of the governing equations.

The initial conditions at time equal zero are:

$$u = v = 0$$

$$T_{air} = T_{food} = T_0 = 17.8^\circ C \quad \text{at} \quad t = 0 \qquad (6)$$

The boundary conditions for the problem are:

$$T = -30^\circ C \quad \text{at} \quad x = 0 \qquad (7\text{-a})$$

$$u = 1.182 m/s \quad v = 0 \quad \text{at} \quad x = 0 \qquad (7\text{-b})$$

$$u = v = \frac{\partial T}{\partial y} = 0 \quad \text{at} \quad y = 0 \qquad (7\text{-c})$$

$$u = v = \frac{\partial T}{\partial y} = 0 \quad \text{at} \quad y = B \qquad (7\text{-d})$$

$$\frac{\partial u}{\partial x} = \frac{\partial T}{\partial x} = v = 0 \quad \text{at} \quad x = A \qquad (7\text{-e})$$

The transient governing equations in the fluid and solid phases have been solved simultaneously. The SIMPLE algorithm [12] has been used to solve the transient Navier-Stocks equations in fluid. Also the transient energy equation in fluid and food are solved. A staggered grid has been applied to solve the velocities. The solution of the fluid flow is transient that achieved the steady conditions and only the energy equation is solved. The model used for phase change is enthalpy method in which the specific heat is replaced by a apparent specific heat that varies with temperature. It includes the specific heat of food, water and ice, and the latent heat of water [5]. A complete model which is include of temperature dependent coefficients was approximated with fifth polynomial functions in turn of temperature by least squares fitting [5] in different temperature range.

$$F(T) = a + bT + cT^2 + dT^3 + eT^4 + fT^5 \qquad (8)$$

where F(T) is thermophysical property of salmon meat. The coefficients *a* to *f* has been presented in ref[5].

Mass transfer has been ignored in this study, because it confines to regions close to the external surfaces of the food. The main objective of this work is direct solution of Navier-Stocks equations in the fluid and energy equation in fluid and solid phases.

Numerical solution procedure

The conjugated forced convection problem with heat conduction was considered numerically. The unsteady and non-linear equations with liquid-solid phase change in the food were solved by control volume method.

The SIMPLE algorithm and power law method has been used to calculate velocity and pressure domain and calculate the convection terms in momentums and energy equations. A line by line numerical method was used to solve the discretized equations. A grid was used to calculate the temperature and pressure values at grid points located at the center of the control volume and the velocity values at the surfaces of control volume. Calculations in the food were performed by considering it as a sub-domain with a large value of source and switching from the air properties to the temperature dependent salmon meat properties that are shown in figure2. A breakage is observed in the these figures when the freezing is begun that is a result of phase change.

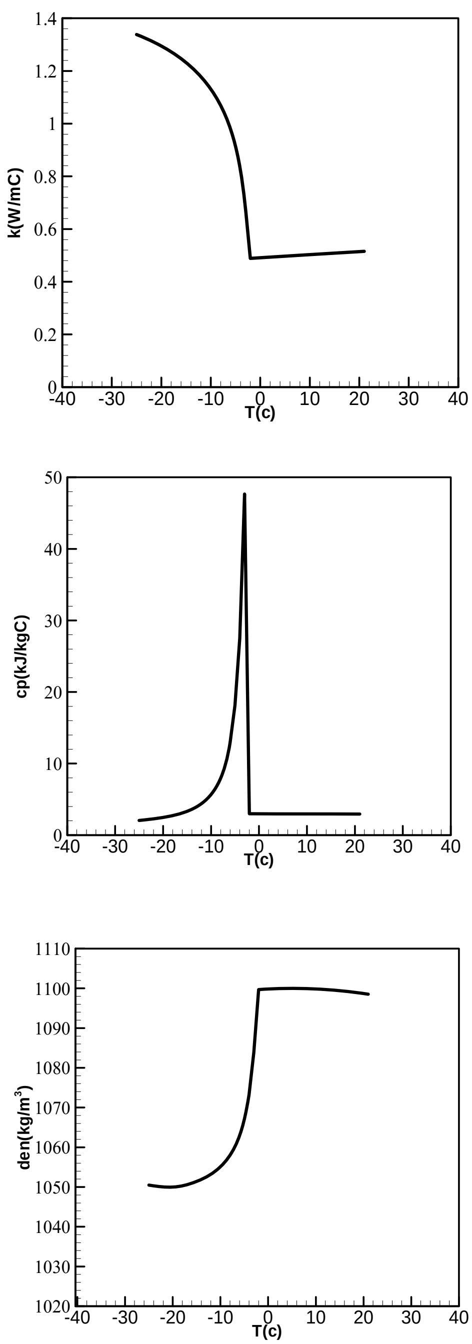
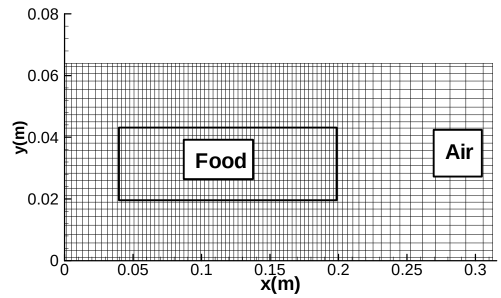


