Freezing Time Estimation of Peas by Experimental and Numerical Methods

THESIS

Submitted to the

G. B. PANT UNIVERSITY OF AGRICULTURE & TECHNOLOGY, ***PANTNAGAR - 263145, UTTARAKHAND, INDIA***

By

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B. Tech (Mechanical Engineering)

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF

Master of Technology
In
Mechanical Engineering
(Thermal Engineering)

July, 2016

ACKNOWLEDGEMENT

First of all I bow my head before 'God' who inspired me to face challenges of uneven times. All my sincere gratitude goes to him for the help he has given to me and his unfailing mercies over my life.

The author expresses his deep sense of reverence and heartfelt gratitude to Dr. A. K. Pratihar, Professor, Department of Mechanical Engineering, Chairman of Advisory Committee for his invaluable guidance, constant encouragement, abundant counsel and constructive suggestions throughout the investigation. The author is extremely indebted to him and thanks him from the bottom of his heart.

With profound sense of gratitude the author expresses his warmest thanks to the members of Advisory Committee, Dr. L. Varshney, Professor, Department of Mechanical Engineering, Dr. D. S. Murthy, Professor, Department of Mechanical Engineering, Dr. N. C. Shahi, Professor, Department of Post Harvest process and Food Engineering for their inspiring and constructive suggestions at every stage of this study.

The author tenders his sincere thanks to Dr. N. S. Murthy, Dean, College of Post Graduate Studies, Dr. H. C. Sharma, Dean, College of Technology, Dr. P. C. Gope, Professor & Head, Department of Mechanical Engineering, Dr. R. N. Rama, Professor and Head, Department of Fisheries Resource Management, College of Fisheries and Mr. Liyakat khan, Lab Assistant, Refrigeration and Air conditioning Laboratory for their keen interest in providing the necessary facilities when needed.

Appreciations are also extended to my friends Akhilesh, Shubaham Neeraj, Kritika, Kalpana, Saurabh, Gagan, Akarsh, Piyush, respected seniors Pradeep, Sandeep, Kamal, Hitendra, Kuldeep, Danish and loving junior Charan Deep for their encouragement and helping hands at various stages of the work.

The author owes a very special word of thanks to his father Mr. Ram Kishor Sharma, mother Mrs. Seeta Sharma and brother Mr. O. C. Sharma for their boundless, generosity, everlasting inspiration, blessing abundant love and affection throughout.

This list is obviously incomplete but allow me to submit as the omissions are inadvertent and I once again record my heartfelt gratitude to all those who helped me directly or indirectly in this endeavour.

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CERTIFICATE-I

This is to certify that the thesis entitled **“Freezing Time Estimation of Peas by Experimental and Numerical Methods”** submitted in partial fulfillment of the requirements for the degree of **Master of Technology** in Mechanical Engineering with major in **Thermal Engineering** of the College of Post-Graduate Studies, G. B. Pant University of Agriculture & Technology, Pantnagar, is a record of bona fide research carried out by **Mr. Manoj Kumar Sharma,** Id. No. **48163** under my supervision and no part of the thesis has been submitted for any other degree or diploma.

The assistance and help received during the course of this investigation and source of literature have been duly acknowledged.

Pantnagar
July, 2016

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CERTIFICATE-II

We, the undersigned, members of the Advisory Committee of **Mr. Manoj Kumar Sharma,** Id. No. **48163**, a candidate for the degree of **Master of Technology** in Mechanical Engineering with major in **Thermal Engineering**, agree that the thesis entitled **“Freezing Time Estimation of Peas by Experimental and Numerical Methods”** may be submitted in partial fulfillment of the requirements for the degree.

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ABBREVIATIONS

Symbols	Description	Units
ALPHABETS		
c	specific heat on mass basis	kJ/(kg-K)
C	volumetric heat capacity	J/(m^3-K)
D	diameter	m
h	heat transfer coefficient	W/(m^2-K)
H	enthalpy	kJ/kg
k	thermal conductivity	W/(m-K)
L	latent heat of fusion	kJ/kg
P & R	geometric factors	-.
Pr	Prandtl number	-
Re	Reynolds number	-
T	temperature	°C
V	volume	m^3
W	percentage water content	-
t	freezing time	sec
GREEK LETTER		
ρ	density of food product	kg/m^3
μ	dynamic viscosity	N-s/m^2
SUBSCRIPTS AND SUPERSCRIPTS		
a	ambient	-
c	cooling air	-
cenv	cold environment	-
d	dispersed phase	-
f	final	-
i	frozen state	-
ip	initial parameter for peas	-
iw	initial parameter for water	-
m	matrix, space node	-
n	time node	-

o	initial	-
p	constant pressure	-
pp	pea at constant pressure	-
s	solid	-
u	unfrozen state	-
α	free stream air	-
s	surface of peas	-
1,2,3,…m	space state points	-
1,2,3,…n	time state points	-
sc	cooling	-
pc	phase change	-
pf	post freezing	-

Introduction

Chapter 1

INTRODUCTION

Fast technological developments and availability of sophisticated cultivation techniques have brought green revolution in India and this has led India to become a nearly self-sufficient country in terms of food requirements. The differential growing conditions of foods in our country lead to their seasonal availability. To ensure their off season availability, it is an excellent idea to exploit proper preservation techniques, developed time to time, worldwide.

Preservation of food reduces the growth rate of fungi, bacteria or other micro-organisms and retards the oxidation of fat also that spoils the food. Preservation of food includes the processes that inhibit deterioration, like enzymatic reaction in potato after these are cut during food preparation. Many methods have been developed to preserve the food materials. Some food preservation methods drastically change the characteristics of the foods. Among all food preservation methods, the cold preservation method is most suitable for fruits and vegetables as it retains their original flavour, nutritional value, colour, aroma and texture.

1.1 Cold Preservation of Food

Food products like vegetables and fruits are perishable, so preservation of these foods is necessary to increase their self-life. At normal temperature, biological and chemical reactions are present in food products. These biological and chemical reactions deteriorate the quality of fruits and vegetables. These chemical reactions cannot be completely stopped by canning, dehydration blanching, ohmic heating, radio-frequency heating, pulsed electric field processing, pasteurization, sterilization, ultra violet light processing, microwave heating and electron beam processing. These methods also lose the texture, flavor and nutrition value of foods. So low temperature preservation is the only means of food preservation which can maintain the important qualities of foods. Cold preservation is an important and suitable application of thermal engineering.

In the design and fabrication of proper refrigeration system, there are some considerations of heat transfer mechanisms. Food products continuously generate heat. This generated heat is called as heat of respiration. As the temperature of food products decreases the heat of respiration also decreases. Food products freeze over a wide range of temperatures. The rate of freezing greatly affects the quality of frozen foods. The velocity of cooling air during cold preservation affects the loss of moisture from the food products in addition to the rate of heat transfer. Initial temperature and cooling air (refrigeration) temperature etc. has great impact on the rate of freezing.

1.2 Types of Micro-organisms (Ciobanu et al., 1976)

The distinction of microorganisms (important from food safety viewpoint) as per their temperature dependence is done into following categories:

a) Thermophilic microorganisms
b) Mesophilic microorganisms
c) Psychrophilic microorganisms

Thermophilic micro-organisms do not produce food poison. These can remain alive between 45°C and 80°C. These micro-organisms are most effective in a temperature range of 50°C to 65°C. A temperature below 45°C and above 80°C is fatal for these micro-organisms. Mesophilic micro-organisms produce food poison. These can remain alive between 10°C and 40°C. These are most effective in a temperature range of 30°C to 35°C. A temperature below 10°C and above 40°C is fatal for these micro-organisms. Psychrophilic micro-organisms produce food poison and remain alive between -7°C and 30°C. These are most effective in a temperature range of 15°C to 20°C. A temperature below -7°C and above 30°C is harmful to these micro-organisms. Therefore, a temperature below -7°C makes the food free from these harmful micro-organisms.

1.3 Properties of Fruits and Vegetables

The literature survey shows that data of thermo-physical properties of fruits and vegetables of Indian origin is rarely found. Each fruit and vegetable can grow only in some specific environmental conditions and thermo-physical properties of these products depend on the growing conditions. So for food preservation it is necessary to determine these properties, viz. specific heat, mass density, thermal conductivity, latent heat of fusion and moisture content of fruits and vegetables which are commonly preserved. Since cold storages are designed according to the purpose of requirement, the above data of properties of food products is necessary for the design of cold preservation equipment.

Most of the thermo-physical properties of the peas have been determined experimentally in this work. Some properties like, thermal conductivity and latent heat of fusion have been taken from literature.

1.4 Freezing Time Estimation

Numerical models for freezing time have been presented in literature. The oldest model has been given by Plank (1941). The developed model is valid for spherical, cylindrical and rectangular shapes. A number of models have also been developed after Plank (1941). But all these methods provide inaccuracies when compared with actual (experimental) results. The mathematical models available in literature can be divided in two categories:

a) Models requiring only hand calculation
b) Models requiring computer calculation

Nagaoka et al. (1956) modified the Plank's model by considering the sensible heat during precooling and post freezing and applied this technique on the regular shaped food products. Rolfe et al. (1967), Cleland and Earle (1977), Lacroix and Castaigne (1987), and Varshney and Ansari (2003) have given the mathematical models which can be solved by hand only. The models are applicable for regular shaped food products only.

Cleland (1985) has given mathematical model based on numerical methods for regular and irregular shapes. Wilson and Singh (1986) have given numerical model and conducted experiments for freezing time of spherical peas. Mittal (1992) has given mathematical model based on numerical methods for regular shaped food products. Muftugil (1986) conducted freezing experiments for cauliflower for different operating conditions.

Numerical model for freezing time estimation for peas has been developed in the present work with better accuracy. In the numerical model, Crank Nicolson scheme (Crank and Nicolson, 1947) for the solution of partial differential equation (parabolic heat equation) has been used. Crank Nicolson scheme (Crank and Nicolson, 1947) is always stable and applicable to all type of regular (rectangular, spherical and cylindrical) shapes. In present work, the numerical model is solved by using MATLAB and Simulink 2013b. Some assumptions are made for developing the numerical model of freezing time. The validation of numerical model has been carried out for other spherical shaped food product (beef meatballs), the results of which have been presented by Zhengfu et al. (2007).

Two cases of freezing have been considered in the numerical model:

(I) Freezing at constant temperature and

(II) Freezing at variable temperature with successive depression in freezing point

It is well known that freezing temperature continuously decreases with advancement of freezing as the concentration of salts increases in the unfrozen liquid in the fruits and vegetables.

It is important to calculate experimental freezing time, so freezing time has been estimated experimentally in this work. Therefore, an experimental setup has been designed and fabricated for determination of freezing time. Freezing time of food product depends on several parameters, therefore, effect of these parameters viz. initial temperature, cooling air temperature and cooling air velocity has also been studied in this work.

1.5 Objectives

The objectives of present work are outlined below:

a) Measurement of thermo-physical properties viz. density, specific heat and moisture content of peas
b) Development of a numerical model to calculate the freezing time of peas for two cases;

    (I) Freezing at constant temperature and

    (II) Freezing at variable temperature with successive depression in freezing point

c) Validation of numerical model
d) Design and fabrication of an experimental setup for determination of freezing time
e) Formulation of an empirical relation for prediction of freezing time of peas.

Review of Literature

Chapter 2

REVIEW OF LITERATURE

2.1 Thermo-Physical Properties

Many analytical, experimental and empirical methods have reported in the literature to determine the different thermo-physical properties of foods which play vital role in the analysis, design & development of food preservation equipment. A critical review of literature related to the relevant properties is as below:

2.1.1 Mass density

Generally, the mass density of any substance is the ratio of mass and volume of the substance. It is a measure of closeness of atoms in the commodity.

Mohsenin (1980) have given a complete description to determine the mass density of different foods. It is simple and better method of calculating the mass and volume of a food sample which gives the approximate accurate results for mass density.

Jain et al. (1981) have said that almost all of the food products have water content in range 50% to 90%. The mass density of food products is greatly affected by water content so it decreases slightly in frozen state. The density of pure water decreases 9 percent, but for the food products it is limited to 6 percent because water part in food commodities is always in bond state with the dispersed food which is in matrix form. Water is found in aqueous form in dispersed solid food constituent. Since some of the products, like fruits and vegetables, have air voids therefore the change in the volume of food products should be taken under consideration while designing the equipment for cold preservation. In fast freezing i.e., immersion freezing in liquid nitrogen (cryogenic freezing), it may lead to build up of high pressure inside the food product, causing breaking of shell of the products.

2.1.2 Specific heat capacity

Specific heat capacity of any substance may be defined as the heat required changing the unit temperature of 1 kg mass of that substance.

Seibel (1872) determined the thermal properties, i.e. specific heat capacity, of foods from its water content. Different investigators have obtained different expressions from experiments which correlate the specific heat capacity of the food product with its water content. The simple equations have been proposed by Seibel (1872).

Nowadays these formulae are widely applied in the food industries at high scale. These formulae give the specific heat for frozen and unfrozen food products as in Equations (2.1) and (2.2):

$$c_u = 33.5W + 840 \tag{2.1}$$

$$c_f = 12.6W + 840 \tag{2.2}$$

Otten et al. (1980, 1981) and Mohsenin et al. (1980) measured the values of specific heat capacity for different products which are generally more accurate and reliable as comparison to the values obtained from Equations (2.1) and (2.2). The simple calorimetric method is extensively used to determine the specific heat capacity of food products. The calorimetric method is also called as the method of heat balance. Calorimeters have also been used to determine the specific heat capacity which is based on the comparison of the cooling curve of the food commodities taken under consideration with respect to the cooling curve of a food of known specific heat capacity. The specific heat of the food product can determine by applying heat balance Equation (2.3).

$$Q = m_{p1}.c_{p1}.\Delta T_{p1} = m_{p2}.c_{p2}.\Delta T_{p2} \tag{2.3}$$

Fennma et al. (1993) found the specific heat variation for living matter experimentally. The results show that the specific heat capacity of aqueous food products decreases abruptly, as shown in the Figure 2.1, as water changes into ice and specific heat continues to decline steadily with further decreases in the temperature. Due to the presence of bound aqueous water, the food commodity is not like ordinary ice but it is a mixture of frozen water constituent and unfrozen dispersed constituent in matrix form.

2.1.3 Moisture content and latent heat of fusion

Moisture content of any substance is the measure of available water in that substance. It is generally expressed in percentage. Latent heat of fusion is the heat extracted from any substance at constant temperature to change it into solid state from liquid state.

Woolrich (1933) and Frihat et al. (2012) told that water content of the food products is generally very high, which varies from 50% to 90%. Water content is also called as moisture content which can be determined by drying the food commodities. Water content of different type of food commodities has been reported in literature. Water content affects the latent heat of fusion of food products. Latent heat of fusion of food products directly varies with its water content and mass density. Latent heat of fusion can directly be calculated from Equation (2.4), given by Woolrich's formula (Woolrich, 1933) given as:

$$L = 3334.65\,W.\rho \tag{2.4}$$

2.1.4 Thermal conductivity

Thermal conductivity of any substance may be defined as the ability to conduct heat.

Maxwell (1904) has explained an equation which provides the thermal conductivity of the mixture of composed small spheres of one constituent in continuous matrix of another constituent.

Euken (1940) adopted the concept of Maxwell (1904) later and the concept is popularly known as Maxwell – Euken equation as given below:

$$k = k_m.\frac{\left(1 - a.\frac{k_d}{k_m}\right).b}{1 + (a - 1).b} \tag{2.5}$$

where,

$$a = 3.\frac{k_m}{2k_m + k_d} \tag{2.6}$$

$$b = \frac{V_d}{V_m + V_d} \tag{2.7}$$

Water is assumed as the continuous matrix for a temperature above the initial freezing point. This is non-aqueous part in food products. Below freezing temperature, thermal conductivity of commodity is first calculated by ice which is continuous matrix & the aqueous constituent and unfrozen dispersed constituent. Then thermal conductivity is also determined by making some reverse assumptions. Then the thermal conductivity of food products is obtained by averaging the above two values. Mostly organic substances have thermal conductivity 0.14 - 0.2 W/m/K.

Appropriate values of thermal conductivity can be obtained by using the above simplified assumptions. In literature there are graphical and tabulated data of thermal conductivity of different products which are calculated from the above expressions, viz. from Equations (2.5) to (2.7). These empirical relations were adopted by the researchers who determined the thermal conductivity of sugar solution and fruit juice, milk and evaporated milk, fats, meats and some other food models.

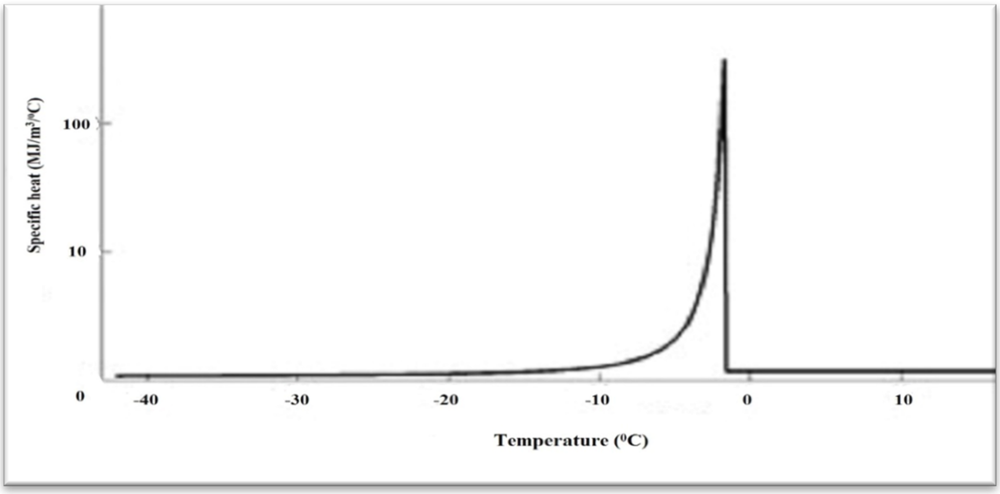

Fig. 2.1 Variation of specific heat with temperature in freezing process [Fennma et al., 1993]

Ajasa et al. (2014) determined the thermal conductivity of some food products by using artificial neural networks. The expressions provided by the Ajasa et al. (2014) are the relations among temperature, moisture content and apparent density. The effect of different parameters on the thermal conductivity values, calculated from Maxwell - Euken Equation (1940) (2.5) has been studied by Ajasa el al. (2014). The thermal conductivity variations of some products with respect to temperature are shown in Figure 2.2.

