Journal of Applied Sciences

ISSN 1812-5654

science alert

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Journal of Applied Sciences 8 (12): 2234-2241, 2008
ISSN 1812-5654

Effect of Some Parameters on Freezing Time of Slab Shaped Foods Under Two Impinging Slot Jets

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Abstract: The influence of jet-to-jet spacing, freezing air velocity and nozzle to food distance on freezing time of slab shaped food is investigated numerically using CFD (computational fluid dynamics). The jet width is 3 cm and the food length and thickness are 120 and 4 cm, respectively. An optimum jet-to-jet spacing is obtained. Continuity, momentum and energy equations were solved using Fluent 6.0 a commercial Computational Fluid Dynamics (CFD) solver. In order to model the turbulent air flow, the standard k-ω turbulence model was applied. The interaction between two jets is found to be most advantageous and the freezing air velocity, nozzle to food spacing is other important factors affecting freezing time.

Key words: Slot jet, Impingement, freezing time, stagnation point, heat transfer coefficient

INTRODUCTION

In the food industry, freezing proves to be very important operation since it offers many challenges from the process engineering point of view, according to the development of new technologies guided to preserve the product quality. In such context, impingement jet systems have been identified as an alternative to conventional methods, giving their high turbulence characteristics, which enhance heat transfer. Although such jets yield very high heat transfer coefficients in stagnation zone, the cooling performance drops rapidly away from the impingement zone. For this reason and to increase the uniformity of the heat flux distribution, jets are often used in arrays. In addition, arrays of jets are used when cooling and freezing industrial products with large surface areas. In such cases the interactions between the jets play an important role in the cooling and freezing routine. The collision of the wall jets after impingement produces a rather complex flow field. Therefore, it is essential that the effect of important parameters on freezing time of foods identified and studied. Foods undergoing freezing, release latent heat over a range of temperatures. Freezing does not occur at a unique temperature. As well, foods do not have constant thermal properties during freezing. As a result, no exact mathematical model exists for predicting the freezing times of foods. The accurate prediction of freezing time of foods can be predicted approximately by either analytical methods or by numerical methods. Also a large amount of work related to impingement heat transfer of multiple jets is available but studies on freezing of foods using two or multiple impingement jets is rare. Gardon and Akfirat (1966) investigated the heat transfer characteristics of two dimensional air jets impinging perpendicular to an isothermal flat plate. The average Nusselt number of a square in-line array of confined circular air jets impinging perpendicular to a flat plate was obtained by Kercher and Tabakoff (1970). Saripalli (1983) studied the flow between two impinging jets. A fountain between two adjacent jets was observed. The interaction between the fountain and the two jets was found to increase with decreasing the jet spacing. The local Nusselt number for staggered arrays of circular air jets impinging on constant heat flux surface was obtained by Behbahani (1983). The heat transfer characteristics for several in-line and staggered arrays of circular air jets impinging on an isothermal plate were investigated by Florschuetz *et al.* (1984). Huber and Viskanta (1994) investigated the effect of jet-to-jet spacing on the convective heat transfer to in-line arrays of round jets. The results show that the local Nusselt number decreases with the jet-to-jet spacing. For a fixed jet-to-jet spacing, the adjacent jet interference before impingement reduces as the nozzle-to-food distance decreases. Slayazak *et al.* (1994) investigated the effect of jet interaction on local heat transfer for slot jets. A maximum convective heat transfer coefficient between two stagnation lines was found. San and Lai (2001) experimentally investigated the effect of jet-to-jet spacing on the local Nusselt number for circular air jets vertically impinging on a flat plate. Thielen *et al.* (2003) using the commercial CFD code FLUENT, studied the effect of geometrical arrangement of

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nozzles in a multiple impinging jet set-up on the flow field and resulting heat transfer. The flow and heat transfer in two planar impinging jets are investigated by Akiyama *et al.* (2005) using Large-Eddy simulation and experiments. Fenot *et al.* (2005) used a technique based on infrared thermography to determine the convective heat transfer on a flat plate on which either a single circular air jet or arrow of jets impinged. Olsson *et al.* (2005) using CFD studied flow and heat transfer prediction of multiple slot air jets impinging on circular cylinders and found that flow characteristics and heat transfer distribution around the cylinders dependent on the distance and the opening between the jets.