Figure 2-thermal properties of salmon meat

The specific heat in before and after freezing temperature is near together. A large peak is made in the initial freezing point that is a result of releasing latent heat.



Figur3- solution domain

Discussion

The location of some points in which the results has been reported, are shown in figure4.

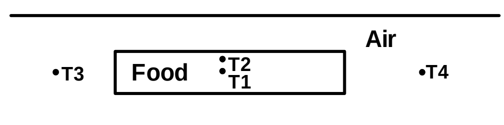


Figure4-The dimensional situation of before the food (T3), after the food (T4), center of the food (T1), near to surface of the food

The velocity profile in before, after and center of the food has been considered for grid sizes of 18×15, 62×21 and 80×28 in figures5,6,7, to show the results is independent from grid size. The grid of 80×28 was found to be efficient.

Another trial was performed for some time steps in transient and steady stages. The temperature profiles in before, after and center of the food has been shown in figures 8,9,10. The results showed when the time step reduced less than 0.01 seconds it will not make sensible change in the solution.

The necessary time that the flow achieves the steady condition is significant, because in this stage the momentum and continuity equations are solved in flow field that takes a long time. The analyse of flow equations are exited from solution procedure after the time that the flow became steady. It means only energy equations in the food and the flow is solved. The results showed that the velocities after 3 seconds will not change. Therefore the flow field takes 3 seconds to get steady. The figure11 shows changes of x-velocity in turn of x after the food. Another investigation was implemented for time step in steady stage. it seems 1 second time step is prepare. 0.5 second time step was used to increase the accuracy of the solution.

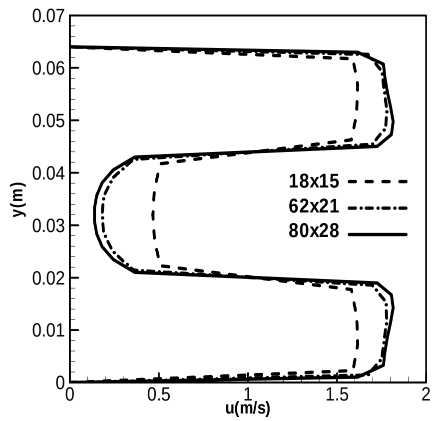


Figure5-Velocity profile before the food for different grids

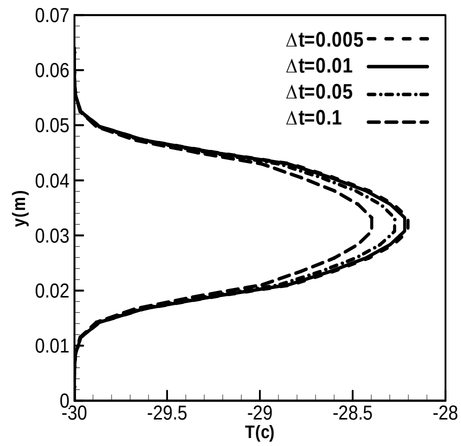


Figure 8-Temperature profile before the food for different time steps in transient stage

