CHAPTER 6

CONCLUSIONS

The thermal gradient characteristics of perishable products have been studied both analytically and experimentally and the investigations are carried out for the following cases.

The problem of air-cooling of moist perishable product is solved in cartesian, spherical and cylindrical co-ordinate systems giving rigorous consideration to the coupled heat and mass transfer effects due to the constantly evaporating moisture film at the product surface. The charts presented here are useful in evaluating the time-temperature characteristics and cooling loads. The problem of heat-cool model is solved by considering the product in the form of a slab initially at a uniform temperature being subjected to a constant heat flux at one end while being cooled by free convection by the ambient unsaturated air.

In both the cases the governing partial differential equations with the boundary conditions some of which are non-linear have been solved numerically using finite difference technique. The experimentally obtained time-temperature characteristics of different food models, fruits and vegetables have been used to determine the thermal property of the products.

A model for freeze-drying of spherical perishable products is presented, and it is suitable for taking into account any arbitrary heat flux condition at the product surface, when it can be expressed as a function of surface temperature. Experiments are also conducted on food models to study the following processes.

Air-cooling of perishable products are investigated at various processing conditions such as cooling air velocity, temperature, relative humidity, product shape, size, and initial temperature. The experiments are conducted in a humidity tunnel and moisture loss and temperature histories of
the products are measured. The air cooling experiments are carried out for all the three geometries and they are applied to specific dimension of the specimen as given below:

Geometry of the specimen used:  
slab  sphere  cylinder

Dimension of the specimen used
60X60X10mm  50.5mm dia.  15mm dia.X 110mm long  
20mm dia.X 110mm long

water  sugar  agar-agar

Composition of the specimen used in air cooling
(weight in grams)  100 : 30 : 3

The experimental results are used to check the accuracy of theoretical predictions and to study the effects of various processing parameters on the air-cooling characteristics.

The time-temperature characteristic of a food model in the shape of a slab heated at one end with a plane heat source while the other end is exposed to ambient where cooling takes place by free convection heat transfer are investigated. The heat-cool experiments are conducted for the following specific dimension of the specimen as given below:

Geometry of the specimen used:  slab

Dimension of the specimen used
60X60X10mm

water  sugar  agar-agar

Composition of the specimen used in air cooling
(weight in grams)  100 : 10 : 3
Similarly the time-temperature histories of a specimen to which a plane heat source giving constant heat flux is sandwiched between the specimen approximating a semi infinite body, are also investigated.

Freeze-drying experiments are carried out in a laboratory freeze-drier. The freeze-drying experiments are carried out using a specimen of 87mm diameter and its height being 15mm (thickness of the product). The freezer chamber temperature is maintained at -30°C while the freezing heater and condenser temperatures are -24°C, 70°C and -50°C respectively.

In the case of gas conduction and convection effects, the composition used are water - 100 and starch - 10 for all the experiments with the total pressure ranging from 0.15 to 0.5 Torr. In the case of effect of product composition, the composition studied are water - 100, starch - 6 for all the cases whereas the agar content is varied from 0 to 10 grams. The effects of product composition on the dehydration and rehydration characteristics are studied. The influence of gas conduction and convection on the energy transfer from the heater to the food surface is investigated.

Cryo-freezing experiments are carried out in a cryostat. Aluminium boxes of rectangular and cylindrical shapes are used for packing the perishable product. The size used:

1) Rectangular shaped mould : 50mm thick, 146mm length and 96mm width.
2) Cylindrical shaped mould : i) 48mm height X 114mm dia.
   ii) 58mm height X 114mm dia.
3) Products studied : fresh mutton of weight 0.75kg, 0.50kg,
   fresh chicken of weight 0.75kg.

The freezing and thawing times are recorded both for spray and immersion type and they are presented in the form of charts. Based on the analytical and experimental results, the following conclusions are drawn.

The constantly evaporating moisture film at the product surface has a significant influence on the heat transfer characteristics during air-
cooling. In the case of air-cooling the quadratic relation between enthalpy of saturated air and its temperature defined in equation (3.9) is written as,

\[ H = 3.951 + 0.0736t + 0.0189t^2 \]  

(3.31)

in Kcal/kg of dry air when \( t \) is in \( ^\circ C \). The above expression arrived is applicable in the temperature range of \( 4^\circ C \) to \( 40^\circ C \) the range encountered in the pre-cooling practice.