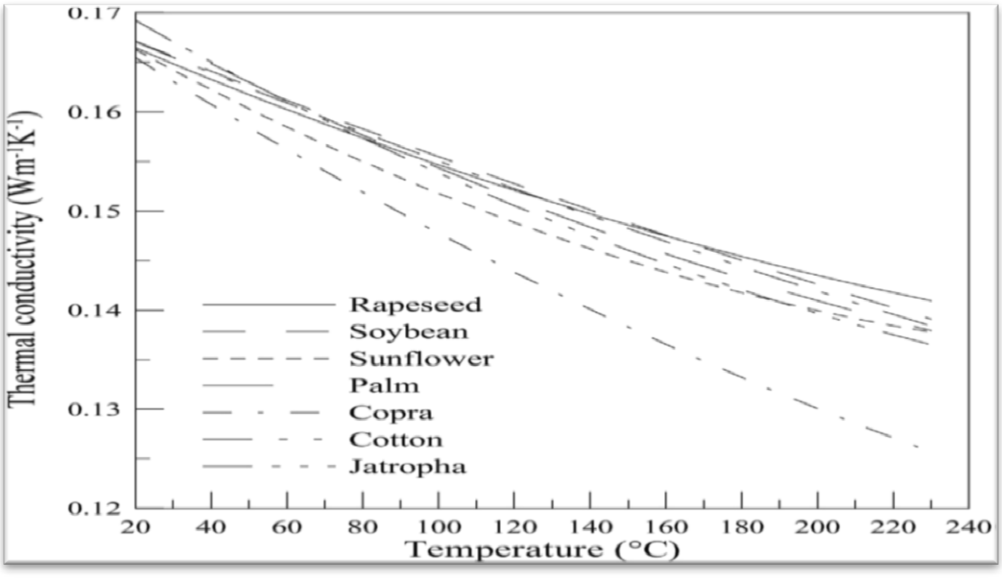

Fig 2.2 Variation of thermal conductivity with temperature [Ajasa et al., 2014]

2.2 Freezing of Foods

Freezing is a complex phenomenon in thermal engineering due to phase change. To predict the freezing parameters during phase change many researchers have used simplified models.

Plank (1941) has given the mathematical relations between the thermal conductivity, freezing temperature, latent heat, heat transfer coefficient & shape of the product. In these mathematical relations, it is assumed that heat transfer occurs between the food items and the surrounded cooling medium by convective heat transfer only. Some assumptions that initially the food products are at freezing point and the freezing temperature is constant throughout the freezing process are taken into consideration. Furthermore, a constant thermal conductivity for the frozen region is assumed. Plank's (1941) freezing time estimation relation is given by Equation (2.8).

$$t = \frac{L.\rho}{T_f - T_{cenv}}\left[\frac{PD}{h} + \frac{RD^2}{k_S}\right] \tag{2.8}$$

Where,

For the infinite slab,	P = 1/2	R = 1/8
For a sphere,	P = 1/6	R = 1/24
For an infinite cylinder,	P = 1/4	R = 1/16

But Plank’s model (1941) has some limitations. Plank (1941) assumed that food freezing takes place at a constant temperature. But in the case of actual food freezing the temperature varies over a range. The thermal conductivity of the frozen food is considered constant, but in reality, the thermal conductivity greatly affected by phase change. Another limitation of Plank's equation (1941) is that it neglects the removal of sensible heat above and below the freezing point.

Nagaoka et al. (1956) modified the Plank’s model (1941) by considering the sensible heat during precooling and post freezing. Nagaoka et al. (1956) applied his technique on the regular shaped food. The expression given by Nagaoka et al. (1956) is given by Equation (2.9) and (2.10).

$$t = \frac{\Delta H}{T_f - T_{cenv}}\left[\frac{PD}{h} + \frac{RD^2}{k_S}\right] \tag{2.9}$$

$$\Delta H = 1 + 0.008T_i\left[C_{pu}\left(T_i - T_f\right) + L + C_{pi}\left(T_f - T_{cenv}\right)\right] \tag{2.10}$$

Nagaoka et al. (1956) model has also some limitations viz. thermal conductivity of the frozen food commodities is taken as constant but, in actual, the thermal conductivity varies greatly during freezing. Nagaoka et al. (1956) assumed that food freezing process occurs at a constant temperature, and not in a temperatures range as is the case in actual food product freezing processes.

Rolfe et al. (1967) estimated the freezing time of food products with the help of mathematical model and as a result he concluded that freezing of foods release latent heat over a range of temperatures. Freezing does not occur at a unique temperature and foods have not constant thermal properties. So there is no exact mathematical model exist for predicting the freezing time. Rolfe et al. (1967) said that the researchers, who have found a solution, by applying either numerical finite difference or finite element methods, is only an approximation of freezing time.

Cleland & Earle (1977) improved Plank's model (1941) by incorporating corrections to account for the removal of sensible heat both above freezing point and below the initial freezing point of the food commodities as well as temperature variation during freezing process. He developed regression equations to estimate the geometric parameters, P and R, for infinite slabs, infinite cylinders and spheres. In his regression equations, the effects of surface heat transfer, precooling and final sub cooling are accounted by means of the Plank number, the Stefan number and the Biot number respectively. The latent heat of fusion is replaced with a new term called the change in volumetric enthalpy of the food in Plank's equation (1941). The mathematical model of Cleland & Earle (1977) is applied to finite slab only which is valid for h = 10 to 500 W/m^2/K, slab thickness should be < 0.12 mm and the temperature of freezing medium should be -15°C to -45°C.

Varma (1984) measured the thermo-physical properties of apples, oranges, peas and potatoes for precooling and peas for freezing as well. Varma (1984) developed analytical procedures to calculate the times of precooling and post freezing. Varma (1984) measured the freezing temperature of peas rectangle in packages.

Wilson and Singh (1986) developed a one dimensional three time level implicit finite difference computer program and predicted time-temperature profiles of individual pea sample. Wilson and Singh (1986) calculated temperature varying thermal properties of the unfrozen product. During freezing, Wilson and Singh (1986) recorded the centre temperature of individual peas being frozen under various conditions. Wilson and Singh (1986) concluded that comparison of experimental results and published data with predicted freezing curves showed good agreement.

Mittal (1992) worked on evaluation of freezing time prediction models for meat patties and evaluated freezing time for meat patties. Mittal (1992) selected ‘Air blast freezing method’ at freezer temperature -14°C and evaluated surface heat transfer coefficient for air blast freezing by the expression developed by Mascheroni & Calvelo (1980) for an infinite slab. Mittal (1992) estimated surface heat transfer coefficients within the range for air blast freezer (17 to 55W/m^2/K) and also calculated thermo-physical properties for meat patties. At last Mittal (1992) compared the experimental freezing time with predicted freezing time obtained by various models. The model is only valid for infinite slab type food product.

Zhang Lin et al. (1996) proposed a simple freezing time prediction method applicable to two-dimensional irregular shapes. The method used the analytical solution for convective cooling of a sphere conjunction with two parameters of geometry determined by empirical algebraic equations. Zhang Lin et al. (1996) determined the real geometric shape related to an equivalent infinite ellipse using dimensional measurements, and the two parameters for the ellipse. Zhang Lin et al. (1996) used test methodology for predicting freezing rates at the thermal centre position for experimental measurements with seven irregular geometric shapes and finite element numerical method. Zhang Lin et al. (1996) observed that the data uncertainties differences in freezing rate were large. The method has theoretical capability to determine mass-average temperatures, but this capability had not been tested experimentally. Zhang Lin et al. (1996) did not find the freezing time for two dimensional objects experimentally. The assumption was that the real geometric shape was related to an equivalent infinite ellipse which was only theoretical possible approach.

Chaiwanichsiri et al. (2001) calculated the freezing time for Cuttlefish. Thermo-physical properties of cuttlefish like moisture content, density, equilibrium freezing temperature, thermal conductivity, and specific heat were determined. Chaiwanichsiri et al. (2001) also determined the relationship between surface heat transfer coefficient and air velocity for air blast freezing. A numerical model for freezing time prediction was developed. Chaiwanichsiri et al. (2001) compared the mathematical freezing times with the experimental values. The results those calculated from the simplified analytical models of Plank (1941), Cleland and Earle (1977) were compared with these experimental results also. As results shows the best prediction with 1.5% average error. The theoretical approach considered by Chaiwanichsiri et al. (2001) is not practically possible. Chaiwanichsiri et al. (2001) has taken the approximation in thermal properties of products in the modeling.

Zengfu et al. (2007) developed one-dimensional mathematical model for unsteady state with variable thermo-physical property parameters. Zengfu et al. (2007) simulated the freezing time of individual food in freezing process. The apparent heat capacity approach is used to solve the phase change problem in the freezing process, and a quadratic curve described the change in physical property. The Crank–Nicolson scheme is used as finite-difference method in numerical algorithm of model. A set of actual experimental data of temperature is used to validate the predicted results of cucumber slice during freezing process. The predicted freezing times of cylindrical and spherical food products are also validated with experimental data. The freezing time results by the mathematical model provide the better accuracies than that of other mathematical models available in the literatures which were based on the same experimental data. The linear regression analysis between predicted and experimental values was done and the linear regression correlation coefficient was 0.989. So the mathematical model of Zengfu et al. (2007) gives the guidance for freezing equipment design, freezing experiments and production of frozen-food.

Filip et al. (2010) investigated the effect of food product composition on freezing time. The research was based on hypothesis that the composition of food product has significant effect on freezing time, considering that the products have the same shape and mass. In the research, Filip et al. (2010) recorded three batches of standard products with forest fruit, vanilla and chocolate respectively at the same freezing conditions and the mass, shape, relief and surface were constant during the research. These products were made from the same ingredients. The limitation was that the constant thermal properties are considered for all the testing models and the models are valid only for slab type shape.

Frihat et al. (2012) conducted cooling and freezing experiments using ground beef in the same shape and location as the acrylic transducer. Taking into account that the moisture content of food products is between 50% -96%, the thermal and physical properties of food products were expressed as a function of moisture content. Frihat et al. (2012) concluded that freezing time and freezing point are the functions of crystallized water fraction in food commodities. The model is valid for ground beef of thicknesses 96 mm to 20 mm. Frihat et al. (2012) used an electronic device to record temperature history curves for the speed of air ranging from 2 m/s to 14.2 m/s and air temperatures from −27°C to −15°C.

2.2.1 Phenomena of phase change in foods

It is well known that food commodities are generally made up of two fractions:

a) Solid constituent and
b) Aqueous solution (water content)

In fruits and vegetables solid constituent is found in matrix form and water fraction is bound in this solid matrix in the form of aqueous constituent. Most of the fruits and vegetables consist of a major part of water in aqueous form therefore the composition of foods is a complex system of solutes and water. The change of phase in foods involves complicated interaction between solid and aqueous fraction. During the freezing process of food solid fraction remains same while the aqueous fraction converts from moisture to ice. The properties of food i.e. thermal conductivity and specific heat depend on percentage of water and these properties of food vary rapidly as aqueous water converts into ice. In freezing there is an initial freezing point above which the thermal properties remains constant and below this point there is rapid change in thermal properties. Thermal conductivity variation and formation of ice in freezing process are shown in Figures 2.3 and 2.4 respectively.

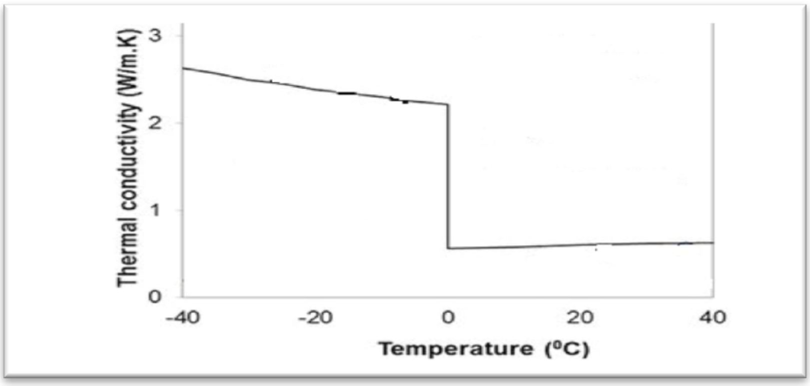

Fig. 2.3 Thermal conductivity variation for a typical foodstuff [Ansari, 1984]

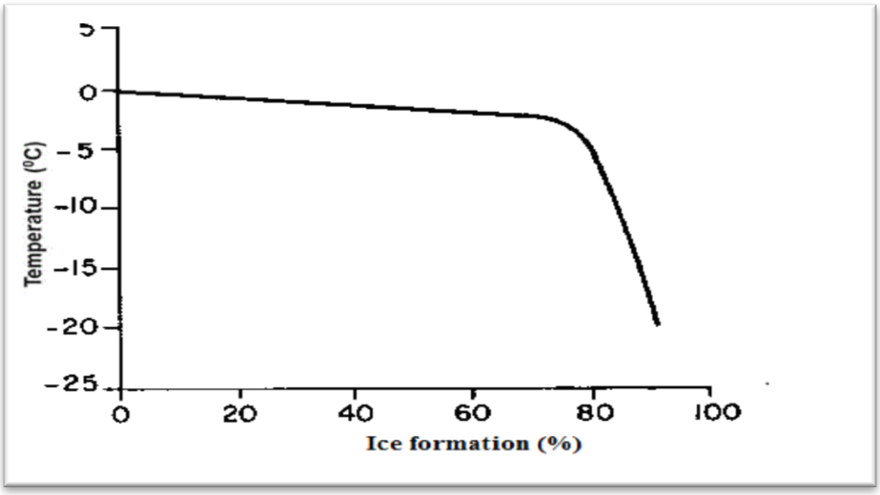

Fig. 2.4 Ice fraction formation for a typical foodstuff [Ansari, 1984]

2.2.2 Phase change formulation (Cleland, 1985)

Generally, in foods i.e. fruits and vegetables, heat is transferred by conduction. The heat conduction equation with constant thermal conductivity and heat generation in spherical coordinates is given by following partial differential equation:

$$\frac{1}{\alpha}\frac{\partial T}{\partial t}=\frac{\partial^2 T}{\partial r^2}+\frac{2}{r}\frac{\partial T}{\partial r}+\frac{e_g}{k} \tag{2.11}$$

In the solution of above partial differential equation non linearity arises due temperature dependent properties. Therefore appropriate assumptions are considered before solving this heat equation. Latent heat of fusion is transferred at constant temperature, is one such assumption. Also the thermal properties undergo a step change at this temperature.

2.2.3 Initial and boundary conditions (Cleland, 1985)

Initial boundary condition can apply to solve heat conduction equation in spherical coordinates. This equation is valid for whole food product at initial time. Following is an initial condition for spherical heat conduction equation:

$$T = T_i \qquad for\ \ 0 < r < R, t = 0 \tag{2.12}$$

The first kind of boundary condition is also known as Dirichlet boundary condition. This boundary condition is valid for surface of the food product at any time.

$$T = T_{env} \qquad for\ \ r = R, \qquad t > 0 \tag{2.13}$$

The third kind of boundary condition is also called as Robin boundary condition. This is valid for the surface of the food product, where conductive heat is equal to the sum of radiative and convective heat.

$$q_{cond} = q_{conv} + q_{rad} \qquad for\ r = R, \qquad t > 0 \tag{2.14}$$

Symmetric condition is applicable at the centre of spherical food product which is placed in a uniform temperature of surrounding. This condition is used to remove singularity from the solution of heat conduction equation.

$$\lim_{r \to 0} \frac{1}{r} \frac{\partial T}{\partial r} = \frac{\partial^2 T}{\partial r^2} \qquad for\ r = 0, \qquad t > 0 \tag{2.15}$$

In actual case both non-uniform and uniform initial boundary occurs. Mathematical modeling can handle both non-uniform and uniform temperature of the food commodity. To make the calculation easier, a uniform temperature is considered throughout the food commodity which is called mean temperature. In practice there is always some surface resistance therefore first and third boundary conditions are seldom the best boundary descriptions possible. The Robin boundary condition is the most realistic boundary condition in food phase change process.

2.2.4 Completion of phase change (Cleland, 1985)

For completion of freezing process it is necessary to know the end freezing point. In moving boundary condition, the end point is clearly visible when the freezing front reaches to thermodynamic centre of the food commodity. When the temperature of thermal centre reaches to the certain limit, this is the best way to confirm the completion of phase change. The end thermodynamic temperature means:

a) If the temperature thermodynamic centre moves and reaches to the end point temperature then phase change completion takes place.

b) The phase change is designed in such a way that the mass average temperature of commodity should not be more than the temperature of thermodynamic centre.

c) The required temperature which can be approximate and assumed sometimes upto which the food commodity is to be freeze.

2.2.5 Numerical methods

The numerical approximate solution of Equation (2.11) requires no assumption related to the actual processes of phase change i.e. freezing. A number of errors in freezing time may introduce from imprecise thermal data & from numerical rounding and truncation errors. In literature many solutions of Equation (2.11) has been used.

Some have been used the finite difference techniques which include:

a) the solutions of simple formulae of explicit schemes where C and k are combined as a term thermal diffusivity, α, which is as a function of temperature of food commodity,
b) the solutions of explicit schemes in which C and k are considered as functions of temperature separately,
c) the solutions of explicit difference schemes based on the transformation of enthalpy,
d) the solutions of two and three time level implicit schemes

Comini and Bonacina (1971) & Cleland and Earle (1984a) have used different finite difference method and as a result they concluded that the accuracy of scheme was superior if an implicit three time level scheme was considered. An implicit three time level scheme is also convergent and stable. The scheme of three time level predicted freezing data about ±11% for spheres, infinite cylinder, rectangular brick shape and slabs.

Albasiny (1960) proposed the methods based on the ADI (alternating direction implicit) scheme for the spherical and infinite cylindrical geometries. A number of ADI schemes have been used for implicit methods for two and three dimensional geometry. Regular configuration of the shape of food product is the only limitation for all the above schemes. Numerical methods for irregular geometries, non-homogeneous materials and two dimensions have been proposed but these are difficult to solve. Many correlations for freezing time prediction of the food products are also available in the literature. Plank’s (1941) formula and related modifications, given by the Equations (2.8) to (2.10), are generally used for the food products. The method of heat balance has also been used to determine the freezing times of slab shaped and cylindrical food products. Freezing time is also determined by Neumann’s solution.

2.3 Findings from Literature Review

From the literature review, it is found that very less research work has been reported on freezing of peas. Although, frozen peas have got a very good market share in the area of frozen foods. Therefore, peas were selected as product for carrying out research in the present work. Further, empirical correlations for prediction of freezing time are not available in the literature, which may prove to be quite useful for the frozen food industry in India. The variety of pea developed in India and commercially available in market, Pant Sabji Matar 3 has been selected for carrying out experiments in this work.