Although there are many research works dealing with impingement heat transfer of jet arrays, but reviews indicate that there is little research on CFD modeling of slot-jet impingement freezing of slab shaped foods. In this work, the effect of jet-to-jet spacing, freezing air velocity and nozzle to food distance on freezing time of slab shaped food is studied using the commercial CFD code FLUENT 6.0. In this study the slot jet is assumed to be large in the span vise direction. Hence the flow configuration can be considered as a two dimensional planar jet.

MATHEMATICAL MODELING

Governing Equations: The fluid flow and heat transfer are governed by three equations: the continuity, the conservation of momentum and the conservation of energy equations:

The continuity equation,

$$\frac{\partial U_j}{\partial X_j} = 0 \qquad (1)$$

The conservation of momentum (in x, y and z directions),

$$\frac{\partial U_i}{\partial t} + \frac{\partial U_i U_j}{\partial X_j} = -\frac{1}{\rho} \cdot \frac{\partial P}{\partial X_i} + \frac{\partial}{\partial X_j}\left[\gamma\left(\frac{\partial U_i}{\partial X_j} + \frac{\partial Uj}{\partial X_i} - \langle u_i' u_j' \rangle\right)\right] \qquad (2)$$

And the conservation of energy,

$$\rho.c_v.\frac{\partial T}{\partial t} + \rho.u_j.c_p.\frac{\partial T}{\partial x_j} = \frac{\partial}{\partial x_j}\left[k.\frac{\partial T}{\partial x_i} - \rho.c_p.\langle u_j' T' \rangle\right] + q_v \qquad (3)$$

In turbulent flow, the velocity magnitude fluctuates with time and these fluctuations are known as the turbulence where the velocity in the turbulent flow can be divided into the average and turbulent components. The decomposition of the flow field into the average and turbulent (fluctuating) components has isolated the effects of the fluctuations on the average flow. However, the addition of the turbulence in the Navier-Stokes equations, as seen above, results in additional terms, known as Reynolds stresses, leading to a closure problem increasing the number of unknowns to be solved. In order to solve this problem, a mathematical path for the calculation of the turbulence quantities must be provided. There are special turbulence models to solve this issue, e.g., k-ε, k-ω, Reynolds Stress Model (RSM) and many others. In this study the standard k-ω turbulence model was applied in Fluent 6.0. The computational domain is shown in Fig. 1.

Initial and boundary conditions: We assume that there is no mass transfer and evaporation during the freezing process although there are phase change and corresponding heat release and the slab shaped food is initially in thermal equilibrium ($T = T_i$). Heat transfer due to radiation from food surface was neglected. With reference to Fig. 1, the mass, momentum and thermal boundary conditions are as follows:

Slot nozzle outlet (1): U_j = constant, $T = T_j$

Outflow boundary (4): $\frac{\partial U}{\partial X} = \frac{\partial V}{\partial X} = 0$

Upper boundary (5): $U = V = 0$ and $\frac{\partial T}{\partial Y} = 0$

On the food surface (3): $U = V = 0$ and $h\left(T - T_j\right) = -k\frac{\partial T}{\partial X}$

On the insulation surface (6): $\frac{\partial T}{\partial Y} = 0$

where, U_j is velocity of air at nozzle exit, T_j is temperature of freezing air, h is convective heat transfer coefficient, K is thermal conductivity, X and Y are coordinates.

FLUENT SIMULATION

The computational domain is shown in Fig. 1. The slab shaped food has a length and thickness of 120 and 4 cm respectively and the slot jet a width 3 cm. The uniform initial temperature of the sample is 10°C. Freezing conditions were: freezing air temperature is -10°, air velocity in the range of 10-80 m sec^{-1}, nozzle-to-nozzle space in the range of 4-74 cm and jet-to food distance 6-36 cm. The impinging jet is assumed to be fully turbulent when exiting the slot jet; a uniform velocity profile is used. The turbulence intensity at the nozzle exit set to be 10%. The convergence criteria were specified as follows: the normalized residuals were kept set 10^{-3} for all variables, except for temperature (10^{-7}). To simplify the solution, the variation of the thermal and physical properties of the air and food with temperature neglected.

