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FREEZING TIME OF CYLINDRICAL FOODSTUFF USING THE ONE-DIMENSIONAL UNSTEADY STATE EXPLICIT MODEL

Charan deep
Research Scholar, Department of Mechanical Engineering,
College of Technology, G.B.P.U.A.T, Pantnagar,
US Nagar, Uttarakhand, India.

Anil Kumar Pratihar
Professor, Department of Mechanical Engineering,
College of Technology, G.B.P.U.A.T, Pantnagar,
US Nagar, Uttarakhand, India.

ABSTRACT

A one-dimensional unsteady state numerical model is developed to predict the freezing time of individual cylindrical foodstuff in freezing process. The model's numerical algorithm is finite-difference method with explicit scheme, which is programmed in MATLAB. It is further used to predict the freezing time of tylose gel for freezing it to - 18°C. The experiment is also performed to verify the predicted results for tylose gel. In all cases, the value of linear regression correlation coefficients (R^2) between experimental and predicted values are over 0.989, which indicates the model can be used to predict the freezing time and temperature variation of cylindrical foodstuff with various thermophysical properties and different air temperatures. The variation of different parameters on freezing time have also been studied. The method is used for predicting freezing time where the cooling air velocity is in range of 2.5 m/s to 5.5 m/s.

1. INTRODUCTION

In the country of 1.34 billion people which is expected to grow to 1.5 billion by 2025, wasting of food makes no sense – economically, environmentally and ethically. So more technological advancements are needed in the food preservation. India being diverse in climatic conditions grows variety of crops but at the same time off season availability is major concern. To ensure off season availability of foods we need to exploit the preservation techniques to their best. Preservation of food restricts the growth of fungi, bacteria and other micro-organisms that spoil the food. Preservation processes drastically changes the food characteristics. Preservation processes are being used from ages, there are lot of preservation processes like canning, pickling, drying, freezing and so on. Out of these, freezing technique is one of the best preservation process which rapidly slows down the microbial growth and also retains the original colour, flavour, texture and nutritional value of food products

As per IIR (International Institute of Refrigeration, 1972), freezing time is the total amount of time required to lower the temperature of foodstuff at its thermal centre to a desired temperature below its initial freezing point. Numerically it is the total sum of time taken to go through all the three processes of precooling, phase change and post freezing (Becker and Fricke, 1999). The factors affecting the freezing time include the velocity of cooling air, initial temperature of the product, temperature of cooling air and the quality of food product.

There are numerous analytical and mathematical models present to predict the freezing times of different foodstuff for various shapes and orientations. The Plank's (1941) model has assumed the temperature to be constant during the freezing and it also assumed the constant thermal conductivity for the frozen region. This model considered only convective heat transfer between foodstuff and the surrounding medium. Nagaoka et al. (1956) modified the Plank's (1941) model by considering the sensible heat during precooling and post freezing. Cleland and Earle (1977) modified the Plank's (1941) model by incorporating corrections to account for the removal of sensible heat both below and above the freezing point. Pham (1984) developed a set of empirical relations to predict freezing time for various geometries of food stuff by dividing the freezing process in three major steps: precooling, phase change, and post cooling.

2. MATERIAL AND METHODS

2.1 Sample Preparation

Tylose gel is a meat analogue substance which is used in this study of freezing operations. It is made of 77% water and 23% methylcellulose i.e. tylose powder. Tylose gel was first used by Riedel in 1960 in Karlsruhe, Germany and from then it is also referred as Karlsruhe test substance. The procedure for preparation of tylose gel is defined by many researchers. The method described by Anderson and Singh (2005) is used in this experiment for sample preparation.

2.2 Thermophysical properties measurement

Mass density, specific heats, moisture content, thermal conductivity and freezing point are measured or reviewed from literature. Mass density is measured for five samples as per the method described by Mohsenin (1980). Moisture content is measured by keeping the five samples at 105°C for 24 hours as described in Anderson and Singh (2005). Thermal conductivity is taken from literature mentioned by Pham (1996).