2.4 Objectives

On the basis of findings from literature review, the following objectives have been drawn for carrying out this work:

a) Measurement of thermo-physical properties viz. density, specific heat and moisture content of peas

b) Development of a numerical model to calculate the freezing time of peas for two cases;

    (I) Freezing at constant temperature and

    (II) Freezing at variable temperature with successive depression in freezing point

c) Validation of numerical model

d) Design and fabrication of an experimental setup for determination of freezing time

e) Formulation of an empirical relation for prediction of freezing time of peas.

Materials and Methods

Chapter 3

MATERIALS AND METHODS

Freezing time of peas has been estimated by conducting actual experiments in the present work. Further, a numerical model has also been developed to predict the freezing time theoretically. Several thermo-physical properties are required for calculation of freezing time. These properties have been measured experimentally in this work.

3.1 Measurement of Thermo-physical Properties

Thermo-physical properties of peas viz. mass density, moisture content and specific heat were determined first for further analysis in the research work. Description of different properties has been given in the following subsections:

3.1.1 Determination of density

The mass density of peas was determined using the mass and the volume of the samples. The masses of the pea samples were measured by a digital electronic balance. The volumes of the pea samples were measured indirectly using a measuring cylinder. A known mass of peas was dipped in the partially filled measuring cylinder with water. The rise in the water level in measuring cylinder indicated the volume of peas. Then density of peas was calculated by using following formula:

$$Density\ of\ peas = \frac{mass\ of\ peas}{\begin{array}{c} volume\ of\ water\ displaced \\ in\ measuring\ cylinder \end{array}} \tag{3.1}$$

The density of 12 samples of pea was determined by using Equation (3.1). The apparatus used in the density determination are shown in Figures (3.1) and (3.2).

3.1.2 Measurement of water content

Following are the main units which were used in the determination of water content of peas:

a) Electronic balance
b) Drying unit (oven)

Electronic balance is shown in Figure 3.2 and drying unit is shown in Figure 3.3. For determination of moisture content or water content, 10 experiments were conducted. The 10 samples of peas were placed in oven at 76.5°C for 24 hours. The masses of samples were measured using electronic balance before and after the drying process. Moisture content is given in percentage (%) and was calculated using following formula:

$$Moisture\ content = \frac{initial\ mass - final\ mass}{initial\ mass} \times 100\ \% \qquad (3.2)$$

Fig. 3.1 Schematic diagram of measuring Cylinder

Fig. 3.2 Schematic diagram of electronic balance

Fig. 3.3 Schematic diagram of oven

Fig. 3.4 Schematic diagram of insulated vessel

Fig. 3.5 Schematic diagram of electronic balance

Fig. 3.6 Schematic diagram of digital thermometer

3.1.3 Determination of specific heat

Specific heat of the peas was determined with the help of calorimetric method. This method is also called as the method of heat balance. In this method, the specific heat was determined using a fluid of known specific heat. Distilled water was used as a reference fluid of known specific heat. Figures 3.4, 3.5, 3.6 show insulated vessel, electronic balance and digital thermometer respectively.

To determine the specific heat of peas, 15 experiments were conducted. First, the mass and the temperatures of pea sample and distilled water were measured, then both peas and water were mixed in an insulated vessel till the thermal equilibrium was achieved and the equilibrium temperature was recorded as the final temperature (T_f). Specific heat of water was taken as C_{pw}= 4.187 kJ/(kg-K). The specific heat of peas was determined using following formula:

$$C_{pp} = \frac{C_{pw}.m_w.(T_f - T_{iw})}{m_p.(T_{ip} - T_f)} \tag{3.3}$$

3.2 Formulation of Numerical Model for Freezing Time Estimation

In literature, there are many mathematical models for freezing time calculation but these show higher degree of inaccuracy. So to obtain better results, it is necessary to develop an accurate mathematical model for the calculation of freezing time. Following are some desirable characteristics for freezing time calculation model:

a) Accuracy is required for wide range of conditions.
b) Calculations should be cheap and simple.
c) Freezing should use unified approach.
d) Model should be applicable to a wide range of biological food of different sizes.
e) Model should be applicable where boundary conditions are time & temperature variable.
f) Requirement of thermal property data should be less.

To make the calculation easier, it is necessary to make some assumptions in the mathematical model. Following are some assumptions made in numerical model:

a) Change in density is negligible during phase change.
b) Food products are spherical.
c) Heat transfer is by conduction only.
d) Internal heat generation is negligible.
e) Mass transfer at the surface is negligible.
f) Material is homogeneous.
g) Material is isotropic.
h) Peas are spherical.

i) Temperature is constant during phase change.
j) The effects of radiation are insignificant.
k) The initial, surface and boundary conditions are constant.
l) Third kind of boundary condition describes the transfer of heat at the boundary.

3.2.1 Definition of freezing time

Numerous researchers have taken a different approach to account for the effects of sensible heat removal above and below the initial freezing point. In these methods, the total freezing time, t, is the sum of the precooling, phase change and post freezing times (Becker and Fricke, 1999):

$$t = t_{\mathrm{sc}} + t_{pc} + t_{pf}$$

Where, t_{sc} is precooling time, t_{pc} is phase change time and t_{pf} is post freezing time.

3.2.2 Introduction to numerical methods

To predict the freezing times of foods, different methods are used in literature which can be divided into following two groups:

a) Analytical methods
b) Numerical methods
    - Finite difference method
    - Finite element method

Analytical methods require integration which is very complex for hand calculation. These have some advantages when compared to the numerical methods. First Plank (1941) had used this method to calculate freezing time of foods. After Plank (1941), some other researchers had also applied this method for the formation of mathematical model of freezing time. But, the major disadvantage of analytical methods is that these methods usually made limiting approximations of physical properties therefore analytical methods were not used further in future.

If the properties of food products are temperature dependent, numerical methods are more accurate than analytical methods therefore, numerical methods are most realistic. Numerical methods are best for moving boundary problems during phase change. Nowadays, computer technology is very advanced which means that computation data storage and computation cost are now cheap so numerical methods become more attractive but deep study of numerical methods and computer programs is also necessarily required to apply these methods. In modern age, the computer programs have become user-friendly as compared to old days.

Numerical methods are advocated as standard methods for the formation of mathematical model to predict the freezing times when compared with the other prediction methods, because the solutions by numerical methods are closest to "exact" solution which exists (Heldman, 1983). A numerical mathematical model can only be accurate if the numerical scheme has correctly formulated and implemented if appropriate data is used. The comparison of the mathematical results with the experimental results is necessary to check the presence of these factors.

Finite difference method can be used for regular shaped food products like spheres, infinite cylinders, infinite rods, slabs and rectangular bricks. These shapes have fixed grids which can be solved by the application of simple finite difference scheme. Solving the problem of irregular shapes, irregularly spaced grids are formed which require a complex finite difference scheme. This is a difficult task to implement in computers. If products of irregular shapes have complex boundary conditions and non- homogeneous composition, finite element method is used. Also, if the temperature profile changes with position, this method provides better results than the results by finite difference method therefore finite element method are used for irregular shapes.

3.2.3 The finite difference method (Cleland, 1985)

The finite difference method is mainly used for the prediction of freezing time and heat transfer of regularly shaped food products. For the problems of regular shaped food products, finite difference method requires less detailed program preparation and has lower computation times. Bonacina and Comini (1971) and Cleland and Earle (1977a) had studied the finite difference methods and found that implicit Crank Nicolson scheme (Crank and Nicolson, 1947) is best for the modeling of freezing time of food products.

Mathematical models using Crank Nicolson scheme (Crank and Nicolson, 1947) for infinite slabs, infinite cylinders and spheres, rectangular rods and rectangular brick shapes are available in literature. These models show the accuracies within about ± 10% when compared with experimental freezing data of slab, infinite cylinder, sphere and rectangular brick (Cleland et al., 1982).

3.2.4 Spherical finite difference scheme formulation

For the spherical geometry the general heat conduction equation is:

$$\frac{1}{\alpha}\frac{\partial T}{\partial t}=\frac{\partial^2 T}{\partial r^2}+\frac{2}{r}\frac{\partial T}{\partial r} \tag{3.4}$$

Spheres are considered as one-dimensional, because these have only an axis of rotational symmetry. Wilson and Singh (1986) have shown that how the Crank Nicolson scheme (Crank and Nicolson, 1947) can be applied to one dimension sphere. Equation (3.5) shows the approximation of Equation (3.4) using Crank Nicolson scheme (Crank and Nicolson, 1947):

$$-\tfrac{\lambda}{2}(1-p)T_{m-1}^{n+1}+(1+\lambda)T_m^{n+1}-\tfrac{\lambda}{2}(1+p)T_{m+1}^{n+1}$$

$$=\tfrac{\lambda}{2}(1-p)T_{m-1}^{n}+(1-\lambda)T_m^{n}+\tfrac{\lambda}{2}(1+p)T_{m+1}^{n} \tag{3.5}$$

The third kind of boundary condition is taken into account in the similar manner as considered by Cleland and Earle (1977b) for slabs and Cleland and Earle (1979a) for spherical geometry.

At the radial centre (m = 0) the method of Albasiny (1960) is as in Equation (3.6):

$$\left[\frac{\partial T}{\partial r}\right]_0^s=\frac{T_1^s-T_{-1}^s}{2.\Delta r}\ ,\qquad s=n+1,n \tag{3.6}$$

The method of Albasiny is used to avoid the singularity. To apply Equation (3.6), Equation (3.5) becomes:

$$[1+3\lambda]T_0^{n+1}-[3\lambda]T_1^{n+1}=[1-3\lambda]T_0^{n}+[3\lambda]T_1^{n} \tag{3.7}$$

At the radial surface (m = M):

$$-\lambda T_{M-1}^{n+1}+\left[(1+\lambda)+\frac{\lambda}{2}.(1+p_M).\frac{2.\Delta r.h}{k}\right]T_M^{n+1}$$

$$=-\lambda.p_M T_{M-1}^{n}+\left[(1-\lambda)-\frac{\lambda}{2}.(1+p_M).\frac{2.\Delta r.h}{k}\right]T_M^{n}+2\lambda(1+p_M).\frac{2.\Delta r.h}{k}.T_{cenv}$$

(3.8)

For m=1, 2, ……., (M-1),

$$-\tfrac{\lambda}{2}(1-p_m)T_{m-1}^{n+1}+(1+\lambda)T_m^{n+1}-\tfrac{\lambda}{2}(1+p_m)T_{m+1}^{n+1}$$

$$= \frac{\lambda}{2}(1 - p_m)T_{m-1}^{n} + (1 - \lambda)T_m^n + \frac{\lambda}{2}(1 + p_m)T_{m+1}^{n} \tag{3.9}$$

3.2.5 Treatment of two cases in numerical model

Two cases considered in this study have been modeled as follows:

(I) Freezing at constant temperature

Here, it is assumed that latent heat of fusion is removed at constant temperature. The time for this heat removal has been calculated using Plank's equation.

$$t_{pc} = \frac{L.\rho}{T_f - T_{cenv}}\left[\frac{PD}{h} + \frac{RD^2}{k_S}\right] \tag{3.10}$$

(II) Freezing at variable temperature with successive depression in freezing point

Frihat et al. (2012) described that the initial freezing point of fruits and vegetables is lower than the freezing point of pure water due to dissolved substances in the moisture within these food products. At the initial freezing point, a portion of water within the food crystallizes and the remaining solution becomes more concentrated, reducing the freezing point of unfrozen portion of the food further. As the temperature decreases, ice crystal formation increases the concentration of the solutes in solution and depresses the freezing point further. Thus, the ice and water fractions in the frozen food, and consequently the foods thermo-physical properties, depend on temperature.

Thermo-physical properties of peas continuously change when the crystallization of water starts. Some expressions for change in thermo-physical properties are given here. Specific heat, thermal conductivity and density of peas have been computed using following relations (Frihat et al, 2012):

$$C_p = 1465 + 1482.7(W_p - 0.5) \tag{3.11a}$$

$$k_p = 0.58 + 1.917(W_p - 0.5) \tag{3.11b}$$

$$\rho_p = 1005 + 208.3(W_p - 0.5) \tag{3.11c}$$

Where, W_p is the present moisture content in the peas.

Moisture content during freezing in the peas has been calculated using following relations (Tchigeov, 1979),

$$x_{ice} = \frac{1.105x_{wo}}{1 + \frac{0.7138}{\ln(t_f - t + 1)}} \tag{3.12}$$

Where, x_{wo} is the mass fraction of water in the unfrozen food, t_f is the initial freezing point of food and t is the instantaneous temperature of the food.

Remaining water content in the food has been calculated using following formula,

$$W_p = \left[\frac{W_o}{100} - x_{wo}\right] \times 100\% \tag{3.13}$$

3.2.6 Computer implementation

The Crank Nicolson scheme (Crank and Nicolson, 1947) was used to form a mathematical model. This scheme is always stable, implicit and of order 2. Equation (3.5) shows Crank Nicolson scheme (Crank and Nicolson, 1947) for spherical coordinates. When different boundary conditions were applied to Equation (3.5), Equations (3.7), (3.8) and (3.9) were obtained for radial centre, convective surface and conductive part of spherical geometry respectively.

To solve Equations (3.7), (3.8) and (3.9), MATLAB was used. The version of MATLAB was 2013 which was installed in the system having following configurations:

Windows: 10, Processor: AMD, RAM: 4GB

3.3 Validation of Mathematical Model

The model of freezing time for spherical shaped product was validated with the known experimental results for constant thermal properties. It was noted for the validation of the model that the assumptions made in mathematical model and in reference were same. Wilson and Singh (1986) have made a mathematical model of freezing time for spherical shape and validated experimentally for meatballs.

Table 3.1 Parameters about beef meatball

c_l	c_s	ρ	L	T_{final}	k_l	k	W_o	D
kJ/(kgK)	kJ/(kgK)	kg/m^3	kJ/(kg)	℃	W/(mK)	W/(mK)	%	m
3.6	2.1	1040	188	-20	0.51	1.5	74	0.038

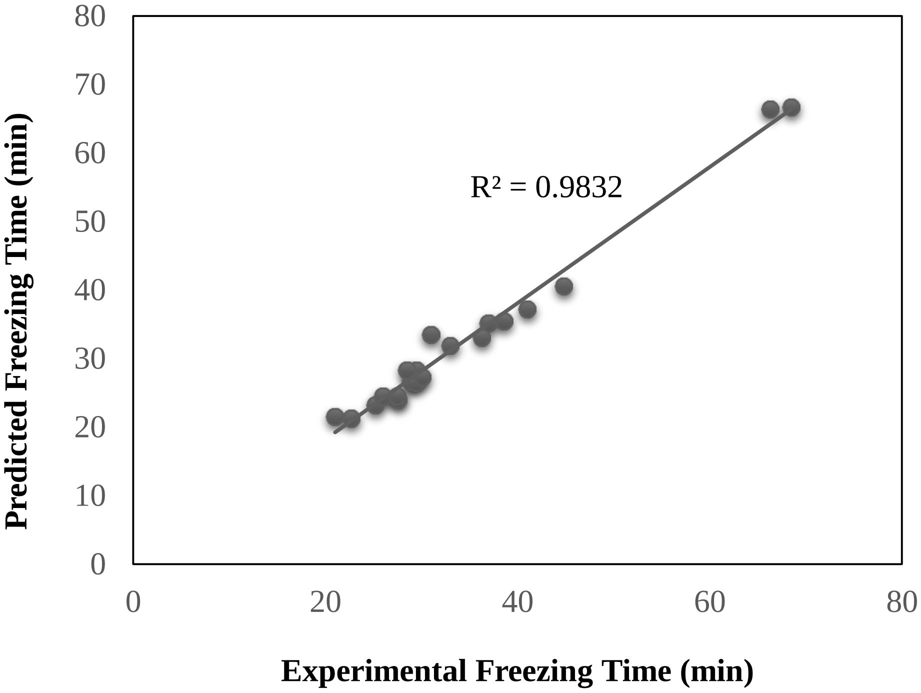

Fig. 3.7 Comparison between predicted and experimental freezing time of beef meatball

Table 3.2 Comparison of results from mathematical model of author and experimental results (Zhengfu et al., 2007)

T_{cenv} (℃)	T_{in} (℃)	h (W/m^2/K)	t_{ref} (min)	t_{num} (min)	E_{ref} (%)
-30.2	6.6	66.5	21.0	21.58	-2.76
-28.9	11.2	59.3	25.2	23.20	7.93
-28.9	1.4	59.3	22.7	21.28	6.26
-24.8	6.6	59.1	28.9	26.67	7.71
-25.0	7.6	59.1	29.4	26.53	9.76
-26.7	0.8	55.6	26.0	24.51	5.73
-23.3	-0.3	55.6	29.5	28.30	4.06
-30.0	17.7	48.2	28.5	28.33	0.59
-30.2	5.9	48.2	27.5	24.56	10.69
-28.9	1.8	42.9	30.1	27.30	9.30
-30.8	13.1	42.9	31.0	33.51	-8.10
-24.8	1.2	42.5	37.0	35.20	4.86
-24.9	10.3	42.5	38.6	35.50	8.03
-29.3	10.9	37.5	33.0	31.88	3.39
-28.9	13.1	37.6	36.3	33.10	8.81
-30.5	19.0	29.4	44.8	40.58	9.42
-30.8	10.4	29.4	41.0	37.20	9.26
-24.9	10.1	21.1	68.5	66.67	2.67
-23.7	1.3	21.1	66.3	66.40	**-0.15**

The present model was validated with the experimental results of Zhengfu et al. (2007) for spherical beef meatballs. Table 3.1 shows the thermo-physical properties of spherical beef meatballs considered for the validation from Zhengfu et al. (2007). Table 3.2 shows the individual predictions for identical conditions and comparison of results of mathematical model and experimental results of Zhengfu et al. (2007) for spherical beef meatballs using the same data. The comparison shows that the deviation in the results varies from -0.15 to 10.69. The regression analysis for the same is also done and it was seen that the value of R^2 is 0.9832 which denotes very good agreement between mathematical results and experimental results.

It was concluded that the mathematical model was valid for freezing time of spherical beef meatballs and therefore, the model was used for the freezing time estimation of peas.

3.4 Description of Experimental Setup

The measurement of experimental freezing time is the 4th objective of the present work. For this an experimental setup was fabricated. The line diagram of experimental setup is shown in Figure 3.8.