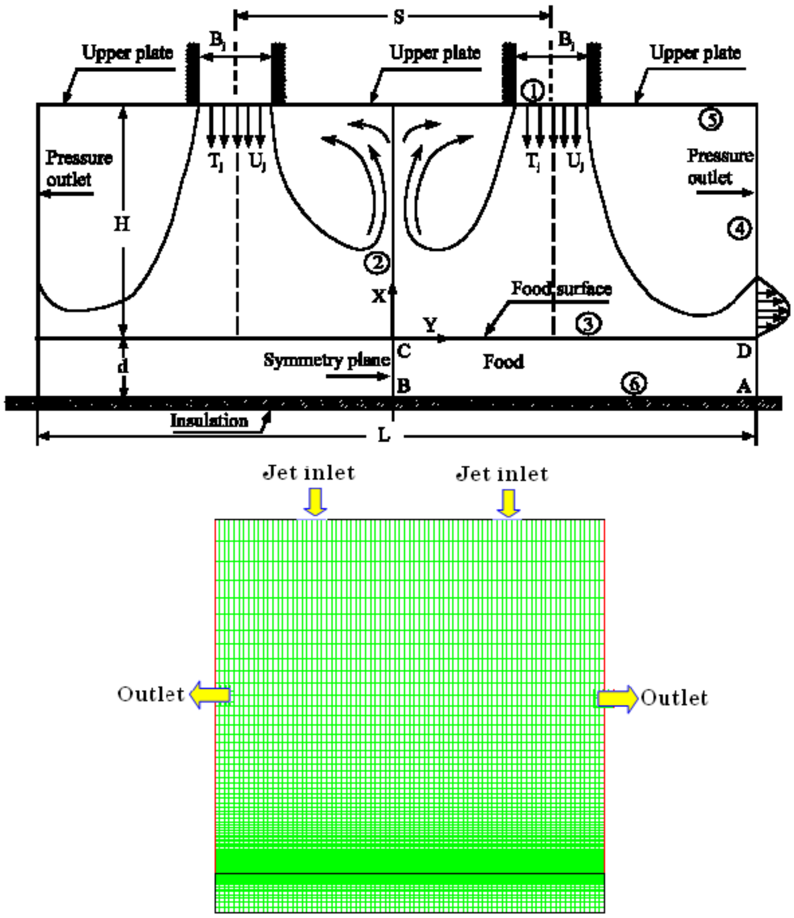

Fig. 1: Computational domain and grid configuration

To ease the computation a symmetry boundary condition between jets and food centerline was assumed. To insure the attainment of grid-independent results, the sensitivities of both grid numbers and grid distributions, three types of the grid were tested for each case: relatively fine grid 320×960 = 307200 cells; a medium grid 480×160 = 76800 cell; a coarse grid 80×240 = 38400 cell. Non-uniform grid distribution is used in this study, with finer grid near impingement plane (food) where the high gradients are expected. A grid density of 320×9600 was found to provide adequate resolution and accuracy and this fine grid has been used. Time steps have been kept consistently small to ensure stability, typically 10^{-3} seconds. Execution times ranging from 80 to 140 h on a Pentium IV 240 GHz with 2 GB RAM. The SIMPLE algorithm is used to solve the coupled system of governing equations.

RESULTS AND DISCUSSION

In order to simulate the effect of various parameters on freezing time we considered a slab food model (beef) which has a length and thickness of 120 and 4 cm respectively at the initial uniform temperature 10°C placed in a horizontal position under two slot air jets. The thermophysical properties used in the model were adopted from Wang *et al*. (2007) and shown in Table 1. Beginning from the initial condition (t = 0) the calculation is repeated until temperature at some points (point A or B in Fig. 1) inside the product reaches a given pre selected value. Figure 2 shows the contours of temperature inside the food after 400 min.