2.3 Surface heat transfer coefficient measurement

Anemometer is used to measure the velocity of cold air over the samples in the test section. The main aim to find the heat transfer coefficient between the cooling air and samples with the help of equation given in Cengel (2002) for the particular case. This Equation (1) is valid for Re 4000 to 40000. The Equation is as follows:

$$Nu = 0.193Re^{0.618}Pr^{1/3} \tag{1}$$

3. MATHEMATICAL MODEL

3.1 Unsteady state heat conduction equation

The thermal conduction takes place due to the temperature gradient in the frozen foodstuff. For simple considerations, we assume that the temperature distribution within the foodstuff is centrally symmetric and there is no evaporation and mass transfer taking place during the course of freezing although there is moisture phase change and heat release.

The transient general heat conduction Equation (2) for a cylinder (radius = R), is as follows:

$$\rho C_p \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(rk\frac{\partial T}{\partial r}\right) \tag{2}$$

Introduce a mesh or nodes r_i, 1, 2, 3….., N with uniform spacing Δr. An explicit scheme is obtained by using a central differences formula for the space derivative and an Euler forward differences formula for the time derivative. Hence, writing $T(r_i,t_j) = T_{i,j}$, the FD (finite difference) analogue is:

$$\rho C_p \frac{T_{i,j+1}-T_{i,j}}{\Delta t} = \frac{1}{r_i}\frac{(kr)_{i+\frac{1}{2}}\frac{T_{i+1,j}-T_{i+1}}{\Delta r}-(kr)_{i-\frac{1}{2}}\frac{T_{i.j}-T_{i-1,j}}{\Delta r}}{\Delta r} \tag{3}$$

and for constant properties, the explicit finite scheme is given by:

$$T_{i,j+1} = T_{i.j} + \frac{\alpha\Delta t}{r_i\Delta r^2}\left(r_{i-\frac{1}{2}}T_{i-1,j} - 2r_iT_{i,j} + r_{i+\frac{1}{2}}T_{i+1,j}\right) \tag{4}$$

which is further a tri-diagonal system of algebraic equations.

3.2 The initial and boundary conditions

The initial condition is the distribution of variable which is to be calculated at the beginning of the unsteady heat transfer process. In the present work, the initial temperature is uniform at the start of freezing process i.e. T_i, so the initial condition can be expressed as:

$$(r, t) = T_i, \qquad (0 \leq r \leq R, t = 0) \tag{5}$$

where R is the radius of the cylinder.

The boundary condition includes the distribution to be defined at the centre and at the surface assuming there are no heat fluxes at centre and there is no evaporation and radiation at the surface:

$$-k(T)\frac{\partial T}{\partial r} = 0 \qquad (r = 0, t \geq 0) \tag{6}$$

$$-k(T)\frac{\partial T}{\partial r} = h(T_s - T_c) \qquad (r = R, t \geq 0) \tag{7}$$

where h is the convective heat transfer coefficient, T_s is the surface temperature and T_c is the cooling air temperature.

Karlsruhe test substance is used for case study for evolution of model and its thermophysical properties are given in literature (Cleland and Earle, 1984).The thermophysical properties vary in freezing zone, for T < T_{freezing} as (Succar and Hayakawa,1983):

$$k_f = 1.573 - 0.00773T + 0.653/T \tag{8}$$

$$\rho_f = 937.908 - 0.154T + 40.8/T \tag{9}$$

$$C_{Pf} = 1418 + 122173/(-T)^{1.696} \tag{10}$$

3.3 Numerical processing of the mathematical model

The nodal approach is used to get the finite difference formula for the boundary condition at r = R, as follows:

$$-k\,\frac{T_{N+1,j} - T_{N-1,j}}{2\Delta r} = h(T_{N,j} - T_\infty) \tag{11}$$

This can be rearranged to give the temperature of the undefined node:

$$T_{N+1,j} = T_{N-1,j} - \frac{2h\Delta r}{k}\left(T_{N,j} - T_\infty\right) \tag{12}$$