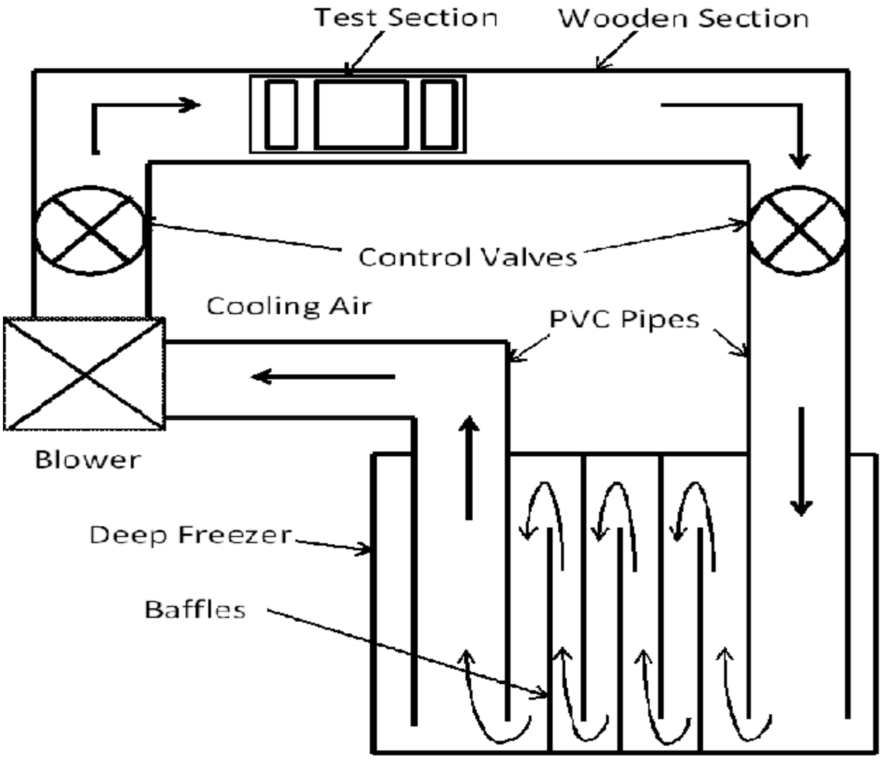

Fig. 3.8 Line diagram of experimental setup

3.4.1 Design of experimental setup

Experimental setup for freezing time determination is shown in Figure 3.9. It consists of following components:

a) Deep freezer
b) Blowers
c) Flow control valves
d) Flow pipes and duct
e) Insulation materials
f) Stand to place setup

Fig 3.9 Schematic diagram of experimental setup

Deep freezer:

Deep freezer in the experimental setup was used as a source of cooling. It is shown in Figure 3.10. The air was cooled in deep freezer and then it was blown over the samples through pipes in duct. This air returns to deep freezer again. The specifications of deep freezer are given in Table 3.3.

Fig. 3.10 Schematic diagram of deep freezer

Table 3.3 Detailed information of deep freezer

Name of deep freezer	Ultra C-340
Manufacturer’s name	New Brunswick, USA
Capacity of freezer	340 Liters
Temperature range	0 to -86˚C
Refrigerant used	R404a, HFC
Input	230 V, 50 Hz , 420W
Material used	Corrosion-resistant stainless steel
Temperature control	Yes
Insulation material	Urethane foam
Internal Dimensions: Height x Width x Depth	760 x 760 x 590 mm
External Dimensions: Height x Width x Depth	1075 x 1340 x 840 mm

Blower:

The experimental setup used two blowers. Both the blowers had same specifications. In the setup, these blowers were used to suck the cold air from deep freezer and force this air to blow over the samples. The blower is shown in Figure 3.11 and Table 3.4 shows the specifications of blowers.

Table 3.4 Specifications of blowers

Type	Centrifugal
RPM	2850
Power consumption	374W
Volume flow rate	0.094 m^3/sec

Fig. 3.11 Schematic diagram of air blower

Flow control valve:

Flow control valves are shown in Figure 3.12. These were used to control the mass flow rate of cooling air in the flow pipes. This mass flow rate is generally used to calculate the heat transfer coefficient of air while passing over the samples.

Fig. 3.12 Schematic diagram of control valve

Pipes and duct:

Pipes were made of PVC and duct was made of wood. The setup had two rigid pipes of different diameters. The diameters of pipes were 38.4 mm and 51.2 mm. The duct had square cross section. Duct was placed between the pipes of diameter 38.4 mm and 51.2 mm. Duct was the main test section in the setup and had three sections. Two of them were for velocity and temperature measurement while third one was for freezing time measurement. Whole setup was covered with the insulating material. The specifications of duct are given in Table 3.5.

Table 3.5 Specifications of test section

Material used	Wood
Length of test section	750 mm
Internal dimensions	120 mm×120 mm
Thickness of wood	20 mm

Insulation material:

To minimize the heat gain to the cold air, the duct and pipes were covered with insulation material. Glass wool was suitable insulation material for this purpose. It has low thermal conductivity. The specifications of insulation material are given in Table 3.6.

Table 3.6 Specifications of insulation material

Insulation material	Glass wool
Thermal conductivity	0.042 W/m/K
Thickness	25 mm

3.4.2 Errors (Cleland, 1985)

When predicted freezing time is compared with experimental freezing time, some lack of agreement is inevitable. This lack in precision may arise from one of following three sources:

a) **Data error:** This error induces due to uncertainty in the data of the material being frozen.

b) **Experimental error:** This error induces due to incomplete knowledge and control of the freezing conditions.

c) **Prediction method error:** This error induces due to inaccuracies arising from the assumptions made in the prediction method.

Thermal property data uncertainty depends on the material used for the experiments. To assess in isolation as far as is possible the magnitude of the third source of inaccuracy, the aim of any experimental procedure or technique is to keep experimental errors randomly distributed and small in size (Cleland, 1985).

The first two sources of errors [(a) & (b)] are arising from imperfect control of experimental conditions. Many variables are controlled to pre-set values. There is control error within each run as well as control problems in attaining the same pre-set value in all similar runs. The ability to reduce the control error can be me assured from the variability of replicate runs for the same set of nominal experimental conditions (Cleland, 1985).

Secondly, there is the error arising from imprecise knowledge of the experimental conditions. Having controlled the experimental conditions during each run the mean values must be measured. Uncertainty can arise as a difference between the measured value of a parameter and the unknown true value. The uncertainty can be reduced by replicate determinations, but measurements are susceptible to systematic errors which replicate determinations will not discern. Systematic errors cannot be easily quantified and can only be minimized by ensuring that the used measurement techniques are valid and accurate. Sources of systematic error include; unwanted edge heat transfer, instrument calibration errors and inhomogeneity in the phase change material due to the presence of air voids (Cleland, 1985).

3.4.3 Temperature measurement

To measure the temperatures of cooling air, environment and samples, data logger was used. Data logger is shown in Figure 3.13 and specifications are given in Table 3.7.

Calibration of data logger:

It was also necessary to calibrate the data logger. Pt-100 sensors were used with the data logger in all channels. Calibration of data logger was done with the help of a thermometer by fitting in a refrigerator. Values of temperatures were measured at every 10th minute by thermometer as well as data logger. Total 102 readings were recorded in calibration process. Calibration table is given in appendix A, Table A1.The schematic diagram of calibration is shown in Figure 3.14. The calibration chart is shown in Figure 3.15.

Fig. 3.13 Schematic diagram of data logger

Table 3.7 Specifications of data logger

Model	708, C0502516
Manufacturer	Instronix India, New Delhi
Sensor	Pt-100
Temperature range	-100 to +600˚C
Resolution	0.1˚C
Number of channel	8
Logging rate	1second to 99 minutes 59 seconds
Data logging	Directly in USB pen drive
Power supply	230V, 50/60Hz AC
Accuracy	±0.1˚C

Regression analysis provides the calibration equation for data logger which is given in Equation (3.14). This equation is valid for every sensor of data logger.

$$T_{act} = 0.9846T_{data\ logger} - 0.6096 \tag{3.14}$$

Fig. 3.14 Schematic diagram of calibration of data logger

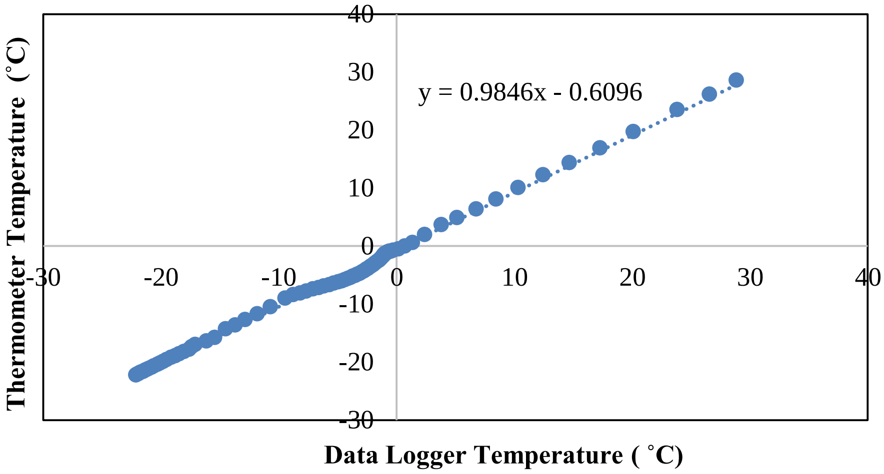

Fig. 3.15 Regression analysis of calibration of data logger

3.4.4 Mass flow rate measurement

Mass flow rate is a variable parameter in the design and analysis of cold storage. In the experimental work, the mass flow rate was measured with the help of an anemometer. To measure the mass flow rate of cooling air, there were two sections of equal size to insert the probe of anemometer inside the test section in flow region. The mass flow rate can be varied with the help of flow control valves as discussed in section 3.4.1. The anemometer is shown in Figure 3.16 and the specifications are given in Table 3.8.

Fig. 3.16 Schematic diagram of anemometer

Table 3.8 Specifications of anemometer

Manufacturer	Omega
Type	Digital
Range	0.3-35 m/s
Accuracy	0.75% of reading ± 1 digit
Dimensions of probe	73 mm × 33 mm
Power supply	2AA Alkaline Battery
Calibrated	Yes

3.4.5 Measurement of surface heat transfer coefficient:

Anemometer is generally used to measure the velocity of air in test section over the samples. The main aim of is to measure the heat transfer coefficient between cooling air and sample by using Equation (3.15) (Cengel, 2002). The equation is valid within $3.5 <$ Re $< 80{,}000$ and $0.7 <$ Pr < 380 and air properties are measured at the temperature of free stream air. μ_s is evaluated at the surface temperature of peas.

$$Nu = \frac{hD}{k} = 2 + \left[0.4Re^{\frac{1}{2}} + 0.06Re^{2/3}\right]Pr^{0.4}.\left(\frac{\mu_{\propto}}{\mu_s}\right)^{1/4} \tag{3.15}$$

3.4.6 Dimension measurement

The dimensions of samples were measured using vernier caliper. The vernier caliper is shown in Figure 1.17 and specifications are given in Table 3.9.

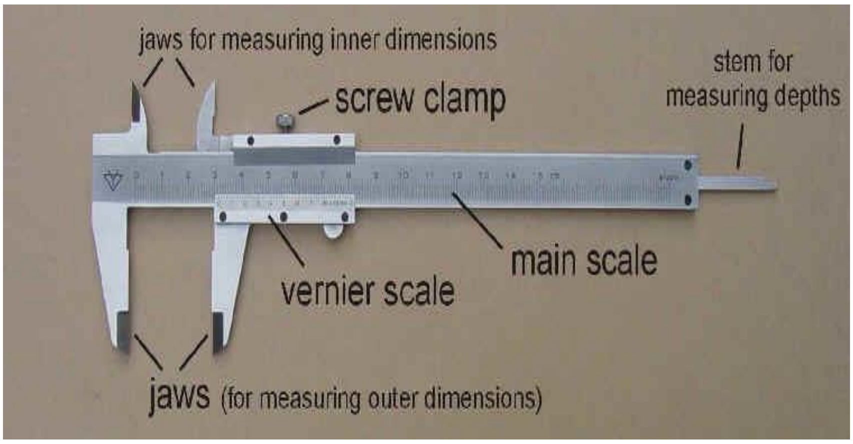

Fig. 3.17 Schematic diagram of vernier caliper

Table 3.9 Specifications of Vernier caliper

Material	Hardened, corrosion-resistant stainless steel
Least count	0.1 mm

3.5 Experimental Procedure

The pea samples were placed inside the wooden test section. The samples were supported with a wire mesh which could be seen from outside through the glass attached in the test section. This test section was connected end to end with the deep freezer through the circular pipes made of PVC. In the circular pipe section two blowers were placed. Each blower was powered by a 275W electric motor. These blowers forced the air inside the duct and over the samples. The diameters of the circular pipes were 38.4 mm and 51.2 mm. Three control valves were also attached in the circular pipes which were used to control and regulate the velocity inside the test section. The valves were able to control the velocity of air inside the test section and different constant velocities could be obtained. The air flow rate could be easily varied between 3 m/s – 14.9 m/s. The temperature inside the deep freezer could be maintained between 0°C to -86°C as per cooling condition requirement. Cooling air was blown between -24°C and -36°C temperature over the sample of peas.

Temperatures were recorded using temperature data logger which auto saves the values of temperatures with respect to time in external USB drive. Temperature sensors were measuring the temperature of cooling air, temperature of environment and central temperature of pea samples. Temperature sensors were attached to centre of individual pea grain. Air velocity was controlled using control valves and measured with an anemometer. Heat transfer coefficient was calculated using Equation (3.12).

The size of peas generally varies between 9 mm to 10 mm. Diameter of pea samples were measured using vernier caliper. Since the peas are not of perfect spherical shape hence the diameter of pea samples were measured for different orientations (eight to ten orientations). Finally the mean value of pea size was calculated and it was seen that the size of each sample was approximately 9.5 mm which was taken under consideration. Hence, there were only three operating variables viz. cooling air temperature, air flow velocity over the samples and initial temperatures of samples so the focus was only on these three variables in numerical solution as well as in experimental analysis.

Results and Discussion

Chapter 4

RESULTS AND DISCUSSION

Freezing times of peas have been estimated by numerical method and by conducting experiments in the present work. Besides this, various thermo-physical properties of peas have been determined experimentally.

The results obtained from numerical methods and different tests and experiments have been presented and discussed in this chapter. Effect of operating variables, viz. cooling air temperature, velocity and initial temperature of pea samples on freezing time has also been presented.

4.1 Thermo Physical Properties

Thermo-physical properties of pea grains viz. mass density, moisture content and specific heat are determined using conventional methods.

4.1.1 Mass density test

The mass densities of twelve pea samples were determined using Equation (3.1). Water was used as the reference fluid to measure the density. From Table 4.1 it is concluded that density of peas is 1037.25 kg/m^3.

Table 4.1 Density calculation of pea samples

S. No.	Mass of pea grains (gm)	Volume of pea grains ($m^3 \times 10^{-6}$)	Density of pea grains (kg/m^3)
1	16.26	16.00	1016.25
2	16.46	16.00	1028.75
3	16.25	15.25	1065.57
4	16.45	16.00	1028.12
5	20.03	19.10	1048.69
6	20.09	19.40	1035.56
7	20.18	19.20	1051.04
8	20.51	19.80	1035.85
9	26.30	26.00	1011.53
10	29.48	28.00	1052.85
11	30.57	29.00	1054.13
12	48.21	46.02	1047.58
	Average density		**1037.25 kg/m³**

4.1.2 Water content test

Ten pea samples were considered to test the moisture content of pea grains. The grains were dried in the oven at 76.5°C for 24 hours. Equation (3.2) was used to calculate the water content. Table 4.2 shows the detailed testing data and indicates that the water content in the pea is 76.03%.

Table 4.2 Moisture content calculation of pea samples

S. No.	Initial mass of pea grains (gm)	Final mass of pea grains (gm)	Loss in mass (gm)	Moisture content (%)
1	25.18	5.89	19.29	76.61
2	24.19	5.57	18.62	76.97
3	32.33	7.86	24.47	75.72
4	32.40	8.02	24.38	75.25
5	26.12	6.24	19.88	76.10
6	28.42	6.84	21.58	75.92
7	29.10	7.08	22.02	75.67
8	40.91	9.77	31.14	76.12
9	39.87	9.52	30.35	76.13
10	37.23	9.00	28.23	75.82
		Moisture Content		**76.03%**

4.1.3 Specific heat test

Fifteen pea samples were considered for determination of specific heat. Specific heat of pea grains was calculated by considering water as reference. Table 4.3 shows the detailed data of specific heat and shows that the specific heat of pea is 3.73 kJ/(kg-K).

Table 4.3 Specific heat calculation of pea samples

S.No	Mass of water (gm)	Mass of pea grains (gm)	Initial temperature of water (°C)	Initial temperature of pea grains (°C)	Final temperature of mixture (°C)	Specific heat of pea grains (kJ/kg/K)
1	30.86	10.11	2.10	13.8	4.76	3.75
2	38.26	16.80	6.30	13.8	8.40	3.70
3	40.12	31.65	2.70	13.8	7.20	3.61
4	35.24	16.34	17.10	1.2	12.70	3.44
5	28.42	15.98	16.00	1.8	11.23	3.76
6	21.29	24.17	7.80	1.7	4.72	3.75
7	30.00	19.02	14.80	2.1	10.21	3.73
8	31.10	18.90	14.50	2.4	10.30	3.65
9	29.10	18.50	14.10	2.7	9.97	3.73
10	29.30	18.60	13.90	3.1	9.99	3.73
11	23.01	17.10	13.80	3.5	9.70	3.71
12	30.02	17.02	17.10	3.9	12.67	3.72
13	30.12	17.12	16.80	4.1	12.54	3.71
14	30.22	17.32	16.50	4.3	12.36	3.74
15	34.10	17.80	16.10	4.6	12.43	3.75
Average specific heat						**3.73kJ/kg/k**

4.2 Results of Numerical and Experimental Study

One hundred twenty six experiments were conducted for estimation of freezing time by varying various variables. The results obtained from experiments and numerical analysis have been presented in the following subsections. The properties of pea grains considered in the experiments have been shown in Table 4.4. The photographs of unfrozen and frozen pea grains have been shown in Figures 4.1 and 4.2 respectively. The variation of freezing time, when the pea samples are taken under different operating conditions, has been shown in Figure 4.3 to 4.11.

Fig. 4.1 Schematic diagram of unfrozen pea grains

Fig. 4.2 Schematic diagram of frozen pea grains

Table 4.4 Parameters about pea samples (Pant Sabji Matar 3)

c_l kJ/(kgK)	c_s kJ/(kgK)	ρ kg/m^3	L kJ/(kg)	T_{final} ℃	k_l W/(mK)	k_s W/(mK)	W_o %	D mm
3.73	1.98	1037.25	263	-20	0.48	0.355	76.03	9.58

The properties, thermal conductivity and latent heat of fusion have been taken from literature (Ansari and Varma, 1985)

4.2.1 Effect of cooling air temperature on freezing time of peas

Pea samples of identical shapes were frozen under variable cooling air temperature considering initial temperature and cooling air velocity as constant. Average data of every two samples were then calculated. This average data was used for further analysis in the work. Figure 4.3 shows the variation of temperature with time during precooling, freezing and post freezing of pea samples. From Figure 4.3, it is clear that as cooling air temperature decreases, freezing rate increases and freezing time decreases.