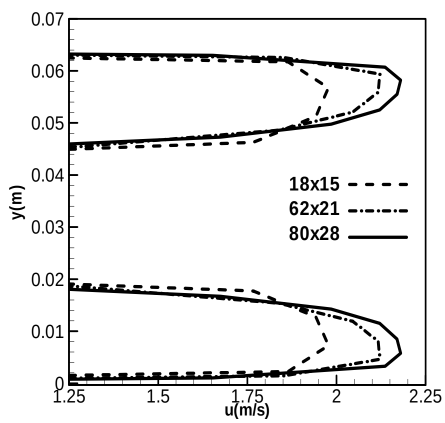


Figure6-Velocity profile at the center of the food for different grids

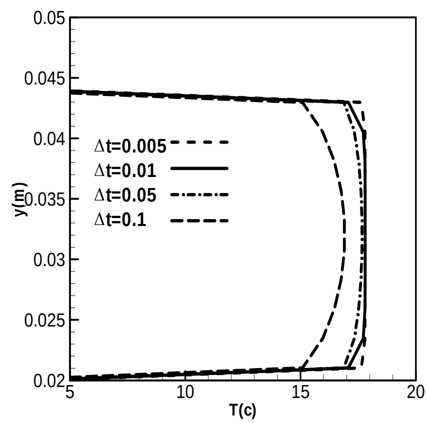


Figure 9-Temperature profile at the center of the food for different time steps in transient stage

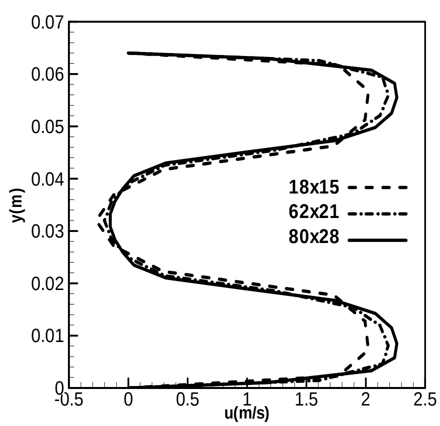


Figure7-Velocity profile after the food for different grids

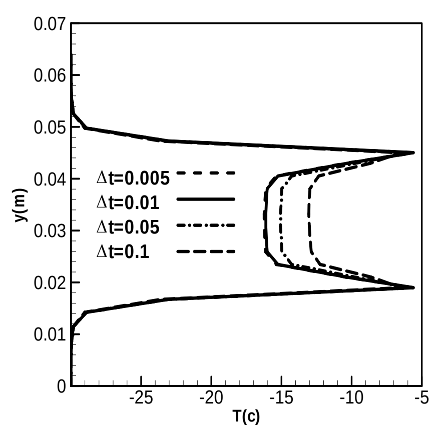


Figure 10-Temperature profile after the food for different time steps in transient stage

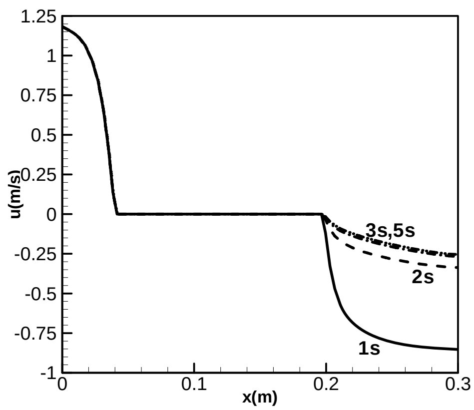


Figure11-Velocity distribution on centre line of the channel for different times

As it has been said no gradient condition was used on the end of channel; In order to consider the validation of using this boundary condition in channel the variations of velocity profile in a channel with 2m in length at 4 nodes in the end of channel has been shown in figure12, Also the velocity profile in the end of channel with .4m in length has been shown in figure13. It is observed that variation of velocity profile at the end of two channels is ignorable, therefore the imposing of mentioned above boundary condition for a length of 0.4m is correct.

The result of numerical solution was validated with experimented results [5].The variation of temperature versus of time inside of the food in two mentioned points has been shown in figure14. The temperature difference of the food and fluid in the first 2000 seconds is high, that is caused to decrease temperature of food more fast than after freezing process. The maximum error of the temperatures between the presented solution and experimental data after freezing is 29%.