On substituting the above result into the finite difference formula for the heat equation at the boundary node gives the following explicit term:

$$T_{N+1,j} = T_{N,j} + \frac{2h\Delta t}{\Delta r^2}\left[T_{N-1,j} - T_{N,j} - \left(\frac{R_p}{R}\right)\left(\frac{h}{k}\right)\Delta r\left(T_{N,j} - T_\infty\right)\right] \tag{13}$$

where $R_m = R - \Delta r/2$ and $R_p = R + \Delta r/2$.

As the finite difference analogue of heat equation gives singularity at r = 0 the nodal approach cannot be used. So a convenient and alternative is to switch to Cartesian coordinate by considering the plane perpendicular at the cylindrical axis at the origin, i.e.

$$\frac{T_{i,j+1}-T_{i,j}}{\Delta t} = h\left(\frac{T_{north,j}-2T_{i,j}+T_{south,j}}{\Delta r^2}+\frac{T_{east,j}-2T_{i,j}+T_{west,j}}{\Delta r^2}\right) \quad (14)$$

where north, south, east and west are nodal points at distance Δr from the origin on the plane normal to the axis of the cylinder. As assumption of axi-symmetry is made, it can be concluded that
Tnorth,j=Tsouth,j=Teast,j=Twest,j=T2,j. Hence it can be rearranged as:

$$T_{1,j+1} = T_{1,j} + 4h\frac{\Delta t}{\Delta r^2}(T_{2,j} - T_{1,j}) \quad (15)$$

These are the equations that are used to give the desired results for the different nodal points within the orientation. Similar model can also be obtained for the spheres and slabs.

3.4 Validation of numerical model

The freezing experimental data of Karlsruhe test substance in the reference (S.R. Ferreira et al., 2016) is used for the validation of the mathematical model. The thermophysical properties given in this are $k_o = 0.55$ Wm^{-1}°C^{-1}, $\rho_o = 1006$ kg m^{-3} and $C_{po} = 3688$ J kg^{-1}°C^{-1}, and initial point is $T_f = -0.6$°C (Cleland and Earle,1984). The time interval of 1 second is used for the prediction of temperatures. The simulation gives the trends shown in Fig. 1, and the comparison of the results can be seen in Table 1, and the linear regression analysis is also done to obtain the accuracy between the results.