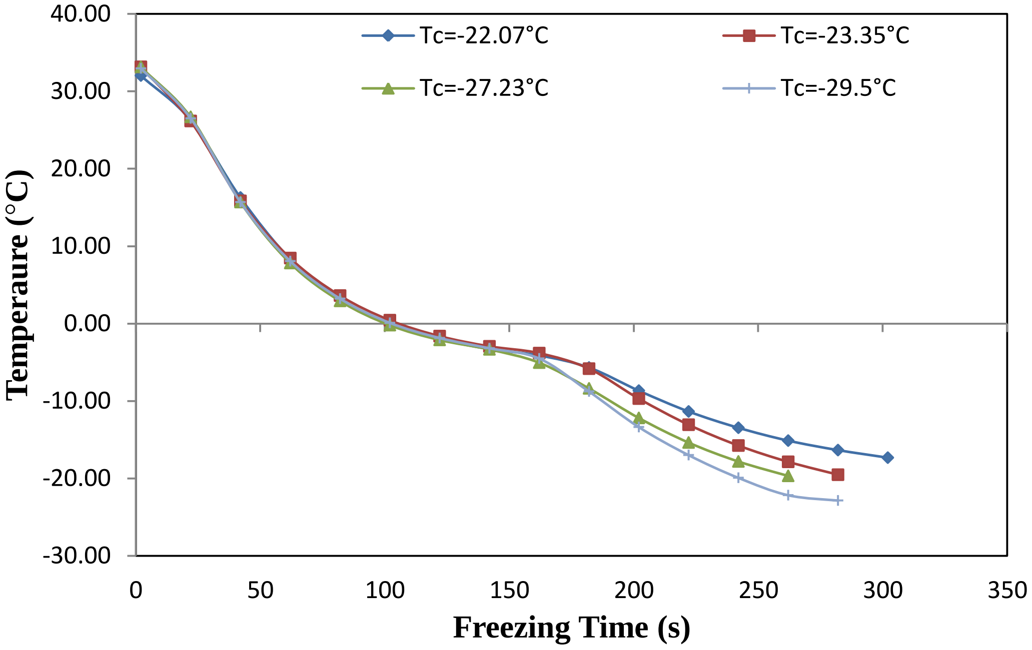

Fig. 4.3 Experimental time-temperature variation in freezing of spherical pea samples for variable cooling air temperature (T_i = 33.5°C and v = 5.2 m/s)

After conducting experiments same data as in experiments was used to calculate the freezing time of pea samples using mathematical model. Figure 4.4 shows the numerical results for each condition as taken in experimental study and shown in Figure 4.3. It also indicates that as cooling air temperature decreases, freezing rate increases and freezing time decreases. When experimental freezing times of samples were compared with numerical freezing times, maximum and minimum percentage deviation in experimental freezing time with respect to numerical freezing time is found to be 7.02% and 0.5%. It means that there is very good agreement between experimental freezing times and numerical freezing times of pea grains.

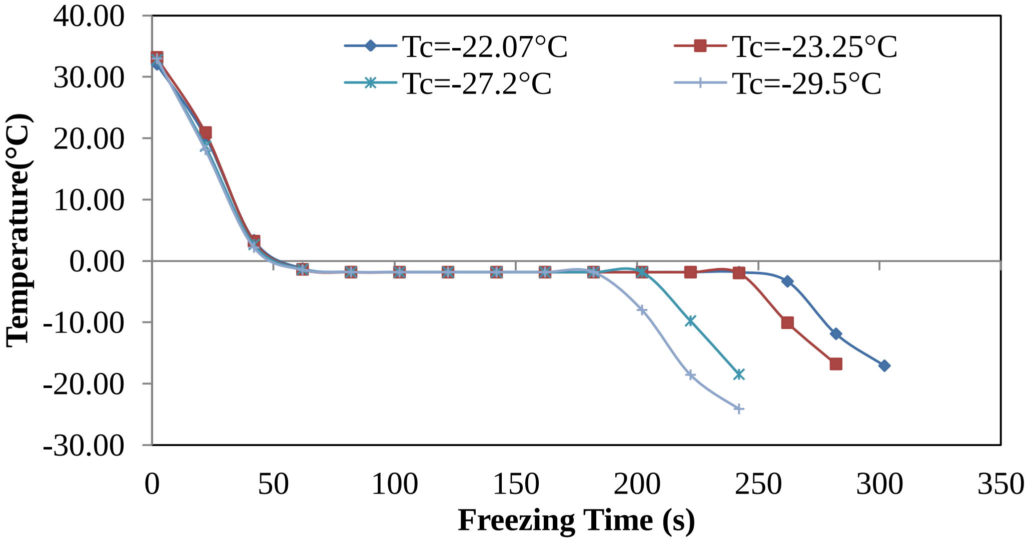

Fig. 4.4 Numerical time-temperature variation in freezing of spherical pea samples with variation of cooling air temperature (T_i = 33.5°C and v = 5.2 m/s)

Figure 4.5 shows time-temperature variations with the variation of cooling air temperature of pea samples at T_i = 33.5°C and v = 5.2 m/s as obtained from numerical and experimental methods. From the literature it is clear that the actual freezing occurs over a range of temperature which is clearly seen from the experimental temperature profiles.

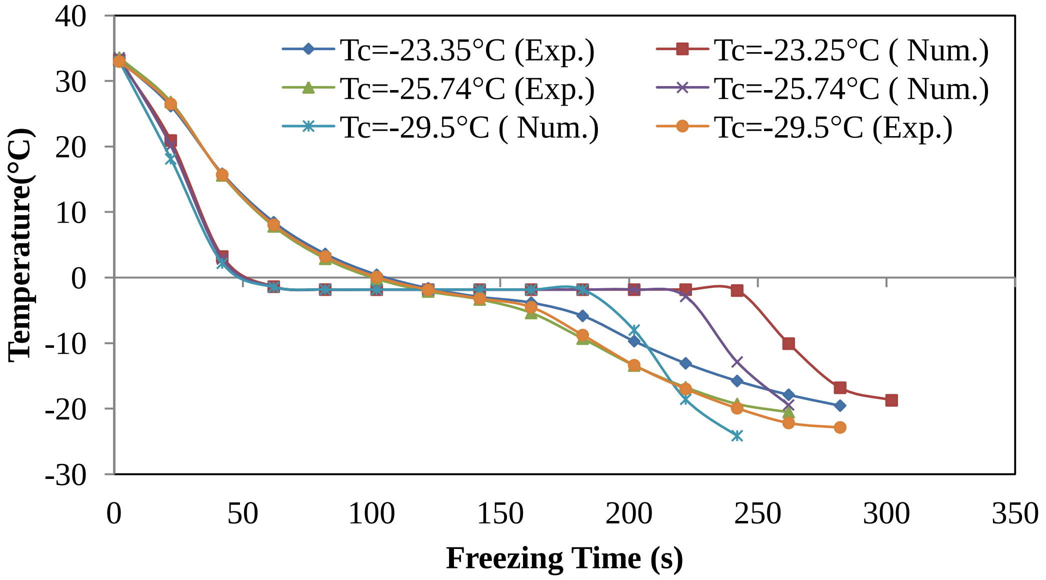

Fig. 4.5 Experimental and numerical time-temperature variation in freezing of spherical pea sample at variable cooling air temperature (T_i = 33.5°C and v=5.2 m/s)

The deviation between numerical results and experimental results at different cooling air temperatures have been given in Table 4.5. It is clear from the deviation table that minimum and maximum deviation in freezing temperatures is -13.8°C and 12.63°C for cooling air temperature of -23.35°C.

Table 4.5 Deviation between numerical and experimental freezing temperatures with time

S. No.	Operating conditions	Freezing Time (s)	Experimental Freezing Temperatures (°C)	Numerical Freezing Temperatures(°C)	Deviation (°C)
1	T_i= 33.5°C v=5.2m/s T_c=-23.35°C	22	26.17	20.92	5.25
2		42	15.85	3.22	12.63
3		62	8.46	-1.38	9.84
4		82	3.61	-1.83	5.44
5		102	0.43	-1.83	2.27
6		122	-1.62	-1.83	0.21
7		142	-2.94	-1.83	-1.11
8		162	-3.82	-1.83	-1.99
9		182	-5.83	-1.83	-4.00
10		202	-9.69	-1.83	-7.86
11		222	-13.07	-1.83	-11.24
12		242	-15.76	-1.97	-13.80
13		262	-17.87	-10.07	-7.80
14		282	-19.53	-16.80	-2.73
15		302	-21.23	-18.72	-2.51
16	T_i= 33.5°C v=5.2m/s T_c=-24.74°C	22	26.81	20.10	6.70
17		42	15.60	2.84	12.76
18		62	7.82	-1.44	9.26
19		82	2.88	-1.83	4.71
20		102	-0.20	-1.83	1.63
21		122	-2.11	-1.83	-0.28
22		142	-3.33	-1.83	-1.50
23		162	-5.39	-1.83	-3.56
24		182	-9.30	-1.83	-7.47
25		202	-13.41	-1.83	-11.58
26		222	-16.74	-2.87	-13.87
27		242	-19.28	-12.86	-6.42
28		262	-20.52	-19.43	-1.09
29					
30	T_i= 33.5°C v=5.2m/s T_c=-29.5°C	22	26.51	18.11	8.41
31		42	15.70	2.19	13.51
32		62	8.07	-1.46	9.52
33		82	3.22	-1.82	5.04
34		102	0.09	-1.83	1.92
35		122	-1.87	-1.83	-0.03
36		142	-3.19	-1.83	-1.35
37		162	-4.51	-1.83	-2.68
38		182	-8.76	-1.83	-6.93
39		202	-13.36	-8.00	-5.36
40		222	-16.99	-18.56	1.58
41		242	-19.92	-24.12	4.20
42					

A minimum deviation of -13.87°C and maximum deviation of 12.76°C has been observed for cooling air temperature of -24.74°C. A minimum deviation of -6.93°C and maximum deviation of 13.51°C has been observed for cooling air temperature of -29.5°C. The deviation between numerical and freezing times is more because freezing temperature in the model has been assumed constant where as it is variable in actual case.

4.2.2 Effect of cooling air velocity on freezing time of pea grains

Pea samples of identical shapes were frozen under variable cooling air velocity considering initial temperature and cooling air temperature as constant. Cooling air velocities were varied from 3.6 m/s to 14.5 m/s. Average data of every two samples were then calculated. This average data was used for further analysis. Figure 4.6 shows the graphical representation of time-temperature experimental data during precooling, phase change and post freezing of pea samples and from the Figure 4.6 it is clear that as cooling air velocity increases, freezing rate increases and freezing time decreases.

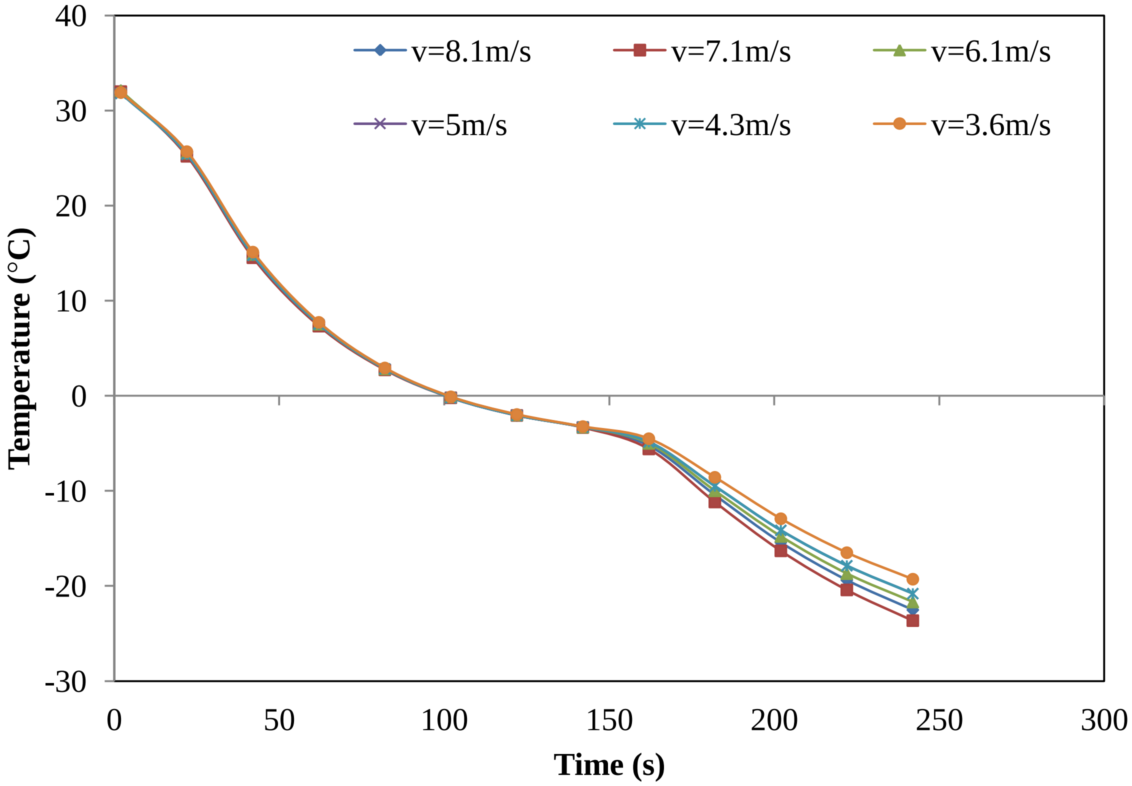

Fig. 4.6 Experimental time-temperature variation in freezing of spherical pea samples for variable cooling air velocity (T_i = 31.9°C, T_C = -28.5°C)

After conducting experiments, same data as in experiments was used to calculate the freezing time of pea samples using mathematical model. Figure 4.7 shows the numerical results for each condition as taken in Figure 4.6. Figure 4.6 also indicates that as cooling air velocity increases, freezing rate increases and freezing time decreases. When experimental freezing times of samples were compared with numerical freezing times, maximum and minimum percentage deviation in experimental freezing time with respect to numerical freezing time is found to be 8.08% and 1.85%. It means that there is very good agreement between experimental freezing times and numerical freezing times of pea grains.

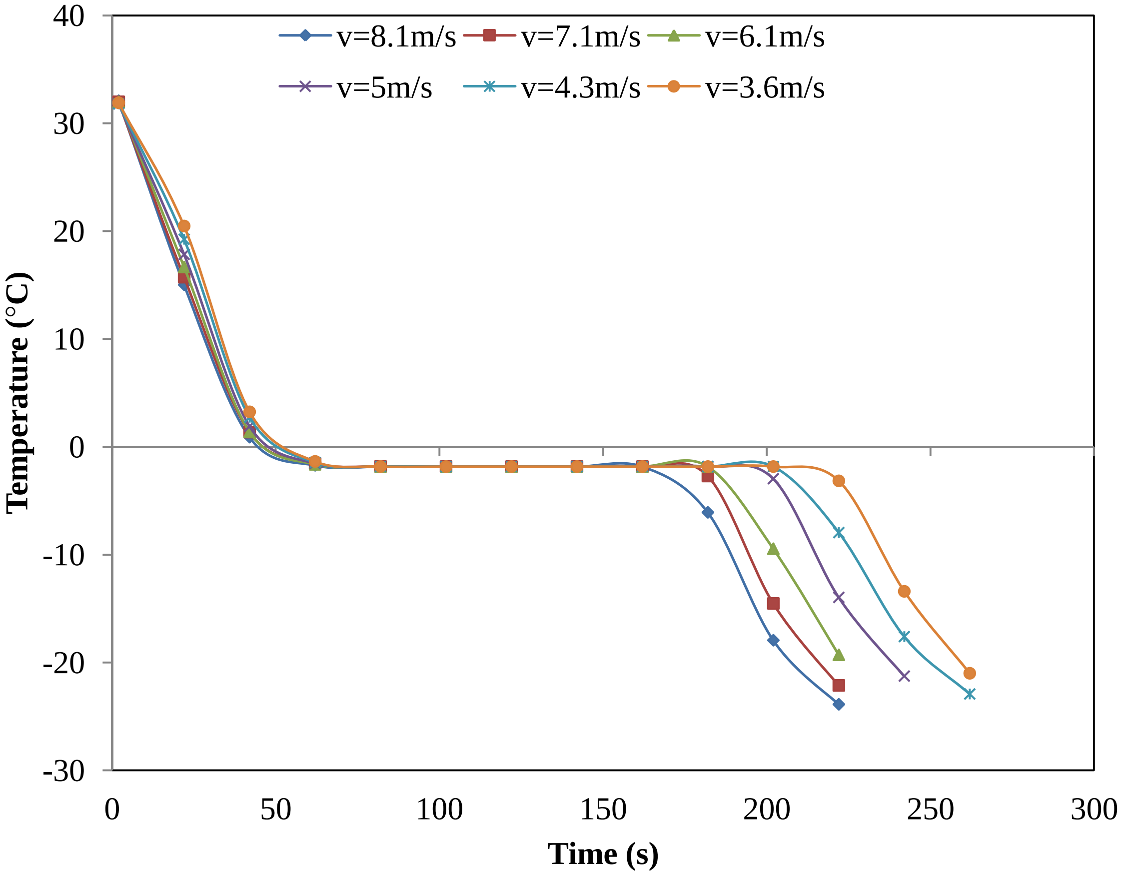

Fig. 4.7 Numerical time-temperature variation in freezing of spherical pea samples for variable cooling air velocity (T_i = 33.5°C and T_C = -28.5°C)

Figure 4.8 shows time-temperature variations with the variation of cooling air velocity of pea samples at T_i = 31.9°C and T_C= -28.5°C as obtained from numerical and experimental methods.