Table 1: Thermal properties used in model

C_i [kJ/(kgK)]	C_s [kJ/(kgK)]	ρ ($kg\,m^{-3}$)	L_f ($kJ\,kg^{-1}$)	k_i [W(mK)]	K_s [W(mK)]	T_f (°C)	T_i (°C)
3.644	2.159	1050	188.0	0.51	1.5	-0.5	10

Effect of jet-to-jet space on flow field: Figure 3 shows the effect of the distance between two jets on the flow field in the domain for the distance between two jets 4, 14, 24, 34, 54 and 74 cm, respectively. From this flow visualization we conclude that jet-to-jet spacing is a very important parameter affecting the flow regime over the impinging surface (food). When distance between nozzles is small

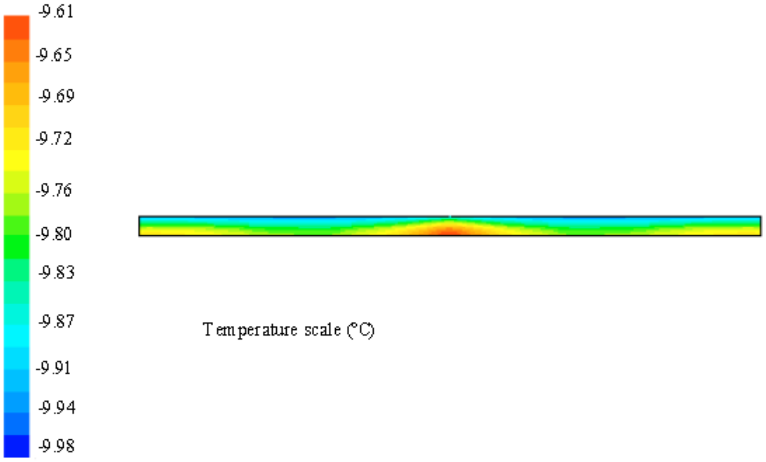

Fig. 2: Contours of temperature inside the food (after 400 min) for the H = 36 cm, U_j = 10 m sec^{-1}, T_j = -10°C

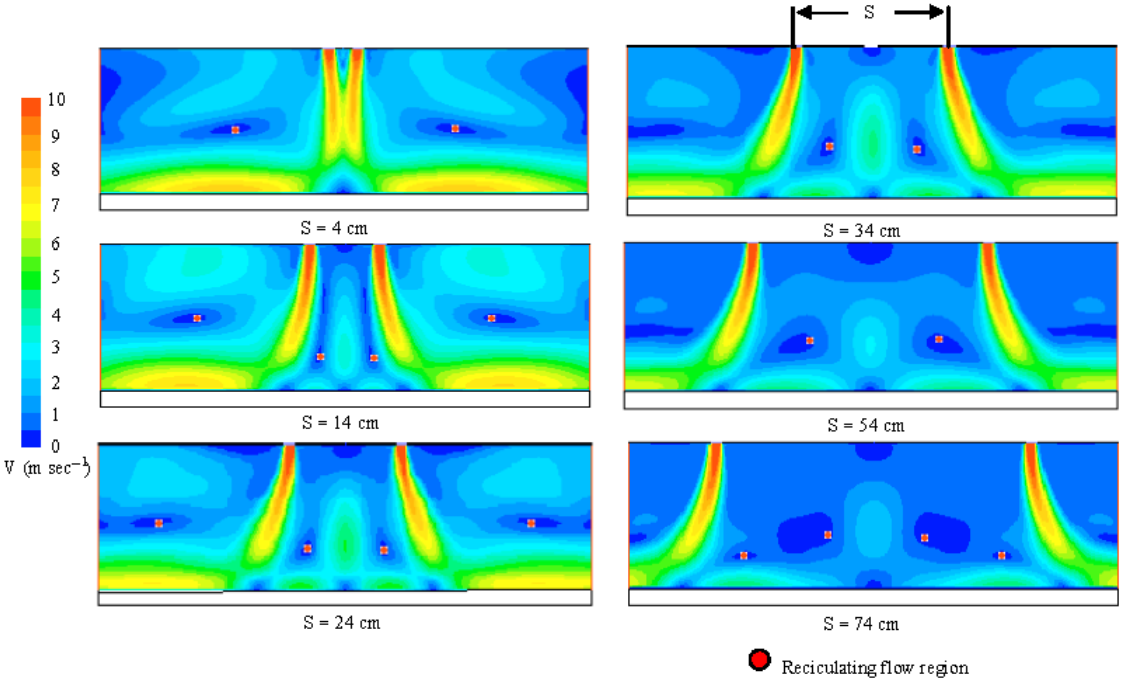

Fig. 3: Effect of jet-to-jet spacing on flow and velocity field for the H = 36 cm, U_j = 10 m sec^{-1}, T_j = -10°C

the interaction between the two jets affects the turbulence intensity and vortex forming between two jets and also forming wall jets. With small jet spacing due to shear layer expansion, interference between two jets will occur before_impingement. This could weaken the jet strength and eventually decrease heat transfer. As the distance increases recirculation flow appears between them. As the distance increases the jets act as single jet.