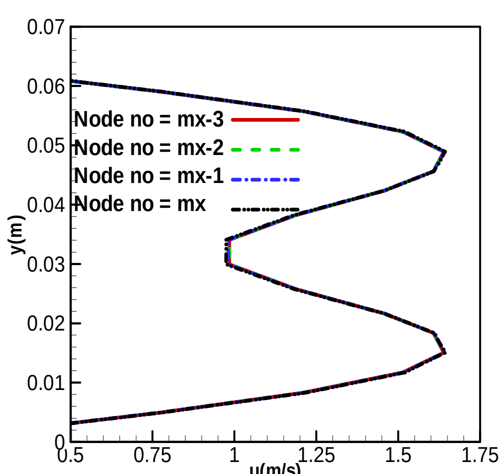


Figure12-velocity profile in the channel with the length of 2m for 4 nodes of channel end

According the importance of the rate of freezing process in quality of the food and the importance of optimal design of cooling systems that makes prepare and desire input temperature, the variation of temperature was con-

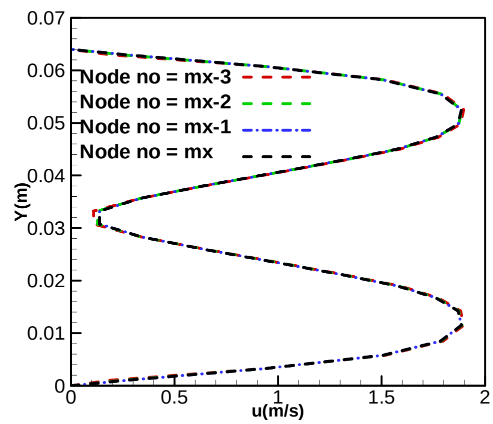


Figure13-velocity profile in channel with the length of 0.4m for 4 nodes of channel end

-sidered in turn of time in some different input temperature.

According the figure15 the total time of freezing process was decreased with reducing in the input temperature in this way that the phase change time reduced rather than another two cases and cooling after freezing decreased the temperature with sharp slop. The effect of Reynolds number on freezing time has been considered in figure16.

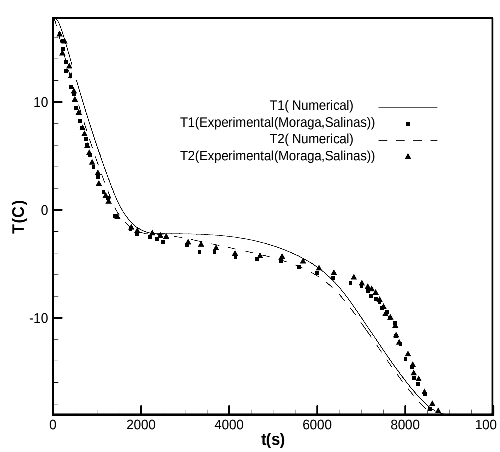


Figure14-temperature distribution at central and near to up surface node (T1),(T2)

The total time of freezing at Reynolds of 5400 is 3000seconds shorter than the freezing time at Reynolds of 2300. It is 8000seconds shorter than the freezing time at Reynolds of 1000. Variations of central temperature to the surface of the food in turn of time have been shown in figure17. Because of temperature gradient in direction of y is zero, the heat transfer in direction of y in depth of the food lessened. Hence it takes more time for phase changes while it is shorter for the near nodes to surface of the food.

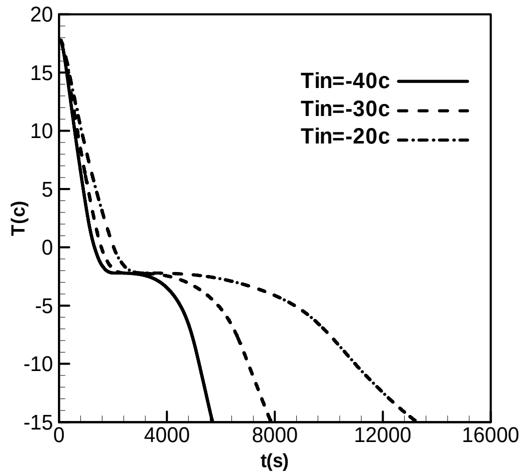


Figure 15- Temperature variation at central point of the food (T1) in turn of time for some different input temperature of air

The slop of temperature figure in turn of time reduced rapidly in the region of before phase change which is a result of temperature difference between the food and its surrounding air. When the temperature of the food became near to surrounding air, the figure fell down with lower slop. The temperature variation at 4 nodes near to up, down, left and right has been shown in figure18. Since the temperature differences at the node near to left surface is maximum, the heat transfer is more than other nodes. So the cooling begins from left boundary then up and down nodes and the last one is the node near to right boundary.