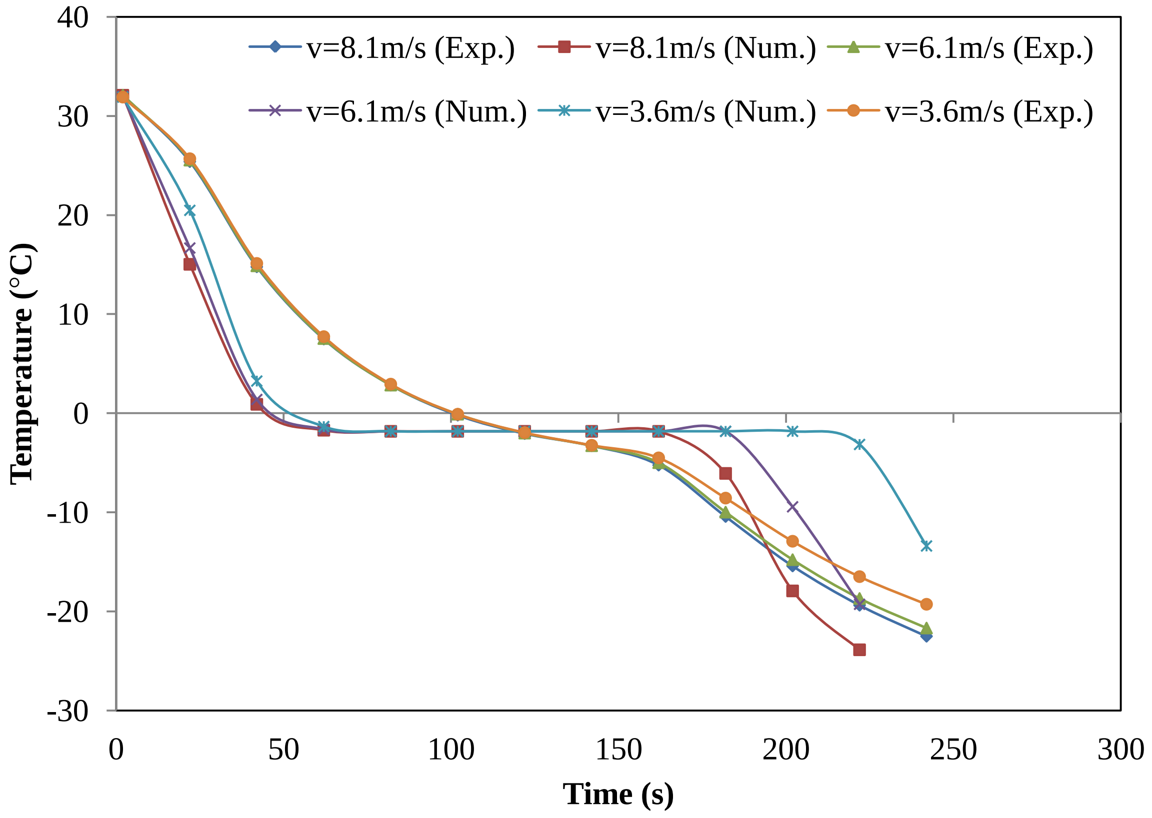

Fig. 4.8 Experimental and numerical time-temperature variation in freezing of spherical pea sample for variable cooling air velocity (T_i = 31.9°C and T_C= -28.5°C)

The deviation between freezing temperatures obtained from numerical method and experimental method at different cooling air velocities have been given in Table 4.6.

The deviation between numerical results and experimental results at different cooling air velocities have been given in Table 4.6. It is clear from the deviation table that minimum and maximum deviation in freezing temperatures is -4.35°C and 13.88°C respectively for cooling air velocity of 8.1 m/s. A minimum deviation of -8.16°C and maximum deviation of 13.49°C has been observed for cooling air velocity of 6.1 m/s. A minimum deviation of -13.34°C and maximum deviation of 11.87°C has been observed for cooling air velocity of 3.6 m/s. The deviation between numerical and freezing times is more because freezing temperature in the model has been assumed constant where as it is variable in actual case.

Table 4.6 Deviation between numerical and experimental freezing temperatures with time

S. No.	Operating conditions	Freezing Time (s)	Experimental Freezing Temperatures, T_{exp} (°C)	Numerical Freezing Temperatures, T_{num} (°C)	Deviation (°C)
1	T_i= 31.9°C v=3.6 m/s T_c=-28.5°C	2	31.9	31.9	0
2		22	25.68	20.47	5.21
3		42	15.11	3.24	11.87
4		62	7.72	-1.35	9.08
5		82	2.93	-1.83	4.76
6		102	-0.1	-1.83	1.73
7		122	-1.96	-1.83	-0.13
8		142	-3.24	-1.83	-1.4
9		162	-4.51	-1.83	-2.68
10		182	-8.57	-1.83	-6.74
11		202	-12.92	-1.83	-11.09
12		222	-16.5	-3.16	-13.34
13		242	-19.28	-13.4	-5.88
14		262	-23.2	-21	-2.2
15	T_i= 31.9°C v=6.1 m/s T_c=-28.5°C	2	32.09	31.98	0.12
16		22	25.54	16.67	8.87
17		42	14.87	1.38	13.49
18		62	7.53	-1.63	9.16
19		82	2.83	-1.83	4.66
20		102	-0.10	-1.83	1.73
21		122	-2.01	-1.83	-0.18
22		142	-3.28	-1.83	-1.45
23		162	-5.00	-1.83	-3.16
24		182	-9.99	-1.83	-8.16
25		202	-14.78	-9.45	-5.33
26		222	-18.70	-19.29	0.59
27		242	-21.68		
28	T_i= 31.9°C v=8.1 m/s T_c=-28.5°C	2	32.09	32.08	0.01
29		22	25.39	15.02	10.37
30		42	14.77	0.89	13.88
31		62	7.48	-1.72	9.20
32		82	2.83	-1.83	4.66
33		102	-0.20	-1.83	1.63
34		122	-2.06	-1.83	-0.23
35		142	-3.28	-1.83	-1.45
36		162	-5.24	-1.83	-3.41
37		182	-10.43	-6.08	-4.35
38		202	-15.42	-17.94	2.52
39		222	-19.38	-23.88	4.50

4.2.3 Effect of initial temperature on freezing time of pea grains

Pea samples of identical shapes were frozen under variable initial temperature considering cooling air velocity and cooling air temperature as constant. Initial temperature of samples was varied from 21°C to 34.2°C. Average data of every two samples was calculated. This average data was used for further analysis. Figure 4.9 shows the graphical representation of experimental data during precooling, phase change and post freezing of pea samples. From Figure 4.9 it is clear that as cooling air velocity increases, freezing rate increases and freezing time decreases.

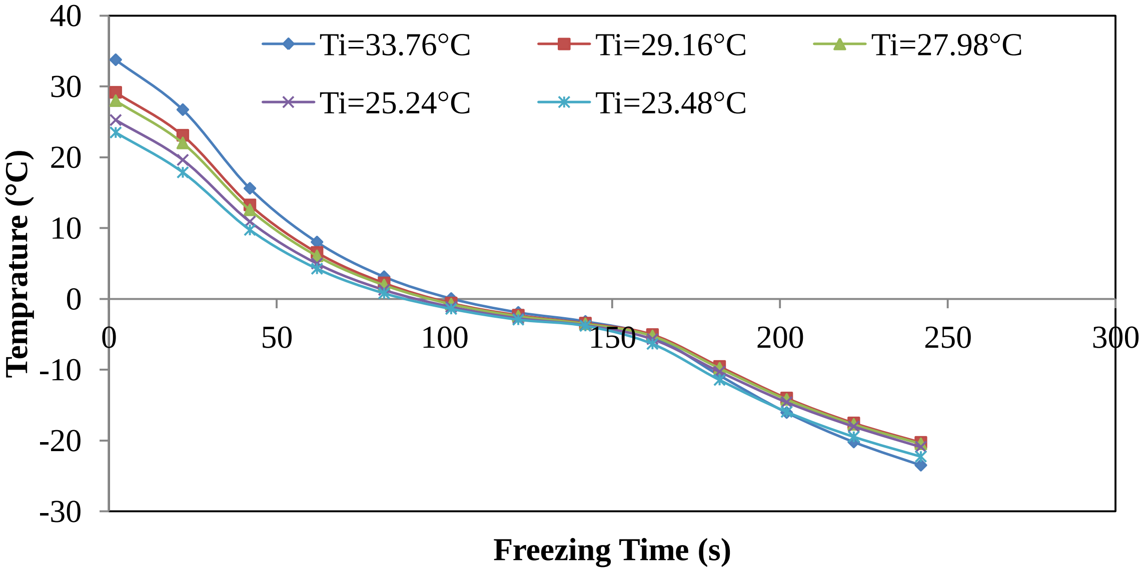

Fig. 4.9 Experimental time-temperature variation in freezing of spherical pea samples for variable initial temperature (v=5.5 m/s and T_C = -28.6°C)

After conducting experiments same data as in experiments was used to calculate the freezing time of pea samples using mathematical model. Figure 4.10 shows the numerical results for each condition as taken in Figure 4.9 respectively. It also indicates that as initial temperature increases, freezing rate decreases and freezing time increases. When experimental freezing times of samples were compared with numerical freezing times, maximum and minimum percentage deviation in experimental freezing time with respect to numerical freezing time is found to be 5.56% and 0.44%. It means that there is very good agreement between experimental freezing times and numerical freezing times of pea grains.

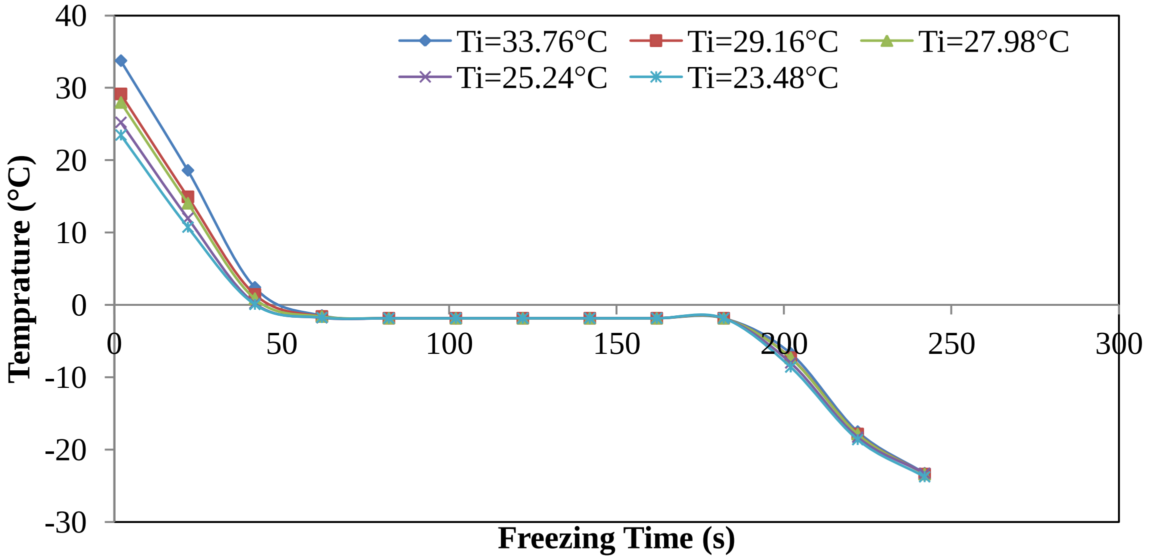

Fig. 4.10 Numerical time-temperature variation in freezing of spherical pea samples for variable initial temperature (v=5.5 m/s and T_C = -28.6°C)

Figure 4.11 shows time-temperature variations with the variation of initial temperature of pea samples at v=5.5 m/s and T_C= -28.5°C as obtained from numerical and experimental methods.

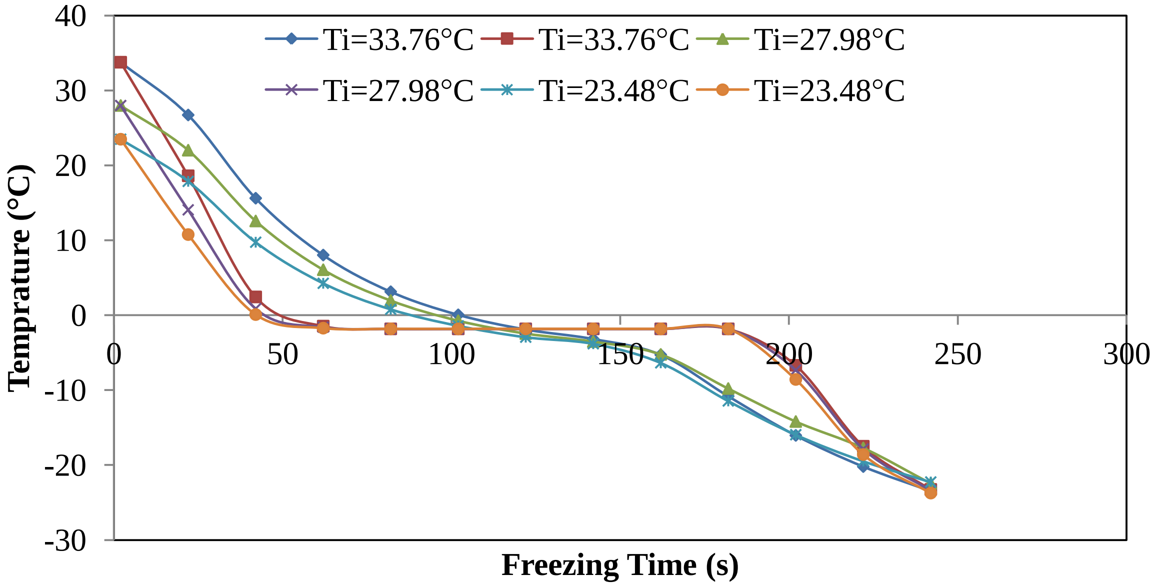

Fig. 4.11 Experimental and numerical time-temperature variation in freezing of spherical pea sample for variable initial temperature (v = 5.5 m/s and T_C= -28.5°C)

The deviation between freezing temperatures obtained from numerical method and experimental method at different initial temperatures have been given in Table 4.7.

Table 4.7 Deviation between numerical and experimental freezing temperatures with time

S. No.	Operating conditions	Freezing Time (s)	Experimental Freezing Temperatures, T_{exp} (°C)	Numerical Freezing Temperatures, T_{num} (°C)	Deviation (°C)
1	v = 5.5 m/s T_C= -28.5°C T_i= 33.76°C	2	33.76	33.76	0.00
2		22	26.71	18.60	8.11
3		42	15.60	2.43	13.18
4		62	8.02	-1.47	9.48
5		82	3.13	-1.83	4.96
6		102	0.04	-1.83	1.88
7		122	-1.91	-1.83	-0.08
8		142	-3.19	-1.83	-1.35
9		162	-5.29	-1.83	-3.46
10		182	-10.82	-1.83	-8.99
11		202	-16.06	-6.70	-9.36
12		222	-20.21	-17.50	-2.71
13		242	-23.49	-23.26	-0.23
14	v = 5.5 m/s T_C= -28.5°C T_i= 27.98°C	2	27.98	27.98	0.01
15		22	22.01	14.05	7.96
16		42	12.57	0.87	11.70
17		62	6.06	-1.60	7.66
18		82	1.95	-1.83	3.78
19		102	-0.74	-1.83	1.09
20		122	-2.45	-1.83	-0.62
21		142	-3.53	-1.83	-1.70
22		162	-5.24	-1.83	-3.41
23		182	-9.79	-1.83	-7.96
24		202	-14.20	-7.32	-6.87
25		222	-17.72	-17.85	0.13
26		242	-22.46	-23.38	0.92
27	v = 5.5 m/s T_C= -28.5°C T_i= 23.48°C	2	23.48	23.48	0.00
28		22	17.85	10.75	7.10
29		42	9.73	0.07	9.66
30		62	4.25	-1.74	5.99
31		82	0.78	-1.83	2.61
32		102	-1.43	-1.83	0.41
33		122	-2.94	-1.83	-1.11
34		142	-3.82	-1.83	-1.99
35		162	-6.37	-1.83	-4.53
36		182	-11.46	-1.83	-9.62
37		202	-15.96	-8.58	-7.37
38		222	-19.48	-18.61	-0.87
39		242	-22.27	-23.75	1.48

It is clear from the deviation table that minimum and maximum deviation in freezing temperatures is -9.36°C and 13.76°C respectively for initial temperatures of 33.76°C. A minimum deviation of -7.96°C and maximum deviation of 11.7°C has been observed for initial temperatures of 27.98°C. A minimum deviation of -9.62°C and maximum deviation of 9.66°C has been observed for initial temperatures of 23.48°C. The deviation between numerical and freezing times is more because freezing temperature in the model has been assumed constant where as it is variable in actual case.

4.3 Prediction of Time-Temperature Variations of Peas using Numerical Model with Variable Freezing Temperature and Comparison with experimental Results

Figures 4.12 and 4.13 show the mathematical results of case–II and experimental results under various operating conditions. Figure 4.12 shows the numerical time-temperature variation for variable cooling air temperatures. It also indicates that as cooling air temperature decreases, freezing rate increases and freezing time decreases.

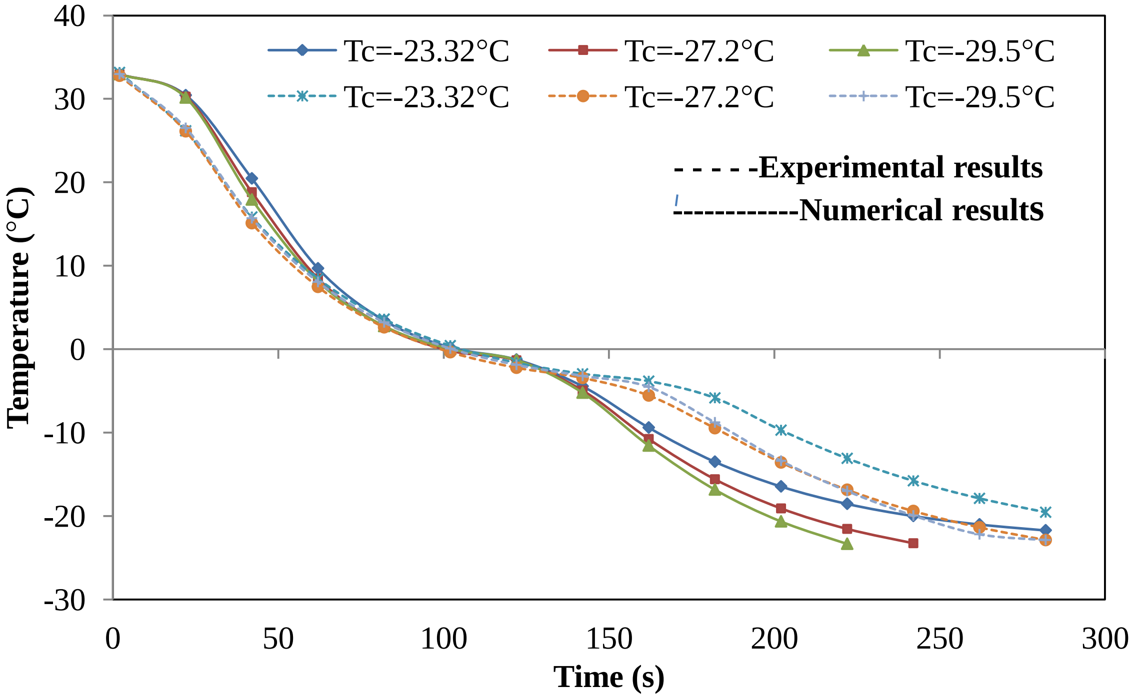

Fig. 4.12 Numerical time-temperature variation in freezing of spherical pea samples for variable cooling air temperature using numerical model of variable freezing temperature (v=5.2 m/s and T_i = 32.97°C)

Figure 4.13 shows the numerical time-temperature variation with variation in cooling air velocity. It also indicates that as cooling air velocity increases, freezing rate increases and freezing time decreases. For different initial temperature of peas, there were insignificant variations in the temperature profiles as well in freezing times. Therefore time-temperature variations for variable initial temperature are not plotted for this case.

