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Finite Element Modeling of Freezing of Coffee Solution

R. Gopirajah, N. Chhanwal and C. Anandharamakrishnan *

Human Resource Development, Central Food Technological Research Institute (CSIR), Mysore-570 020, India.

Corresponding Author: C. Anandharamakrishnan, *E-mail: anandharamakrishnan@cftri.res.in

Abstract: Freeze-Drying is widely used in the food and pharmaceutical industry to dry high quality thermolaible product. Freeze-drying is a three stage process namely, freezing, primary drying and secondary drying. A finite element model was developed using COMSOL to study the coffee freezing process. Freezing was carried out in ultra low freezer at -65°C. A solution containing 3.6% coffee and 9 mm bed thickness was used for the study. Temperature during freezing cycle was recorded using T-type thermocouples. Phase change during ice formation has been defined by including latent heat effects in the specific heat value. Simulation predictions were validated with experimental measurements of coffee temperature. Model predictions were in good agreement with the experimental measurements. Linear decrease followed by steady state temperature (ice formation period) and further sudden drop in temperature was observed. In this study, the ice formation with respect to time has been tracked.

Keywords: Coffee, Freezing process, Ice fraction

1. Introduction

Freezing process consist of ice formation with nucleation, crystal growth and vitrification. Freezing step has a critical importance during freeze drying processes because subsequent ice sublimation rates are strongly related with ice crystal morphology and corresponding textural and structural parameters are mostly fixed during freezing step. Thus, during freezing step, the control of ice crystal morphology (i.e. ice crystal mean sizes, ice crystal shapes, ice crystal size distribution, etc.) is a major challenge for freeze-drying process optimization (Hottot et al. 2006; Nakagawa et al. 2007). Sudden changes occur in thermo physical properties such as specific heat, thermal conductivity, density and viscosity of material near freezing point. It is very difficult to account these sudden changes in thermo physical properties using non-linear partial differential equation. Inclusion of latent heat in heat transfer equation which allows phase changes over a very small temperature range is a key problem during modeling of freezing process (Pham, 2006). Significant work has been reported for the modeling of freezing process. However, tracking of the ice formation during freezing was overlooked. Hence, the present study was aimed to develop a FEM model for the coffee freezing process and also to investigate the effects of temperature on ice formation.

2. Experimental details

A 3.6% coffee solution was prepared using Nescafe classic coffee granules (100% coffee, Nescafe India Ltd. New Delhi) dissolved in deionized water. This coffee solution was slowly poured into the steel plate to attain a thickness of 5 mm coffee layers. Rapid cooling of coffee solution was carried out in ultra low freezer at -65°C (So-Low Environmental Equipment Co., Inc. Cincinnati, Ohio USA). Temperature was measured using calibrated T-type thermocouples, which were connected to data logger (VR-18, Brainchild Electronics Co. Ltd. Taipei, Taiwan). Temperature at the center was obtained through inserting T-type thermocouples at a pre-determined location. Outside air temperature was also measured near to the plate.

3. Mathematical Modeling

3.1. Boundary conditions

The three dimensional geometry of the open pan was created and meshed as shown in Figs.1 (a) & (b). The mesh size was optimized for solution time with the total numbers of 1505 elements.

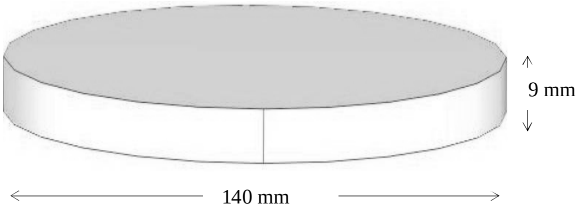

Figure 1 (a). 3D geometry of pan

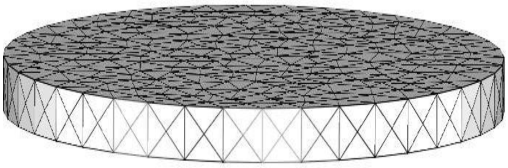

Figure 1 (b). Meshed pan

Heat balance equation

General heat transfer equation was used in this model.

$$\rho C_p \frac{\partial T}{\partial t} = \nabla.(k\nabla T) \qquad (1)$$

Boundary conditions for heat and mass transfer

Heat transfer occurs through convection from the surface and it was given by following equation

$$-k\nabla T = h(T_\infty - T) \qquad (2)$$

Thermal conductivity (W/m C) and specific heat (J/kg C) of coffee solution in liquid state were given from Telis-Romero et. al (2010) as function of temperature:

$$k=0.154 + 0.391 \text{ x } W + (1.48 \text{ x } 10^{-4}) \text{ x } T \qquad (3)$$

$$Cp= 1439.65 + (2633.72 \text{ x } W) + 1.99 \text{ x } T \qquad (4)$$

where, W is the water content.

Thermal conductivity and specific heat of coffee solution in frozen state were given from Ferguson et al. (1993).

Ice Fraction was calculated considering values between zero (for liquid) and one (for ice) based on the liquid and ice front temperatures. HP workstation xw6600 was used for running the simulation.

4. Result and Discussion

4.1. Experimental validation

Fig. 2 clearly indicates that the simulation predictions were in good agreement with the experimental measurement of temperature. Linear decrease followed by steady state temperature (ice formation period) and later linear decrease in temperature observed till it reaches to equilibrium temperature. There was no distinct latent heat effect during ice crystal formation in experimental predictions (fig.2), this may be due to rapid freezing (i.e., -65°C) of the sample. The similar trend was also observed in the model predictions.