Effect of jet-to-jet space on heat transfer coefficient: Figure 4 shows as distance between increases heat transfer coefficient initially increases then again decreases. Optimum nozzle –to-nozzle is a very important parameter in design of food freezing systems.

Effect of jet-to-jet space on freezing time: Figure 5 shows with small jet spacing freezing time increases this is due to shear layer expansion, interference between two jets will

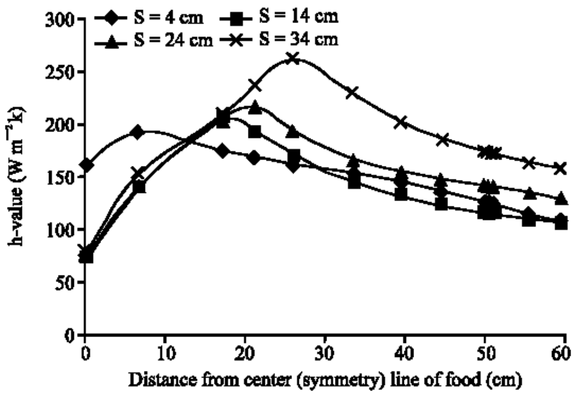

Fig. 4: Effect of nozzle-to-nozzle distance on heat transfer coeff. (h)

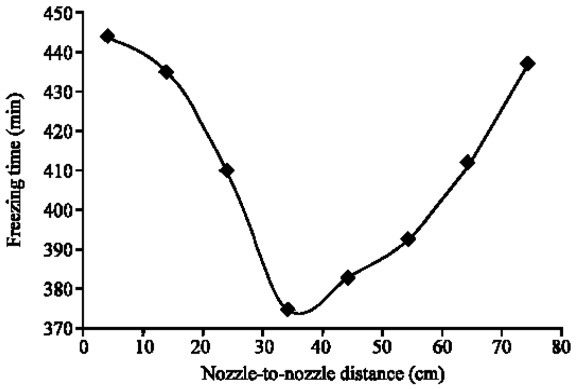

Fig. 5: Effect of jet-to-jet spacing on freezing time for the H = 36 cm, U_j = 10 m sec^{-1}, T_j = -10°C

occur before impingement. Figure 5 shows that the minimum freezing time occurs when jet-to-jet spacing is about 34 cm for this case (nozzle to food distance 36 cm and air velocity 10 m sec^{-1}).

Effect of freezing air velocity on flow field: Figure 6 shows as freezing air velocity increases flow field changes. Displaying path lines by Hyper Cam shows flow circulation regions in the flow field (some of them are shown in Fig. 3). Flow recirculation influences on heat transfer.

Effect of freezing air velocity on freezing time: It is clear that with increasing air velocity the freezing time decreases, but beyond critical point, it changes slowly. With increasing air velocity potential core length increases. Figure 7 shows when the potential core is not completely decayed, the flow at stagnation may be laminar. The laminar flow becomes turbulent downstream, resulting in peak heat-transfer coefficients where the flow