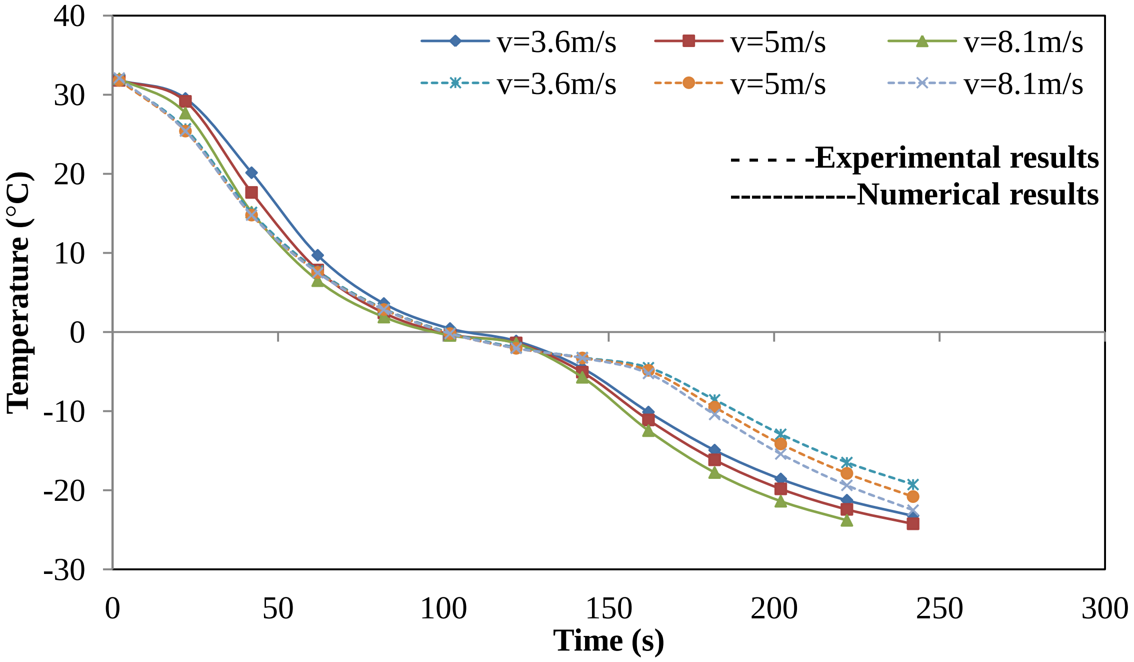

Fig. 4.13 Numerical time-temperature variation in freezing of spherical pea samples for variable cooling air velocity using numerical model of variable freezing temperature (T_i =32°C and T_c = -28.5°C)

4.4 Comparison of Numerical and Experimental Temperature-Time Variation

It is clear from review of literature (Jain et al., 1981) that almost all of the food products have water content in range 50% to 90%. From the experimental results, given in Section 4.1.2, the moisture content in the pea samples taken in this study has been found to be 76.03%. The thermo-physical properties of food products are greatly affected by water content so these vary slightly in frozen state. The freezing point temperature of food products decreases because water part in food commodities is always in bond state with the dispersed food which is in matrix form and percentage concentration of unfrozen (dispersed) food increases as the water content in the food freezes. Figures 4.12 and 4.13 show the variation in freezing point of peas as pea grains move toward the final freezing state. The deviations, between experimental results and numerical results with variable freezing point, are given in Tables 4.8 and 4.9.

4.4.1 Comparison of numerical and experimental temperature-time variation for variable cooling air temperature

The deviation between freezing temperatures obtained from numerical model of variable freezing temperatures and experimental method at different cooling air temperature have been given in Table 4.8.

Table 4.8 Deviation between numerical and experimental freezing temperatures with time

S. No.	Operating conditions	Freezing Time (s)	Experimental Freezing Temperatures, T_{exp} (°C)	Numerical Freezing Temperatures, T_{num} (°C)	Deviation (°C)
1	v = 5.2 m/s T_C= -23.3°C T_i= 32.97°C	2	33.17	32.97	0.20
2		22	26.17	30.44	-4.27
3		42	15.85	20.47	-4.63
4		62	8.46	9.70	-1.24
5		82	3.61	3.45	0.16
6		102	0.43	0.22	0.21
7		122	-1.62	-1.23	-0.39
8		142	-2.94	-4.42	1.48
9		162	-3.82	-9.38	5.55
10		182	-5.83	-13.47	7.64
11		202	-9.69	-16.43	6.74
12		222	-13.07	-18.51	5.44
13		242	-15.76	-19.97	4.21
14		262	-17.87	-20.98	3.12
15		282	-19.53	-21.69	2.16
16	v = 5.2 m/s T_C= -27.2°C T_i= 32.97°C	2	32.78	32.97	-0.19
17		22	26.12	30.27	-4.14
18		42	15.11	18.82	-3.71
19		62	7.48	8.48	-1.00
20		82	2.64	2.72	-0.09
21		102	-0.35	-0.18	-0.17
22		122	-2.21	-1.32	-0.88
23		142	-3.43	-4.93	1.50
24		162	-5.54	-10.75	5.22
25		182	-9.45	-15.58	6.13
26		202	-13.56	-19.07	5.51
27		222	-16.84	-21.53	4.69
28		242	-19.38	-23.24	3.86
29	v = 5.2 m/s T_C= -29.5°C T_i= 32.97°C	2	32.97	32.97	0.01
30		22	26.51	30.16	-3.65
31		42	15.70	17.95	-2.25
32		62	8.07	8.15	-0.08
33		82	3.22	2.78	0.44
34		102	0.09	0.04	0.05
35		122	-1.87	-1.28	-0.58
36		142	-3.19	-5.19	2.01
37		162	-4.51	-11.53	7.02
38		182	-8.76	-16.80	8.04
39		202	-13.36	-20.62	7.25
40		222	-16.99	-23.30	6.32

It is clear from the deviation table that minimum and maximum deviation in freezing temperatures is -4.63°C and 7.64°C for cooling air temperature of -23.35°C. A minimum deviation of -4.14°C and maximum deviation of 6.13°C has been observed for cooling air temperature of –27.2°C. A minimum deviation of -3.65°C and maximum deviation of 8.04°C has been observed for cooling air temperature of -29.5°C.

4.4.2 Comparison of numerical and experimental temperature-time variation for variable cooling air velocity

The deviation between freezing temperatures obtained from numerical model of variable freezing temperature and experimental method at different cooling air velocities have been given in Table 4.9.

Table 4.9 Deviation between numerical and experimental freezing temperatures with time

S. No.	Operating conditions	Freezing Time (s)	Experimental Freezing Temperatures, T_{exp}(°C)	Numerical Freezing Temperatures, T_{num} (°C)	Deviation (°C)
1	v = 3.6 m/s T_C= -28.8°C T_i= 32.1°C	2	31.90	31.80	0.10
2		22	25.68	29.51	-3.83
3		42	15.11	20.13	-5.01
4		62	7.72	9.69	-1.97
5		82	2.93	3.60	-0.67
6		102	-0.10	0.44	-0.54
7		122	-1.96	-1.14	-0.83
8		142	-3.24	-4.56	1.33
9		162	-4.51	-10.11	5.61
10		182	-8.57	-14.93	6.36
11		202	-12.92	-18.57	5.65
12		222	-16.50	-21.26	4.76
13		242	-19.28	-23.22	3.93
14	v = 5 m/s T_C= -28.8°C T_i= 32.1°C	2	31.80	31.80	0.00
15		22	25.39	29.14	-3.75
16		42	14.77	17.63	-2.86
17		62	7.53	7.83	-0.30
18		82	2.83	2.41	0.42
19		102	-0.20	-0.31	0.11
20		122	-2.06	-1.38	-0.68
21		142	-3.28	-5.08	1.79
22		162	-4.85	-11.12	6.26
23		182	-9.50	-16.15	6.66
24		202	-14.15	-19.82	5.68
25		222	-17.87	-22.42	4.55
26		242	-20.80	-24.24	3.44
27	v = 8.1 m/s T_C= -28.8°C	2	32.09	31.99	0.10
28		22	25.39	27.66	-2.27
29		42	14.77	15.14	-0.37
30		62	7.48	6.49	0.99
31		82	2.83	1.88	0.95
32		102	-0.20	-0.44	0.24
33		122	-2.06	-1.45	-0.62

34	T_i= 32.1°C	142	-3.28	-5.73	2.44
35		162	-5.24	-12.47	7.23
36		182	-10.43	-17.76	7.33
37		202	-15.42	-21.39	5.97
38		222	-19.38	-23.80	4.42

It is clear from the deviation table that minimum and maximum deviation in freezing temperatures is -5.01°C and 6.36°C respectively for cooling air temperature of 3.6m/s. A minimum deviation of -3.73°C and maximum deviation of 6.66°C has been observed for cooling air velocity of 5 m/s. A minimum deviation of -2.27°C and maximum deviation of 7.33°C has been observed for cooling air velocity of 8.1 m/s. The results indicate that at higher velocities numerical model over predicts the freezing temperature in post freezing zone.

4.5 Development of an Empirical Relation

An empirical relation of freezing time of peas has been developed as a function of operating variables viz. cooling air temperature, initial temperature of pea grains and cooling air velocity by the regression analysis of a large set of experimental results. The relation has been given in Equation (4.1). It is seen from Equation (4.1) that freezing time of pea grains has parabolic relations with cooing air temperature while linear relationship with initial temperature whereas freezing time varies with cooling air velocity of degree 2.5. The empirical relation applies to peas of diameters between 9.4 mm to 9.9 mm.

$$\boldsymbol{t = -0.16v^{2.5} + 0.1T_C^2 + 9.814T_C + 0.1275T_i + 450} \qquad (\mathbf{4.1})$$

This empirical relation gives best results for following conditions:

$$\boldsymbol{-32}℃ \leq \boldsymbol{T_C} \leq \boldsymbol{-26}℃$$

$$\boldsymbol{21}℃ \leq \boldsymbol{T_i} \leq \boldsymbol{34}℃$$

$$\boldsymbol{5.5m/s \leq v \leq 8m/s}$$

4.6 Relative Comparison among Experimental Freezing Times, Predicted Freezing Times by Numerical Model and Predicted Freezing Times by Empirical Relation

The comparison between experimental freezing times, predicted freezing times by numerical model and predicted freezing times by empirical relation are discussed here. These comparisons are shown by Figures 4.14 to 4.17.

Figure 4.14 shows that all the three curves are close to each other. It means that there is very good agreement in the three freezing times. Table A2 in Appendix A shows the three freezing times for variable cooling air temperatures.

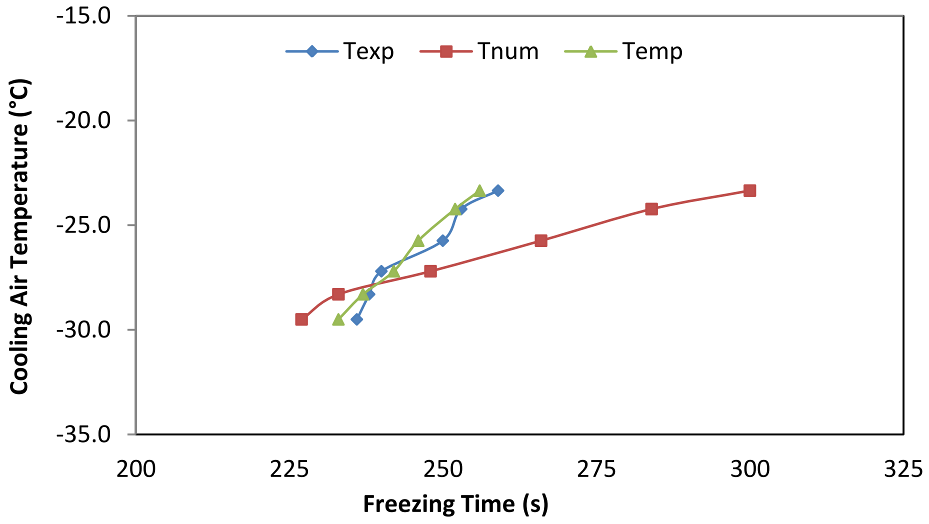

Fig. 4.14 Experimental, numerical and empirical time-temperature variation in freezing of spherical pea samples at T_i = 33.17 °C, v = 5.2 m/s

4.6.1 Comparison of experimental freezing time and predicted freezing times

Table A3 in Appendix A shows the three freezing times for variable operating conditions. Figure 4.14 shows the comparison between experimental freezing time and predicted freezing time using numerical model. The correlation coefficient of linear regression, R^2, is 0.966 which denotes that both the freezing times are in good agreement. The maximum and minimum errors in numerical freezing time are 5.17% and 5.04% respectively.

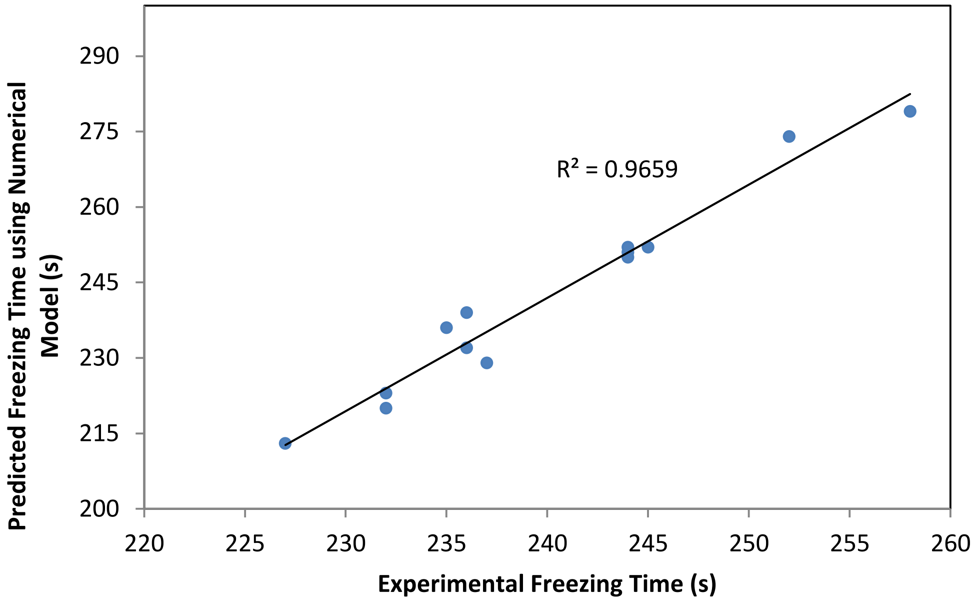

Fig. 4.15 Comparison between experimental freezing time and predicted freezing time using numerical model

Figure 4.16 shows the comparison between experimental freezing time and predicted freezing time using empirical relation. The correlation coefficient of linear regression, R^2, is 0.985 which denotes that both the freezing times are in good agreement. The maximum and minimum errors in empirical freezing time are 1.55% and 0.43% respectively.

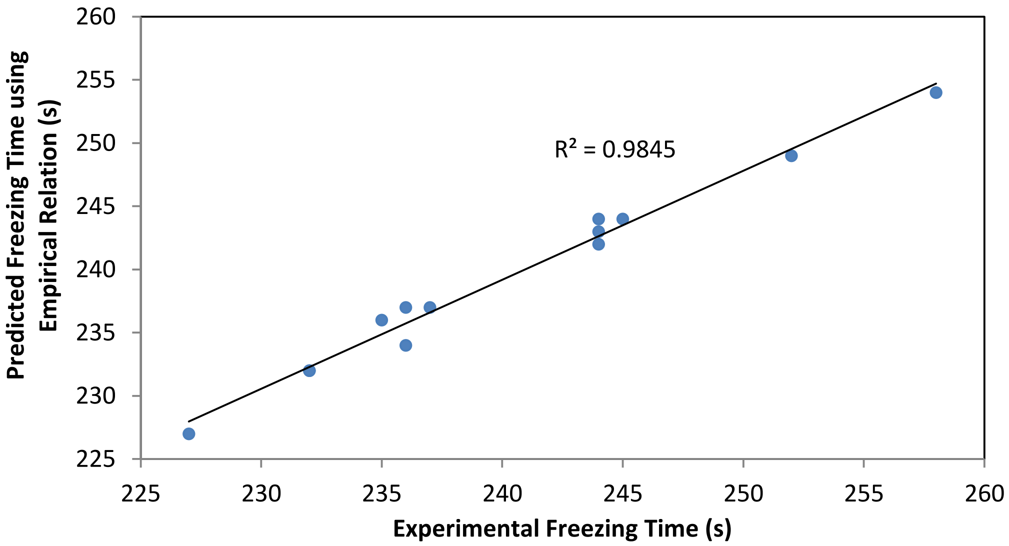

Fig. 4.16 Comparison between experimental freezing time and predicted freezing time using empirical relation

Summary
and
Conclusions

Chapter 5

SUMMARY AND CONCLUSIONS

5.1 Summary

Freezing temperature-time study for peas has been carried out by numerical and experimental methods in this work. Effect of different parameters, viz. cooling air temperature, cooling air velocity and initial temperature, on freezing times has also been studied besides the properties of peas.

Various thermo-physical properties of peas, viz. specific heat, density, moisture content etc., were determined using conventional methods. These properties were used for further calculations and analysis. Numerical models, with removal of latent heat of fusion at constant temperature and at variable temperature, were developed. To solve partial differential equation of conduction heat transfer in spherical coordinate, Crank Nicolson method was used. An experimental setup was designed and fabricated and freezing times of pea samples, under different operating conditions, were recorded thereafter. Freezing time calculated by numerical model, case-II, with variable freezing point, agrees very well with experimental data. Based on the experimental results, an empirical relation of freezing time as a function of cooling air temperature, cooling air velocity and initial temperature, was developed. Regression analysis, of experimental freezing times was carried out to develop an empirical relation as a function of three parameters, viz. cooling air velocity, initial temperature and cooling air velocity. Freezing times predicted by empirical relation were in good agreement with experimental data.