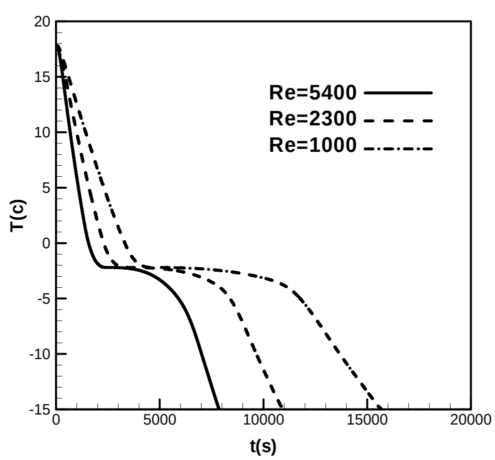


Figure16-temperature variation in turn of time for central point of the food over different Reynolds

Heat transfer on the top and bottom faces has been shown in figure 19 that is symmetric and this confirms the symmetry of the problem domain. figure 19 shows the heat transfer on the top face of the food decreases along the flow direction in each time due to the growth of the boundary layer in the direction of flow.

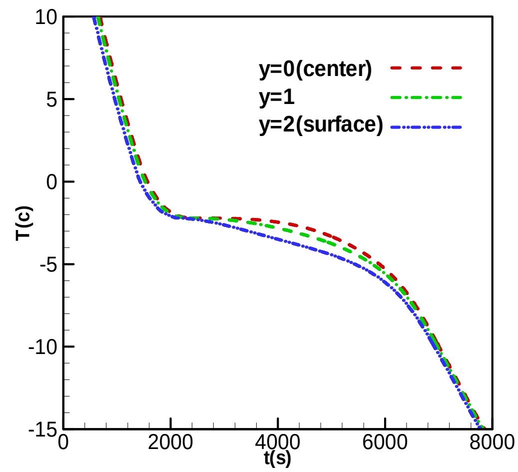


Figure17- temperature variation in turn of time from the central point to near to the surface of the food

This means the heat transfer coefficient through the top surface of the food decreases along the flow direction. Also the pass of time causes to reduce the temperature difference in the fluid and food and hence the heat exchange between food and air decreases with respect of time. According to figure 19 the heat transfer rate about 6000s in the leading edge of the food is zero because the difference of temperature at the interface of the food and fluid is equal zero. This process occurs from the leading to trailing edge of the food as time passes. The variation of heat transfer in the bottom surface is similar to the cited top face but its direction is opposite of it.

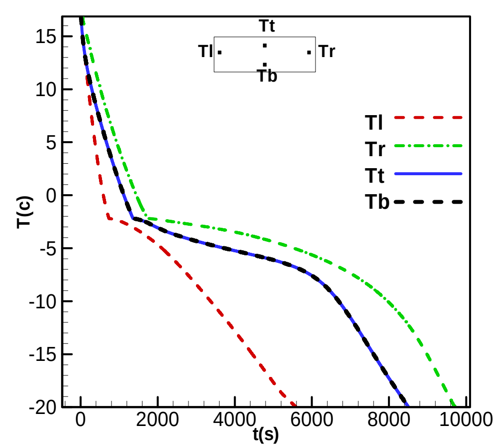


Figure18-temperature variation in turn of time for top, bottom, left and right points of the food

figure 20 shows that the heat transfer on left surface of the food has reached to zero sooner than the top, bottom surfaces that occurs after 9500s for them because the boundary layer grows less than the value in the top and bottom faces due to its short length, so the food temperature becomes equal to the flow temperature sooner than the two faces in top and bottom of the food.