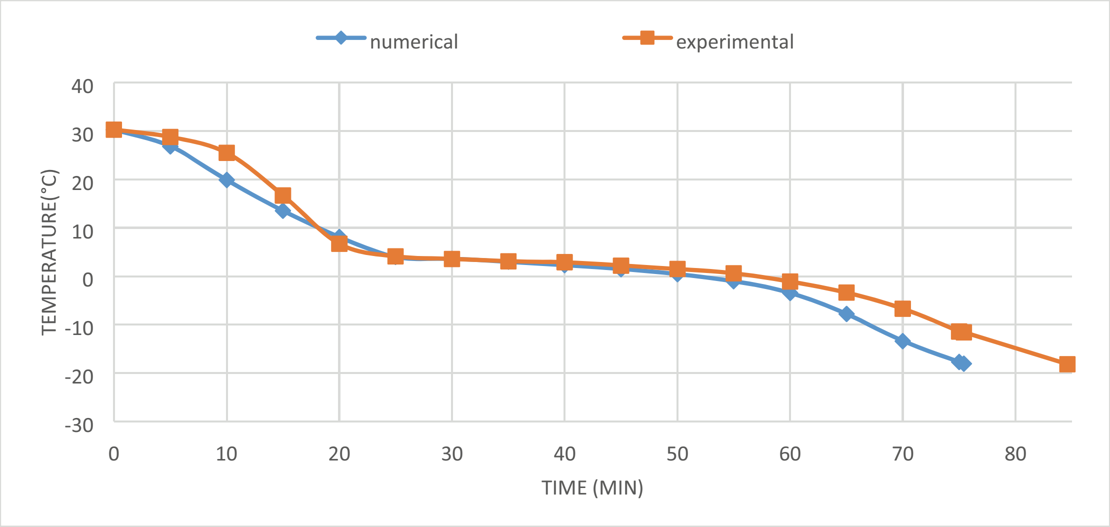

Fig 1. Experimental and numerical temperature curves in the freezing process

These curves are quite similar to a typical freezing curve for the foodstuff. This validates the mathematical model to be used for the analysis of experimental work and can also be used to predict the temperature history and freezing times for the cylindrical foodstuff with the cooling air velocity above 2m/s. The linear aggression analysis of the same can be seen in the next section.

4. RESULTS AND DISCUSSION

4.1 Test and analysis of developed model

Table 1. shows the experimental data obtained from literature (Cleland,1977), and freezing was done to reach the temperature of -10°C, and the calculated freezing times (Cleland and Earle ,1979) and the data obtained by the developed program is compared with it as numerical time in the table. The linear regression for the same is done, in Fig. 2. and the linear regression coefficient value of R^2 is 0.9744, which shows good feasibility between the results.

Table 1 – Experimental times by Cleland (1977) for KTS infinite cylinder to reach centre temperature -10°C (Cleland 1977, Cleland and Earle, 1979) and the predicted results by developed program.

Sr. no	R (m)	h (W/m^2)	T_0 (°C)	T_c (°C)	t exp. (hours)	t num. (hours)	% Error
1	0.07675	36.4	28.4	-21	8.36	8.3333	0.319378
2	0.05225	27.2	30	-20.3	6.14	6.7289	-9.59121
3	0.026	35.5	28	-19.9	2.16	2.1822	-1.02778
4	0.07675	36.4	21	-20	8.3	8.333	-0.39759
5	0.05225	27.2	19	-20	5.82	5.8758	-0.95876
6	0.026	35.5	19.7	-20	1.98	1.985	-0.25253
7	0.07675	36.4	27.2	-33.5	6.1	4.65	23.77049
8	0.05225	27.2	27.8	-33.1	4.1	3.8244	6.721951
9	0.026	35.5	26.8	-33.4	1.28	1.2878	-0.60938
10	0.026	35.5	17.2	-33.2	1.18	1.0369	12.12712
11	0.07675	36.4	26.7	-19.8	8.9	8.3333	6.367416
12	0.07675	36.4	27.6	-19.8	9.36	8.3333	10.96902
13	0.05225	27.2	20.1	-25.6	4.56	4.4436	2.552632
14	0.05225	27.2	19.6	-25.8	4.74	4.3358	8.527426
15	0.026	23.9	15.4	-40.2	1.34	1.1233	16.17164
16	0.026	23.9	25.3	-30.2	2.1	1.8822	10.37143