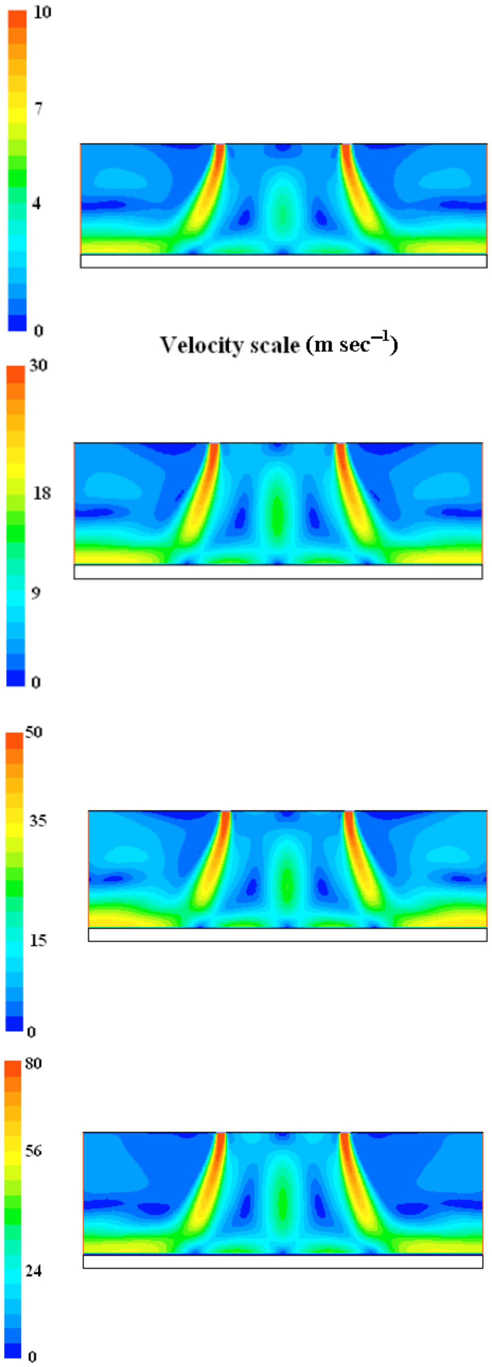

Fig. 6: Effect of freezing air velocity on flow field for the S = 34 cm, H = 36 cm, T_j = -10°C

transitions from laminar to turbulent. This result is because heat transfer in turbulent flows is higher than laminar flows. When the food (impinging surface) is positioned near of the potential core of the jet, turbulence

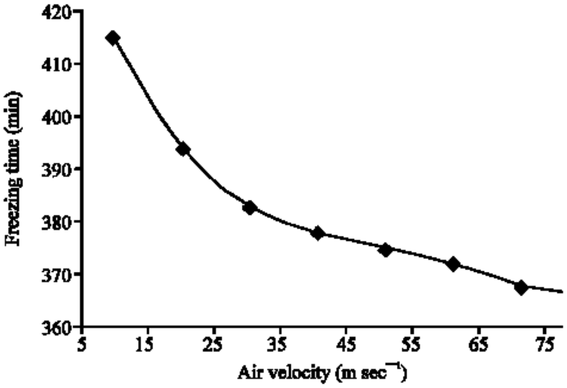

Fig. 7: Effect of freezing air velocity on freezing time for the S = 34 cm, $U_j = 10$ m sec^{-1}, $T_j = -10$°C, H = 36 cm

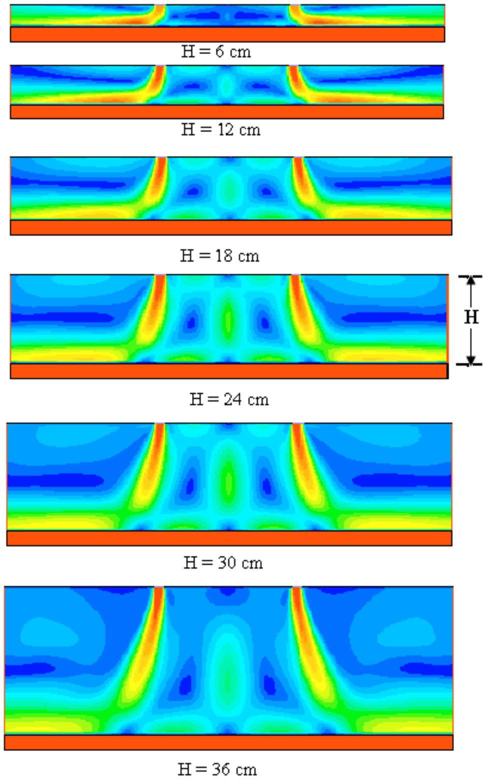

Fig. 8: Effect of nozzle-to-food distance on flow pattern for the S = 34 cm, $U_j = 10$ m sec^{-1}, $T_j = -10$°C