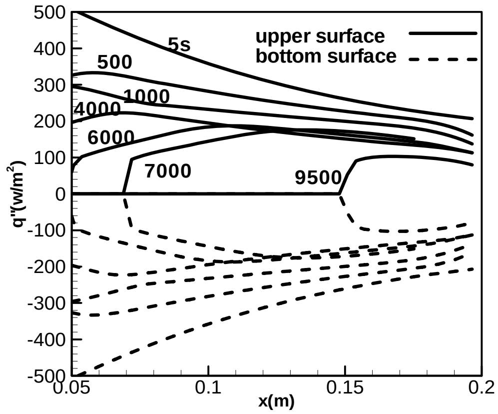


Figure19-heat transfer rate on the top and bottom surfaces of the food in different times

Also according to figure 20 it has been seen the heat transfer rate in the center of left surface of food is maximum due to the boundary layer thickness that is small in the stagnation point,. This thickness increases in two side of the left surface of the food symmetrically so the heat transfer rate reduced.

In figure21 isotherm lines have been shown in the flow field for some different time. The advance of cooling layers is observed. The food corners are affected rapidly. Therefore the freezing process begins from left surface of the food and advance through the food.

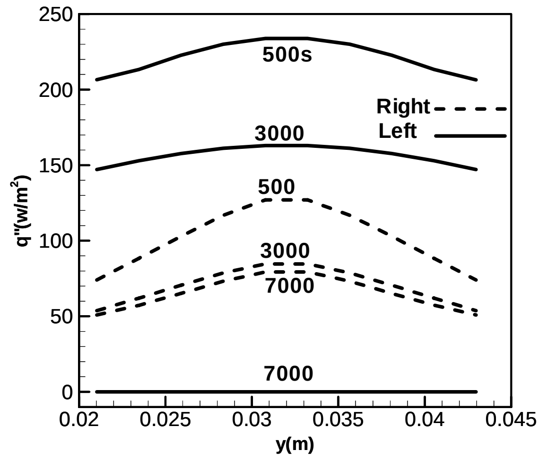


Figure20-heat transfer rate on the left and right surfaces in different times

Conclusion

The comparison of numerical results with experimental results shows good agreement.

The increase of Reynolds number which is result of increasing velocity, cause that freezing takes place rapidly because of increasing in heat transfer coefficient. Also the decrease of temperature results in reducing of freezing time. When the input temperature decrease, The temperature difference between the food and air become more. Therefore the heat transfers quickly. Variation of heat transfer on top and down surfaces is concluded that heat transfer decrease through these surfaces, it means the freezing begins from leading corners and advance to right side.

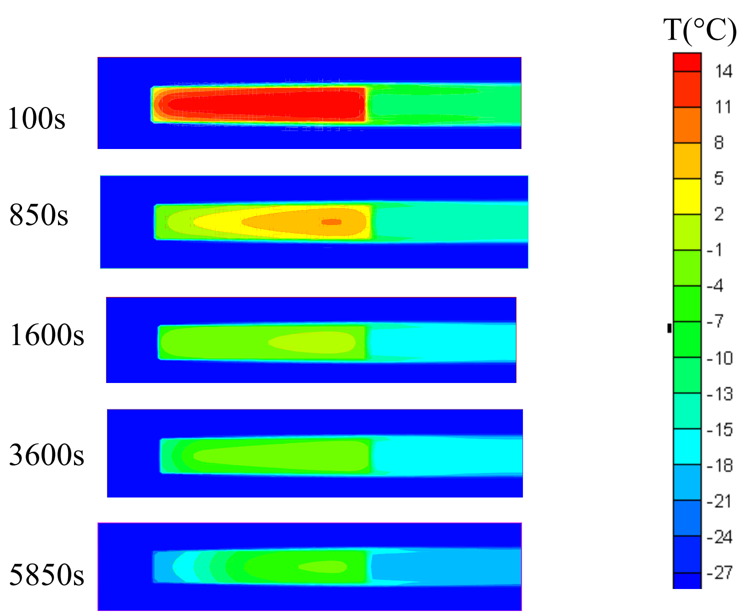


Figure21-Isotherm lines in channel in Reynolds of 5400 and different times

a Length of the shaped food
b Height the shaped food
c_p Apparent specific heat of the food
Thermal conductivity
k Pressure
p Reynolds number, $U_{in}Y/v$
Re Time
t Temperature
T Initial air and food temperature
T_0 x-direction velocity
U x-direction velocity at x=0
U_{in} y-direction velocity
V horizontal coordinate
X vertical coordinate
Y thermal diffusivity
α dynamic viscosity
μ density
ρ
Subscripts

a Air
0 initial

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