5.2 Conclusions

The present work, on the freezing time estimation of peas by experimental and numerical methods, can be concluded as follows:

a) Thermo-physical properties (specific heat, density, moisture content etc.) of green peas were determined. Specific heat, density and moisture content of peas were found to be 3.73 kJ/(kg-K), 1037.25 kg/m^3 and 76.03% respectively.
b) Numerical models for freezing time estimation of peas were developed. In first model latent heat of fusion was assumed to be removed at constant temperature and in second model, latent heat of fusion was considered to be removed at successively lower freezing points which are in the case of actual freezing.

c) The numerical model for freezing time estimation of peas was validated successfully with Zhengfu et al. [2007] for beef meatball.

d) An experimental setup was designed and fabricated to calculate experimental freezing times of pea samples. The effect of three operating parameters, viz. cooling air temperature, cooling air velocity and initial temperature of peas, was studied on freezing times.

e) The freezing temperatures measured from experiments were compared with the temperatures predicted by numerical model, case-I (removal of latent heat of fusion at constant temperature) over a range of freezing time. Following conclusions were drawn from this study:

   I) For variable cooling air temperature, maximum and minimum deviation in experimental freezing times with numerical freezing times were found 13.51°C and -13.87°C respectively. Other conditions are; initial temperature =33.5°C and cooling air velocity= 5.2 m/s.

   II) For variable cooling air velocity, maximum and minimum deviation in experimental freezing time with numerical freezing time was found 13.88°C and -13.34°C respectively. Other conditions are; initial temperature =31.9°C and cooling air temperature= -28.5°C.

   III) For variable initial temperature, maximum and minimum deviation in experimental freezing time with numerical freezing time was found 13.18°C and -9.66°C respectively. Other conditions are; cooling air temperature= -28.5°C and cooling air velocity= 5.5 m/s.

f) The freezing temperatures measured in experiments were compared with the temperatures predicted numerical model, case-II (removal of latent heat of fusion at variable temperature) over a range of freezing time. Following conclusions were drawn from this study:

   IV) For variable cooling air temperature, maximum and minimum deviation in experimental freezing times with numerical freezing times were found 8.04°C and -4.63°C respectively. Other conditions are; initial temperature =32.97°C and cooling air velocity= 5.2 m/s.

   I) For variable cooling air velocity, maximum and minimum deviation in experimental freezing time with numerical freezing time was found

7.33°C and -5.01°C respectively. Other conditions are; initial temperature =32.1°C and cooling air temperature= -28.8°C.

g) On the basis of experimental results, an empirical relation of freezing time as a function of cooling air temperature, cooling air velocity and initial temperature, was developed. The empirical relation provides best results within $-32℃ \leq \mathrm{T_C} \leq -26℃$, $21℃ \leq \mathrm{T_i} \leq 34℃$ and $5.5\ \mathrm{m/s} \leq \mathrm{v} \leq 8\ \mathrm{m/s}$ with very good accuracy.

h) The results obtained from empirical relation were compared with experimental results and numerical results.

Thus it was concluded that predicted results using numerical model and predicted results using empirical relation gave very good agreement when compared with experimental results.

5.3 Recommendations for future work

The present work leaves a huge extent of research work for the future generation of researchers to come. Some suggestions for the future work are as given below:

a) This work can be extended for studying freezing of packets of peas because packets of peas are frozen practically instead of individual pea grains.

b) Empirical relations for freezing times for other foods can be developed.

c) The same work can be extended for irregular shaped food products.

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Appendices

APPENDIX A

Table A1. Calibration of data logger

Time (min)	Probe 1 (°C)	Probe 2 (°C)	Probe 3 (°C)	Probe 4 (°C)	Probe 5 (°C)	Thermometer readings (°C)	Average data logger values (°C)
0	28.5	28.8	28.6	29.2	29.1	29.2	28.84
10	26	26.5	26.2	27.1	27	27.1	26.56
20	23.1	23.5	23.5	24.5	24.5	24.6	23.82
30	19.3	19.8	19.7	20.8	20.8	20.9	20.08
40	16.5	17	16.9	17.9	18	18.1	17.26
50	13.9	14.3	14.4	15.3	15.4	15.5	14.66
60	11.6	12.2	12.3	13	13.1	13.2	12.44
70	9.5	10.1	10.1	10.9	11	11.1	10.32
80	7.9	8.1	8.1	9	9.1	9.2	8.44
90	6.2	6.6	6.4	7.2	7.3	7.4	6.74
100	4.4	5	4.9	5.6	5.7	5.8	5.12
110	3.1	3.6	3.7	4.3	4.3	4.4	3.8
120	2	1.4	2	3.4	3.1	3.2	2.38
130	0.4	0.6	0.6	2.5	2.6	2.7	1.34
140	-0.2	0	0	1.8	1.8	1.9	0.68
150	-0.7	-0.3	-0.5	1.1	1.1	1.2	0.14
160	-1	-0.7	-0.7	0.5	0.5	0.6	-0.28
170	-1.1	-0.7	-0.9	0.1	0.2	0.3	-0.48
180	-1.2	-0.9	-0.9	0	0	0.1	-0.6
190	-1.3	-1	-1	-0.3	-0.1	-0.1	-0.74
200	-1.3	-1.1	-1.1	-0.3	-0.1	-0.1	-0.78
210	-1.4	-1.1	-1.2	-0.5	-0.3	-0.3	-0.9
220	-1.5	-1.1	-1.2	-0.5	-0.3	-0.3	-0.92
230	-1.5	-1.2	-1.3	-0.5	-0.3	-0.3	-0.96
240	-1.6	-1.2	-1.3	-0.5	-0.3	-0.3	-0.98
250	-1.6	-1.2	-1.4	-0.5	-0.3	-0.3	-1
260	-1.7	-1.3	-1.5	-0.5	-0.3	-0.3	-1.06
270	-1.8	-1.3	-1.5	-0.5	-0.4	-0.4	-1.1
280	-1.8	-1.3	-1.6	-0.5	-0.4	-0.4	-1.12
290	-1.9	-1.1	-1.7	-0.5	-0.4	-0.4	-1.12
300	-2	-1.2	-1.8	-0.5	-0.4	-0.4	-1.18
310	-2.1	-1.3	-1.9	-0.5	-0.4	-0.4	-1.24
320	-2.2	-1.4	-2.1	-0.5	-0.4	-0.4	-1.32
330	-2.3	-1.5	-2.2	-0.5	-0.4	-0.4	-1.38

340	-2.4	-1.5	-2.3	-0.5	-0.4	-0.4		-1.42
350	-2.5	-1.6	-2.5	-0.5	-0.4	-0.4		-1.5
360	-2.7	-1.8	-2.6	-0.5	-0.5	-0.5		-1.62
370	-2.9	-2.1	-2.8	-0.5	-0.5	-0.5		-1.76
380	-3	-2.3	-3	-0.5	-0.5	-0.5		-1.86
390	-3.2	-2.5	-3.2	-0.5	-0.5	-0.5		-1.98
400	-3.4	-2.7	-3.4	-0.5	-0.5	-0.5		-2.1
410	-3.5	-2.9	-3.5	-0.5	-0.5	-0.5		-2.18
420	-3.6	-3.2	-3.6	-0.5	-0.5	-0.5		-2.28
430	-3.8	-3.4	-3.8	-0.5	-0.5	-0.5		-2.4
440	-3.9	-3.6	-3.9	-0.5	-0.5	-0.5		-2.48
450	-4.1	-3.8	-4	-0.5	-0.5	-0.5		-2.58
460	-4.2	-4.1	-4.2	-0.5	-0.5	-0.5		-2.7
470	-4.3	-4.3	-4.3	-0.5	-0.5	-0.5		-2.78
480	-4.5	-4.6	-4.5	-0.6	-0.6	-0.6		-2.96
490	-4.7	-4.9	-4.7	-0.6	-0.6	-0.6		-3.1
500	-4.9	-5.2	-4.8	-0.7	-0.6	-0.6		-3.24
510	-5	-5.6	-4.9	-0.7	-0.7	-0.7		-3.38
520	-5.2	-5.9	-5.1	-0.7	-0.7	-0.7		-3.52
530	-5.4	-6.2	-5.2	-0.9	-0.8	-0.8		-3.7
540	-5.6	-6.6	-5.4	-1	-0.9	-0.9		-3.9
550	-5.8	-7	-5.6	-1.1	-1.1	-1.1		-4.12
560	-6	-7.4	-5.8	-1.3	-1.4	-1.4		-4.38
570	-6.2	-7.8	-6	-1.6	-1.7	-1.7		-4.66
580	-6.5	-8.1	-6.2	-1.9	-2.1	-2.1		-4.96
590	-6.8	-8.5	-6.4	-2.3	-2.7	-2.7		-5.34
600	-7	-8.9	-6.7	-2.8	-3.2	-3.2		-5.72
610	-7.4	-9.3	-6.9	-3.4	-3.9	-3.9		-6.18
620	-7.7	-9.7	-7.2	-4	-4.5	-4.5		-6.62
630	-8.1	-10.1	-7.4	-4.7	-5.2	-5.2		-7.1
640	-8.5	-10.6	-7.8	-5.5	-6	-6.0		-7.68
650	-8.9	-11	-8.1	-6.3	-6.7	-6.7		-8.2
660	-9.3	-11.5	-8.4	-7.2	-7.5	-7.5		-8.78
670	-9.9	-12	-9	-8.3	-8.1	-8.1		-9.46
680	-10.9	-12.7	-10.5	-10.3	-9.2	-9.2		-10.72
690	-11.9	-13.6	-11.7	-11.7	-10.3	-10.3		-11.84

700	-12.9	-14.5	-12.7	-12.8	-11.4	-11.4		-12.86
710	-13.7	-15.2	-13.6	-13.8	-12.3	-12.3		-13.72
720	-14.5	-16.1	-14.3	-14.5	-13.2	-13.2		-14.52
730	-15.3	-16.8	-15.8	-15.3	-14.1	-14.1		-15.46
740	-16.2	-16.9	-16.4	-15.8	-15.4	-15.4		-16.14
750	-16.9	-17.3	-17	-17.4	-16.9	-16.9		-17.1
760	-17.3	-17.6	-17.4	-17.5	-17.2	-17.2		-17.4
770	-17.8	-17.9	-17.8	-17.4	-17.2	-17.2		-17.62
780	-18.2	-18.3	-18.2	-17.9	-17.7	-17.7		-18.06
790	-18.6	-18.7	-18.6	-18.3	-18.1	-18.1		-18.46
800	-18.9	-19	-18.9	-18.7	-18.5	-18.5		-18.8
810	-19.3	-19.4	-19.2	-19	-18.8	-18.8		-19.14
820	-19.6	-19.8	-19.6	-19.4	-19.2	-19.2		-19.52
830	-20	-20	-19.9	-19.7	-19.5	-19.5		-19.82
840	-20.2	-20.3	-20.2	-20	-19.8	-19.8		-20.1
850	-20.5	-20.5	-20.4	-20.2	-20	-20.0		-20.32
860	-20.7	-20.8	-20.7	-20.5	-20.3	-20.3		-20.6
870	-20.9	-21	-20.9	-20.7	-20.5	-20.5		-20.8
880	-21.1	-21.2	-21.1	-21	-20.8	-20.8		-21.04
890	-21.3	-21.4	-21.3	-21.1	-20.9	-20.9		-21.2
900	-21.4	-21.5	-21.4	-21.3	-21.1	-21.1		-21.34
910	-21.6	-21.7	-21.6	-21.4	-21.2	-21.2		-21.5
920	-21.7	-21.8	-21.7	-21.6	-21.3	-21.3		-21.62
930	-21.8	-21.9	-21.8	-21.7	-21.5	-21.5		-21.74
940	-21.9	-22	-21.9	-21.8	-21.6	-21.6		-21.84
950	-22	-22.1	-22	-21.9	-21.6	-21.6		-21.92
960	-22	-22.1	-22	-21.9	-21.7	-21.7		-21.94
970	-22.1	-22.2	-22.1	-22	-21.8	-21.8		-22.04
980	-22.1	-22.3	-22.2	-22.1	-21.9	-21.9		-22.12
990	-22.2	-22.3	-22.2	-22.1	-21.9	-21.9		-22.14
1000	-22.2	-22.3	-22.3	-22.1	-21.9	-21.9		-22.16
1010	-22.3	-22.3	-22.3	-22.2	-22	-22.0		-22.22

Table A2. Results by experiments, numerical model and empirical relation at variable cooling air temperature (v=5.2 m/s and T_i=33.17°C)

Cooling air temp. (°C)	experimental freezing time (sec)	numerical freezing time (sec)	empirical freeing time (sec)
-23.4	259	300	256
-24.2	253	284	252
-25.7	250	266	246
-27.2	240	248	242
-28.3	238	233	237
-29.5	236	227	233

Table A3. Results by experiments, numerical model and empirical relation

Initial Temp. (°C)	Velocity (m/s)	Cooling Air Temp. (°C)	Texp (s)	Tnum (s)	Temp (s)	Enum (%)	Eemp (%)
28.3	6.9	-31.1	232	220	232	-5.17	0.00
32.7	5.7	-30.9	236	232	234	-1.69	-0.85
31.9	5.6	-30.4	235	236	236	0.43	0.43
27.5	6.2	-29.1	237	240	237	1.27	0.00
31.2	6.8	-28.2	244	248	242	1.64	-0.82
30.9	6.2	-27.8	244	250	243	2.46	-0.41
31.9	5.4	-27.5	245	252	244	2.86	-0.41
30.5	5.7	-26.9	244	254	244	4.10	0.00
33.2	4.1	-26.5	252	258	249	2.38	-1.19
32.1	5.6	-26.1	258	271	254	5.04	-1.55

VITAE

The author, Manoj Kumar Sharma, was born on 20th May 1993 in Suhag Nagla in Rampur district of Uttar Pradesh. He passed his High School and Intermediate Examination from Jain Inter College, Rampur (affiliated to U.P. Board) in 2008 and 2010 respectively. He earned his bachelor's degree with honours in Mechanical Engineering from Shri Shiddhi Vinayak Institute of Technology, Bareilly (affiliated to Uttar Pradesh Technical University) in 2014. He took admission in the College of Post Graduate Studies at Govind Ballabh Pant University of Agriculture & Technology, Pantnagar in July 2014 for Master's degree in Mechanical Engineering with major in Thermal Engineering.

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ABSTRACT

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Thesis Title : **Freezing Time Estimation of Peas by Experimental and Numerical Methods**

Advisor : Dr. Anil Kumar Pratihar

Freezing temperature-time variation of peas has been studied both by numerical as well as experimental methods in the present work. Various thermo-physical properties of peas, viz. density, moisture content and specific heat were experimentally determined. Further, effect of different parameters, viz. cooling air temperature, cooling air velocity and initial temperature, on freezing times has also been studied.

Numerical models were developed for two cases; (a) freezing at constant temperature and (b) freezing with successive depression in freezing point. Crank Nicolson method was used for the formulation of mathematical models and is solved using MATLAB. The numerical models have been duly validated. Numerical models predict the experimental data with a minimum and maximum error of 0.4% and 8.1% respectively. An experimental setup was also designed and fabricated for determination of freezing time. One hundred twenty six samples of peas were frozen under different operating conditions and time-temperature behaviour of every sample was recorded using data logger. Freezing time calculated by numerical model agrees very well with experimental data. Based on the experimental results, an empirical relation of freezing time as a function of cooling air temperature, cooling air velocity and initial temperature, was developed. The empirical relation predicts the experimental data with a minimum and maximum error of 0.43% and 7.2% respectively which shows that Freezing times predicted by empirical relation are in good agreement with experimental data.

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शोध ग्रंथ शीर्षक : **प्रायोगिक और संख्यात्मक विधियों से मटर के हिमीकरण समय का आकलन**

सलाहकार : डा० अनिल कुमार प्रतिहार

वर्तमान कार्य में मटर के हिमीकरण तापमान-समय परिवर्तन को संख्यात्मक तथा प्रयोगात्मक दोनों विधियों द्वारा अध्ययन किया गया है। इस कार्य में मटर की विभिन्न ऊष्मीय-भौतिक गुणों जैसे घनत्व, नमी की मात्रा और विशिष्ट ऊष्मा को प्रयोगात्मक विधि द्वारा निर्धारित किया गया है। आगे मटर के हिमीकरण समय पर विभिन्न चरो, जैसे शीतल हवा का तापमान, शीतल हवा का वेग और प्रारंभिक तापमान, का अध्ययन भी किया गया है।

दो परिस्थितियों के लिए संख्यात्मक मॉडल विकसित किए गए; (क) स्थिर तापमान पर हिमीकरण और (ख) लगातार गिरते हिमांक पर हिमीकरण । क्रैंक निकोलसन विधि का प्रयोग करके गणितीय मॉडल का सूत्रीकरण किया गया तथा MATLAB का प्रयोग करके इसे हल किया गया। संख्यात्मक मॉडल विधिवत मान्य किये गये हैं। संख्यात्मक मॉडल (ख), प्रयोगात्मक हिमीकरण समय का आकलन क्रमश: 0.4% और 8.1% की न्यूनतम और अधिकतम त्रुटि के साथ करते हैं। हिमीकरण समय निर्धारित करने करने के लिए प्रयोगात्मक सेटअप भी निर्मित किया गया। मटर के एक सौ छब्बीस नमूनो को विभिन्न परिचालन की स्थितियों मे हिमीक्रित किया गया तथा डेटा लोगर की सहायता से प्रत्येक नमूने के तापमान-समय व्यवहार को दर्ज किया गया। संख्यात्मक मॉडल द्वारा प्राप्त हिमीकरण समय प्रयोगात्मक समय के साथ बहुत अच्छी तरह से सहमत हैं। प्रयोगात्मक परिणामों के आधार पर, हिमीकरण समय का अनुभवजन्य संबंध शीतल हवा के तापमान, शीतल हवा के वेग और प्रारंभिक तापमान के फलन के रूप मे विकसित किया गया। अनुभवजन्य संबंध द्वारा प्रयोगात्मक विवरण का आकलन क्रमश: 0.43% और 7.2% की न्यूनतम और अधिकतम त्रुटि के साथ किया गया जो प्रदर्शित करता है कि अनुभवजन्य संबंध से आकलित हिमीकरण समय प्रयोगात्मक समय के साथ बहुत अच्छी तरह से सहमत है।

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