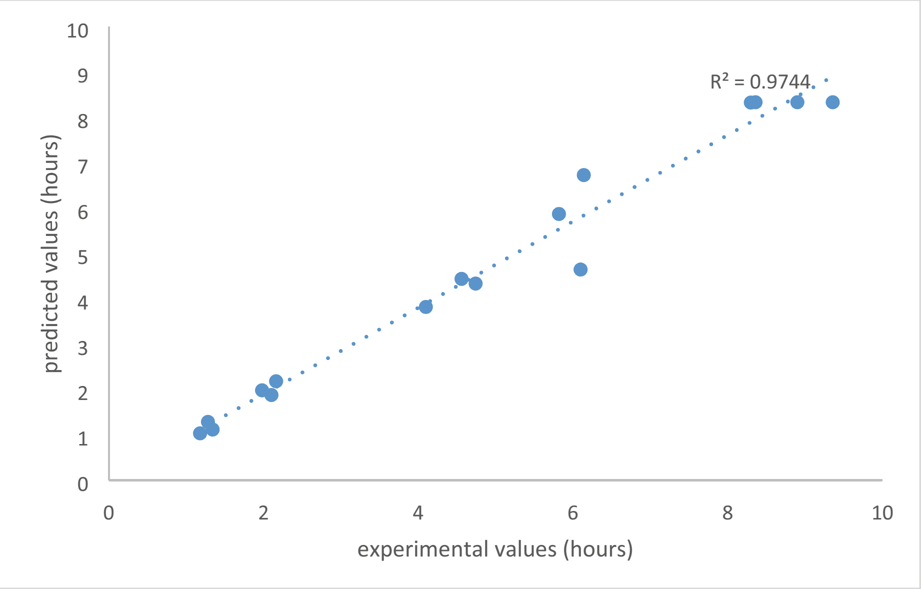

Fig. 2.Linear regression analysis diagram of freezing time of cylinder of KTS

4.2 Measurement and estimation of thermophysical properties for freezing time calculations

Some experiments were also performed to measure the desired thermophysical properties. The results obtained from the experiments and from the literature are the parameters mentioned in Table 2.

Table 2. Parameters about Tylose gel

C0 (kJ/kgK)	Cf (kJ/kgK)	ρ (kg/m^3)	k0 [W/(mK)]	kf [W/(mK)]	L (kJ/kg)	w□ (%)
3.78	2.1	1013	0.53	1.5	255	77.5

4.3 Estimation of the freezing time for cylindrical foodstuff

There were 30 experiments performed for the cylindrical foodstuff and there freezing times were estimated. The same initial conditions were used in the developed program in MATLAB to predict the freezing times. And the results shown are in great resemblance with the experimental results. The linear regression analysis for the experimental and predicted freezing time is illustrated in Fig.3. The value of correlation coefficient of linear regression (R^2) is 0.9898, indicating the obtained results are in good agreement.

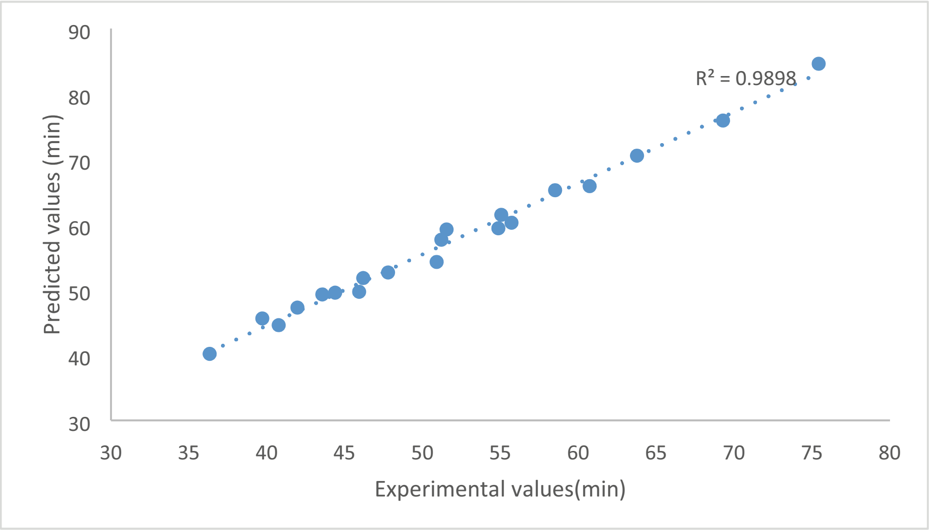

Fig. 3.Linear regression analysis diagram of freezing time of cylinder of Tylose gel (for T_{final}= -18°C)

From all the result and analysis, it can be concluded that the developed numerical model can be used for the prediction of freezing times and the temperature profile for freezing for the cylindrical foodstuff with diameter of 2.8±1 cm and the velocity of cooling air between 2m/s to 6m/s. And this type of similar models can also be developed for slabs and spheres.