The final values obtained are as follows:

\[ t^* = 0.0700 \]  

(3.32)

\[ C_1 = -Bi (t^* - t_{wb}) \]

\[ C_2 = -Bi(0.3724 + 2t_{wb}) \]

\[ C_3 = -Bi(1.307 - 0.5981 t_{db} + t_{db}^2) \]

\[ -C_2 t_{db} - C_1 t_{_{in}} \]  

(3.33)

It is also seen that the latent heat transfer due to the moisture evaporation at the product surface along with the sensible heat transfer increases the cooling rate. It is observed that faster cooling is achieved at higher air velocities, lower wet bulb temperatures, higher product initial temperatures, and the lowest temperature attainable at the product surface is the wet bulb temperature of the cooling air, when the air is unsaturated. No change in the cooling rate is observed for a fixed wet bulb temperature of the air irrespective of the dry bulb temperature. The relative humidity of the cooling air is an important parameter which controls the cooling process, and at lower relative humidity of the cooling air, surface evaporation effects are more significant. It is also observed that surface evaporation effects are more significant at higher a) air velocity and b) product initial temperature, and the charts presented are highly useful in evaluating the cooling load requirements.

It is observed that higher air velocities and lower air humidities are accompanied by increased dehydration of the product. Also products with lesser sugar content cools faster than a product with higher sugar content and surface evaporation effect increases with decrease in sugar content. In
the case of heat-cool model, two temperature fronts are observed one at the heated surface and the other at the cooled surface. It is observed that the movement of temperature fronts depend on the rate of heating or cooling intensities. The values of constants a, b and c in the heat-cool model are:

\[ a = 46.9821 \]
\[ b = -2.496 \quad (3.34) \]
\[ c = 0.0673 \]

These values are obtained for the temperature range of 25°C to 60°C. The final values thus obtained are given below.

\[ t^+ = 0.2241 t \quad (3.35) \]
\[ C_1 = (t_i^+ - t_{wb}^+) \]
\[ C_2 = 2t_{wb}^+ - 10.4096 \]
\[ C_3 = 45.9917 - 11.3909 t_{db}^+ + t_{db}^+ \left( \frac{1-\Phi}{t_i^+ - t_{wb}^+} \right) - C_2 t_{db}^+ - C_1 t_{db}^+ \]

The analysis could be used to evaluate the time-temperature characteristics of moist materials, and a finite body could be used to approximate the thermal behaviour of a semi-infinite body. It is also observed that the thermal property values of moist materials are process dependent.

In general, thermal gradient of a perishable increases with increase in cooling air velocity and product initial temperature. But a decrease in thermal conductivity/diffusivity occurs at i) lower wet bulb temperatures of the cooling air, and ii) with decrease in moisture content. Both thermal conductivity and heat capacity are sensitive to change in the wet bulb temperature of the cooling air.

The freeze-drying model presented here is useful in evaluating the dehydration characteristics of spherical perishable products under complicated surface heat flux conditions. Experimental investigations show that the
combined effects of gas conduction and convection play a significant role in addition to the radiation from the heater to the food surface. Also experimental evidences reveal that gas conduction-convection effects become stronger at higher chamber pressures. The problem of freeze-drying of spherical particle is fully defined in dimensionless form by the following set of equations.

\[
\frac{1}{R} \frac{\partial^2 \theta^*}{\partial R^2} (R \theta^*) = \left( \frac{3}{R} \right) \frac{\partial \theta^*}{\partial \theta^*} \quad \text{for} \quad \delta^* \leq R \leq 1
\]

\[
t^* = 0 \quad \text{for} \quad 0 \leq R \leq 1 \quad \text{at} \quad \theta^* = 0
\]

\[
\delta^* = 1 \quad \text{at} \quad \theta^* = 0
\]

\[
\frac{\partial t^*}{\partial R} = G_1(t^*_s) \quad \text{at} \quad R = 1, \quad \theta^* > 0
\]

\[
\frac{\partial t^*}{\partial R} = - \frac{\rho_1 \lambda_1 \mu_g a L_1}{K(t_1 - L_1)} \frac{ds^*}{d\theta^*}
\]

\[
t^* = 0 \quad \text{at} \quad R = \delta^*_d \quad \text{and} \quad \theta^* > 0
\]

The above theoretical model presented here is useful to identify that at higher values of heater temperatures, the drying rates are higher but the surface temperature rise is steeper. It is observed during the experiment that increased agar content results in higher drying rates and with excess sugar content the product dehydrate quickly. It is also observed that the drying time increases with increased starch content. It is also found that the freeze dried product is tougher and rehydrates slower as the starch content is increased, and product composition has very little effect on the interface temperature.

Cryo-freezing experiments are carried out in two cryostats designed and fabricated for this purpose and experiments are conducted. Aluminium boxes of rectangular and cylindrical shapes are used for packing the food products. After calibration of the copper constantan thermocouples, the experiments are conducted using rectangular cryostat and cylindrical cryostat. It is found that freezing time is less in immersion type (cylindrical) freezing compared to spray type, and also the consumption of
liquid nitrogen is less in immersion type compared to spray type. The charts presented for various parameters are useful in evaluating the above conclusions. Freezing time increases with the increase in thickness of the product or packing mould, and thawing time also increases with the increase in thickness of the product or packing mould. It is observed that surface freezes faster than centre. When products are unpacked and frozen, the freezing time is less compared to packed ones but surface cracks, change in colour, odour and taste occur.