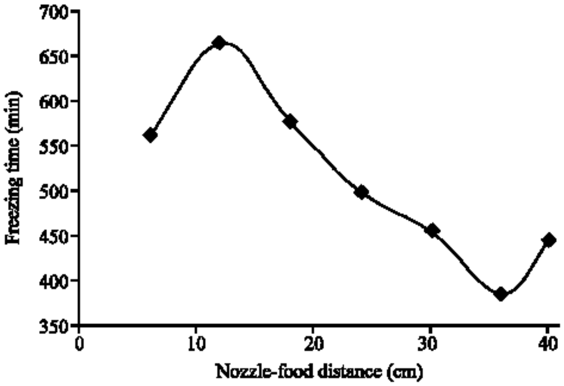

Fig. 9: Effect of nozzle to food distance on freezing time for the S = 34 cm, $U_j = 10$ m sec^{-1}, $T_j = -10$°C

level in the jet flow approaching the food is becoming high due to an increased entrainment of surrounding air to the jet flow, therefore a higher h-value number at the stagnation point can be expected. When the food is positioned downstream of the potential core the freezing air velocity is degraded from its nozzle exit value, the energy of the jet decayed because of the turbulence in free jet region causing lower heat-transfer coefficient.

Effect of nozzle-to-food distance on freezing time: Figure 8 shows as the nozzle to food distance increases the potential core disappears completely before stagnation point. The presence of the potential core region results in lesser degree of vorticity at stagnation point causing a transition to turbulence in the wall region close to stagnation point and the result is a lower heat transfer coefficient. A wide range of experimental data on heat transfer measurements exists in this regard. Sarkar and Singh (2004) have suggested an optimal distance in the range of 6-8 jet widths. The present research shows this distance in range of 10-12 slot jet width. Shorter distances can cause confinement, resulting in disturbance to the main jet streams. In Fig. 9, jet-to-jet spacing is 34 cm and jet to food distances are 6-12-18-24-30-36 cm. This figure shows as the nozzle to food distance increases, initially freezing time increases and then again increases. Optimum distance is about 36 cm.

CONCLUSIONS

In the present study, the CFD code FLUENT 6 is used to determine the flow and heat transfer characteristics of two slot impinging jets. In this study only the effect of jet-to-jet spacing, nozzle exit to food distance and air velocity on freezing time investigated. The CFD simulation results show how these parameters affect the freezing time of slab shaped foods and the information on these may be used in further optimization studies. The results of this study show that:

- Heat transfer is strongly affected by the distance between jets. If the spacing is too large, one ends up with many single jets, with a poor heat flux. If they are too close, the jets start to influence each other and a fountain between two jets appears. Jet interference before impingement and jet fountain reduces the strength of the jets; this consequently reduces overall heat transfer.
- Freezing air velocity effects the freezing time. With increasing air velocity the freezing time decreases, but beyond critical point, it changes slowly.
- Nozzle-to-food distance influences the flow field and heat transfer. For an increase of the nozzle-to-food distance shear layer expands wider before jet impingement and heat transfer decreases. A decrease in the nozzle-food spacing results in increasing in freezing time. Optimum nozzle-to-food distances in the region of 10-12 are best because they ensure that the potential core is fully decayed and there is no excessive energy dissipation.

ACKNOWLEDGMENTS

The corresponding author would like to thank to Mr. M. Mohammadpour Fard, Mechanical Engineering Ph.D Student of Mechanical Engineering Faculty, University of Tabriz for his valuable help during this study.

NOMENCLATURE

B_j : Width of jet
d : Thickness of slab shaped food
H : Nozzle-to-food distance
h : Convective heat transfer coefficient
C_i : Specific heat of unfrozen food
C_s : Specific heat of frozen food
C_P : Heat capacity at constant pressure
C_v : Heat capacity at constant volume
K : Thermal conductivity
k_i : Thermal conductivity of unfrozen food
k_s : Thermal conductivity of frozen food
L : Length of slab shaped food
L_f : Latent heat of freezing
P : Pressure
q_v : Internal source term due freezing
S : Nozzle-to-nozzle distance
T : Average temperature
T_f : Freezing temperature of food
T_i : Initial temperature of freezing food
T_j : Temperature of freezing air
T' : Fluctuating component of temperature
t : Time
U : Average velocity
U_j : Velocity of air at nozzle exit
u' : Turbulent component of velocity
$u'_i u'_j$: The average value of the fluctuating component of the velocity
X : Stream wise coordinate
Y : Coordinates perpendicular to stream wise coordinate direction
ρ : Density
γ : Kinematics viscosity of the air

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