4.4 Estimated and predicted temperature profiles for cylindrical foodstuff

The model is used to predict the temperature profile of the cylindrical foodstuff during the course of freezing. For similar cases, the temperature history was recorded experimentally and is plotted in the Fig.4.

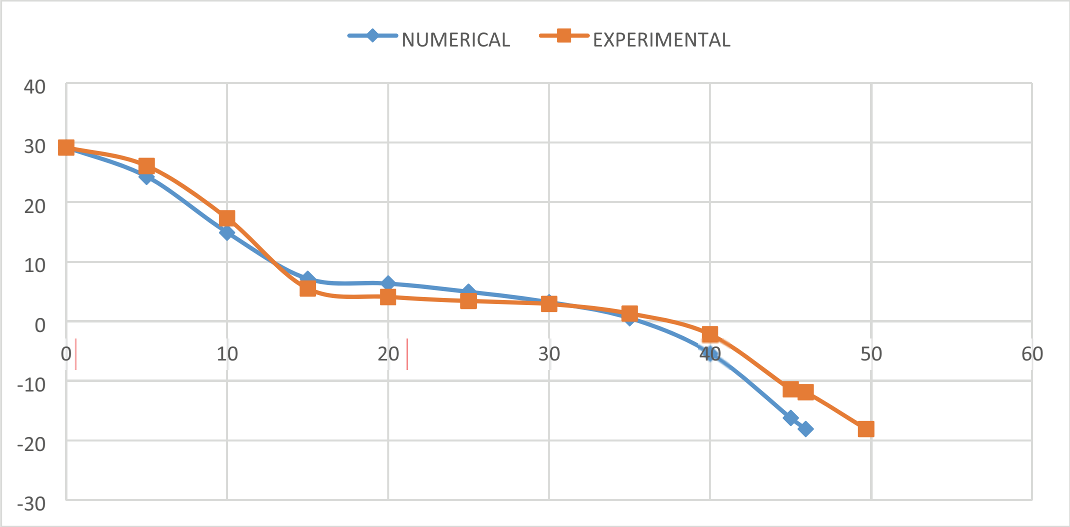

Fig. 4 Experimental and numerical (predicted) temperature profiles for cylindrical tylose gel

4.5 Effect of variation of parameters

During experimental analysis, the variable parameters like cooling air velocity and cooling temperature have been varied and their effect on the freezing time is studied. The experimental and predicted temperature profiles obtained for different cooling air velocities can be seen in Fig. 5 and Fig.6 respectively.