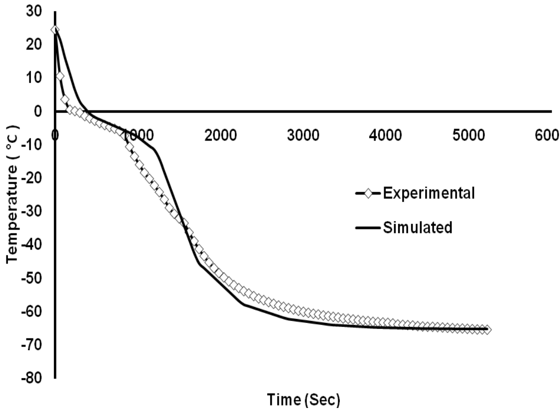

Figure 2. Validation of simulation predictions with experimental results of freezing of coffee solution**.**

4.2. Comparison of Temperature profile and liquid fraction in coffee solution during freezing process

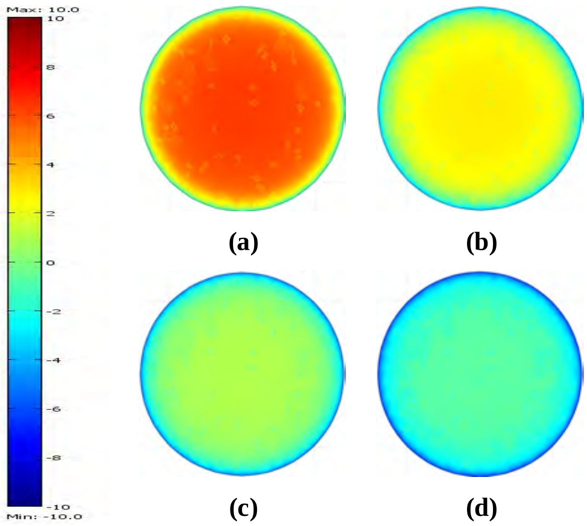

Figure 3. Temperature profiles during coffee freezing process at (a) 240 s (b) 300 s and (c) 360 s (d) 420 s.

Fig. 3 and Fig. 4 show the temperature profile and ice fraction during freezing process at various time intervals, respectively.

Temperature of coffee solution decreased from the outer surfaces due conduction effects at outer region and bottom of the plate. Similarly, ice crystallization starts from outer regions and reaches to core regions slowly with different layer of ice formations. It could be noted that ice crystal formation starts at 240 s and completes in 420 s.

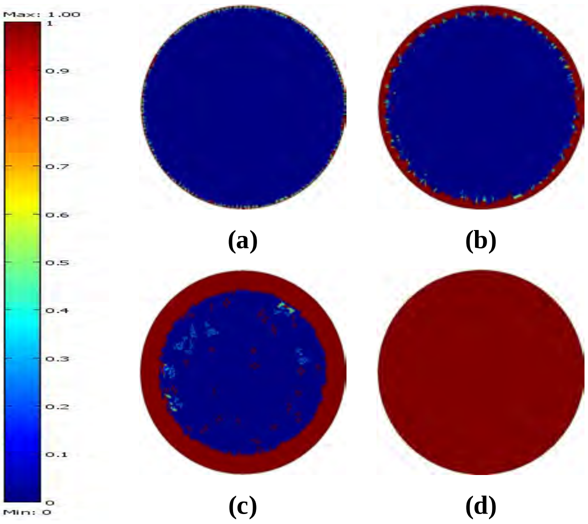

Figure 4. Ice formation during coffee freezing process at (a) 240 s (b) 300 s and (c) 360 s (d) 420 s

4.3. Effect of coffee solution thickness on freezing time during freezing process

Different thickness (4, 6, 8 and 10 mm) of coffee solutions was used to study its effect on freezing time. Fig 5 shows the effect of different thickness of coffee solution on freezing time. Coffee solution with 4 mm thickness achieved equilibrium freezing temperature (i.e, -65°C) at 3240 s, whereas 8 mm thickness attained equilibrium condition at 4320 s.

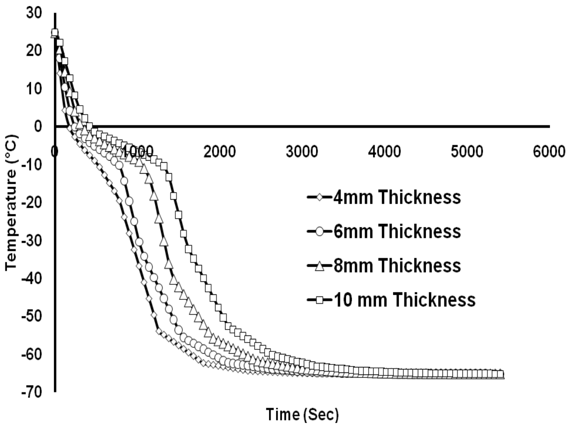

Figure 5. Effect of product thickness on freezing time

Thus, this model will help to track and/or monitor the ice formation during freezing stage. This will help to manipulate the pore structure in the food products.

5. Conclusions

A three dimensional finite element model for the coffee freezing process was developed using COMSOL. The model predictions were validated with the experimental measurement. This model can predict the ice formation during freezing process with respect to time and temperature. Hence, this model can be used for predicting the temperatures gradients and track the ice formation during the freezing process, which in turn helps to manipulate the food structures.

6. Acknowledgement

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7. References

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