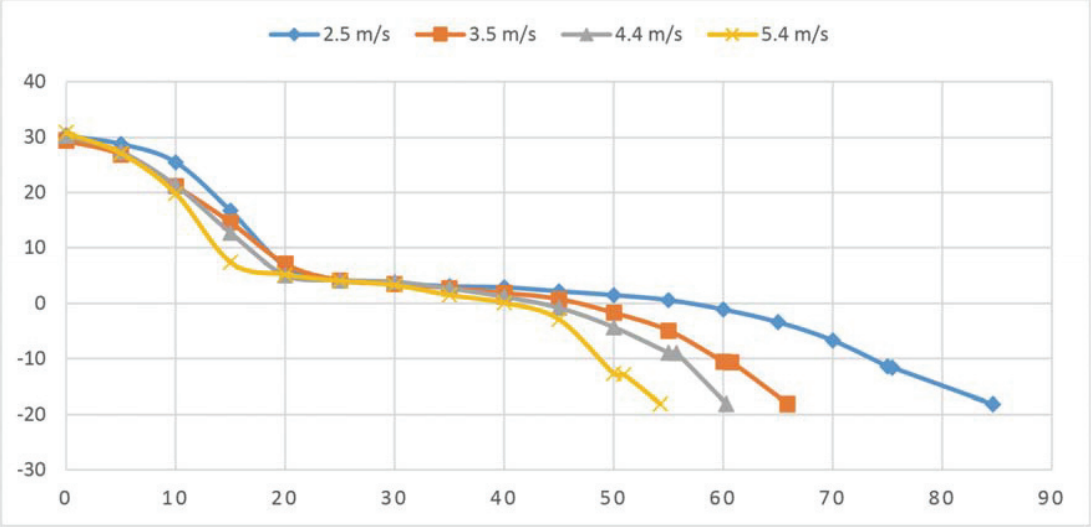

Fig. 5 Experimental temperature profiles for different cooling air velocities at cooling air temperature of -22 ± 5 °C

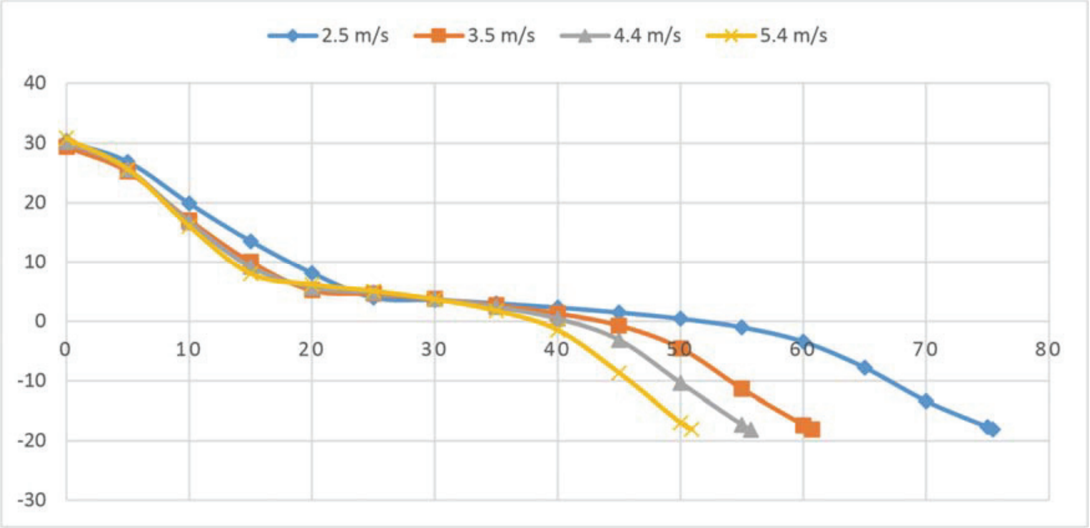

Fig. 6 Numerical (predicted) temperature profiles for different cooling air velocities at cooling air temperature of -22 ± 5 °C

The variation of cooling air temperature also affects the freezing time of the foodstuff. The experimental and predicted temperature profiles obtained for different cooling air temperatures can be seen in Fig.7 and Fig. 8 respectively.

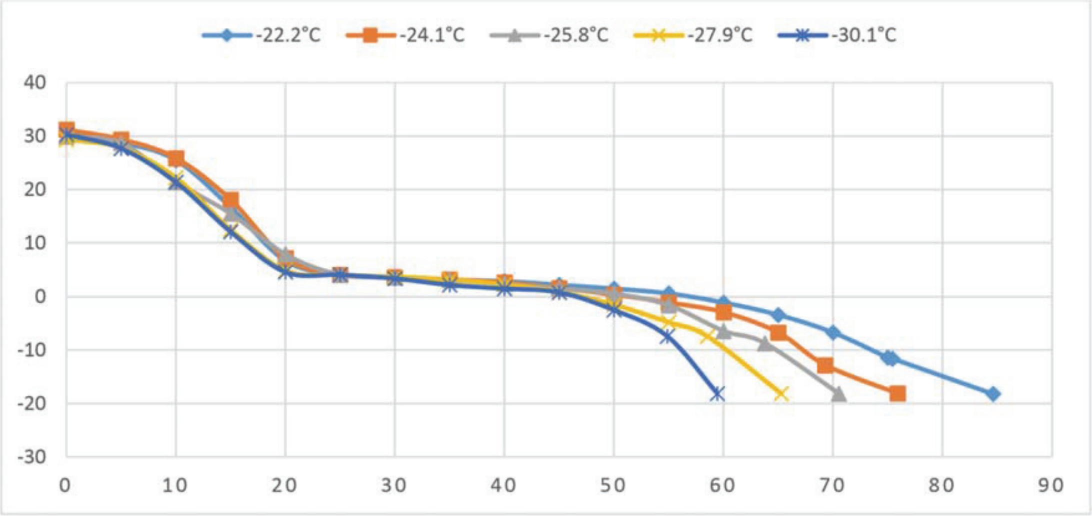

Fig. 7 Experimental temperature profiles for different cooling air temperatures at cooling air velocity of 2.5 m/s

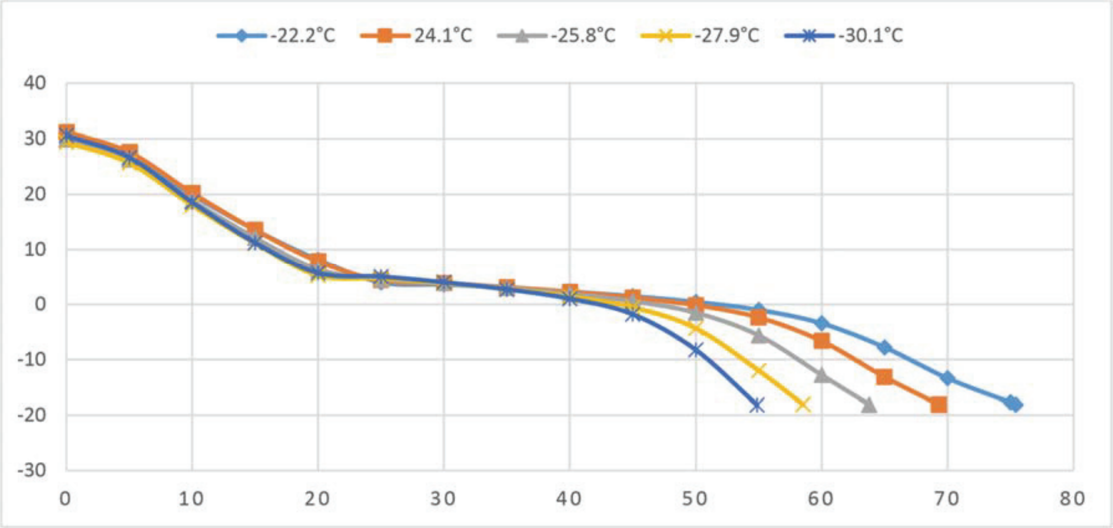

Fig. 8 Numerical (predicted) temperature profiles for different cooling air temperatures at cooling air velocity of 2.5 m/s

From Fig.5 and Fig. 6, we can conclude that on increasing the cooling air velocity the freezing time reduces for the cylindrical foodstuff. As we keep on increasing the velocity of cooling air from 2.5 to 5.5 m/s the freezing time kept on decreasing. The further increase of velocity may lead to moisture loses.

From Fig.7 and Fig. 8, we can conclude that on reducing the cooling air temperature the freezing time reduces for the cylindrical foodstuff. As we keep on decreasing the cooling air temperature from 21 to -31°C the freezing time kept on decreasing. The further reduction of cooling air temperature can also be done keeping in mind energy consumption.

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