6 Preservation by Refrigeration

6.1 Introduction

All living things age with time. For fruit and vegetables, ageing can be extended beyond harvesting. The process of ripening can be slowed by cold storage. However, a carefully controlled temperature must be maintained that is sufficient to slow down the ripening processes and the activities of bacteria and fungi yet sufficient to prevent it from failing to ripen, ripen too quickly and go rotten, or be very prone to attack by fungi. Grapefruit, oranges and tomatoes, for example, are required to be stored at 7°C while bananas require a higher temperature of between 12°C and 14°C and. Apples range from -1°C to 4°C.

The fact that the activity of bacteria is reduced at low temperatures is of great importance in extending the shelf life of foods. It means that meat can be eaten which has taken several weeks to arrive from overseas in cold storage. Lamb produced in New Zealand, for example, is frozen before it is packed into the refrigerated holds of meat-carrying ships in which the temperature is held at -13°C to -12°C. Very little flavour is lost during the long voyage to Europe. If stored for longer than three months, flavour and tenderness is lost and the meat begins to deteriorate through surface dehydration.

For some kinds of food, such as wet fish, a damp atmosphere is maintained in cold stores. Poultry, on the other hand, are generally wet and warm when it arrives at the cold store. Dry, cold air is circulated so that excess moisture and heat are removed.

6.2 Definition of Freezing

Freezing will occur at different rates at different points in the piece or package of food. The location that cools slowest is known as the thermal centre and the freezing times are usually defined with reference to this point. The highest temperature at which ice crystals have a stable existence in a food material is conventionally known as the freezing point of that material. However, because of the nature of foodstuffs and the presence of water-soluble constituents, not all of the water solidifies at this temperature. Under equilibrium conditions and at a temperature just below the freezing point, a certain fraction of the water present remains in a fluid phase. This fraction falls when the temperature is lowered and the eutectic mixtures may separate from the unfrozen fluid, but unfrozen water is still present at comparatively low temperatures. Thus, it is not possible to define a clear endpoint to the freezing process.

The freezing time of a body may be defined as the time taken for its thermal centre to fall through the zone of maximum ice crystal formation. A body may be regarded as quick frozen if the period is two hours or less. The effective freezing time has been defined as the time required to reduce the temperature of the product from its initial average value to a given thermal centre. If the temperature is monitored at the thermal centre of a food as heat is removed, a characteristic curve shown in Figure 6.1 is obtained.

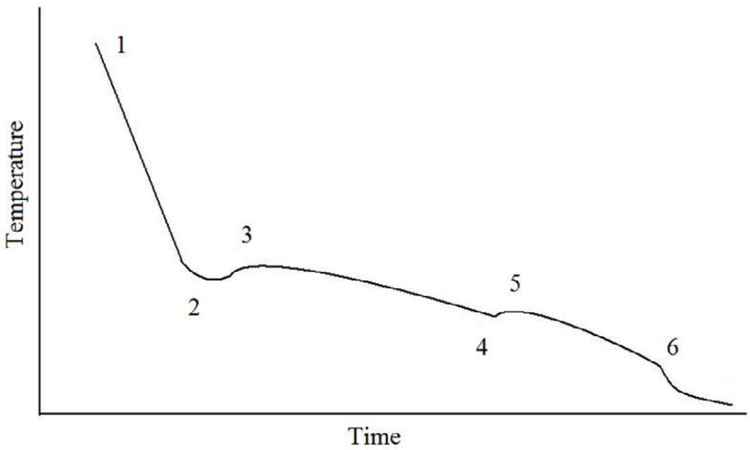

Figure 6.1 Freezing curve

The main features of the curve are:

AS The food is cooled to below its freezing point, which, with the exception of water, is always below 0°C. At point S the water remains liquid, although the temperature is below the freezing point. This phenomenon is known as super-cooling and may be as much as 10°C below the freezing point.

SB The temperature rises rapidly to the freezing point as ice crystals begin to form and latent heat of crystallisation is released.

BC Heat is removed from the food at the same rate as before. Latent heat is removed and ice forms, but the temperature remains almost constant. The freezing point is depressed by the increase in solute concentration in the unfrozen liquor, and the temperature therefore falls slightly. It is during this stage that most of the ice forms.

CD One of the solutes becomes supersaturated and crystallises out. The latent heat of crystallisation is released and the temperature rises to the eutectic temperature for that solute.

DE Crystallisation of water and solute continues. The total time taken for the freezing plateau is determined by the rate at which heat is removed.

EF The temperature of the ice-water mixture falls to the temperature of the freezer.

The total amount of heat to be removed by the freezing equipment consists of sensible heat change needed to cool the food to its freezing point, the latent heat of fusion involved in solidifying the liquid water in the food to ice and, finally, the sensible heat change to cool the frozen piece to its final temperature. Thus

$$Q = m\int c_{p(unfrozen)}dT_1 + m_w\lambda + m\int c_{p(frozen)}dT_2$$

There are various ways in which the specific heat of a food material can be expressed.

The change in enthalpy of cooled foods can alternatively be determined from experimental data which, by convention, the enthalpy is taken as 0 kJ.kg^{-1} at -40°C. The specific enthalpy and thermophysical properties of some foods are given in Tables 6.1 and 6.2.

It is worth noting at this point that the thermal conductivity of ice is some five times greater than that of water and the thermal diffusivity is some ten times greater than that of water. It is therefore easier to propagate temperature in ice rather than water. The thermal conductivity for foods is less than that for ice because not all the food is ice and also food, generally, has a large voidage.

Example:

The latent heat of a food is found by experiment to be 2.3x10^5 J.kg^{-1}. Estimate the moisture content of the food from this value.

Solution:

The latent heat of fusion of ice is 333 kJ.kg^{-1}. The moisture content is therefore found from

$$x_f = \frac{\lambda}{333} = \frac{2.3 \times 10^5}{333 \times 10^3} = 0.69$$

That is, a moisture content of 69%.

Table 6.1 Specific Enthalpy of Some Foods

	x_f (%)	Specific Enthalpy (kJ.kg^{-1}) -30°C	-20°C	-15°C	-10°C	-5°C	0°C	+5°C	+10°C	+20°C	+30°C
Strawberries	89.3	16.7	38.9	53.5	72.8	109.2	364.0	343.1	401.2	440.1	482.8
Peaches	85.1	25.1	44.8	65.3	95.0	146.4	348.5	366.9	-	-	-
Orange Juice	89.0	16.7	38.5	55.6	75.3	118.8	356.9	377.0	400.8	437.6	479.1
Peas	75.8	17.6	43.5	60.7	86.6	144.8	312.5	330.5	347.3	384.5	390.4
Spinach	90.2	16.7	33.0	48.5	62.8	88.7	362.7	387.0	402.5	444.3	485.7
Carrots	87.5	25.5	45.2	60.2	102.5	124.3	358.1	376.1	-	-	-
Beef 5% fat	74.0	19.2	41.4	54.4	72.4	104.2	298.3	314.6	333.0	368.2	402.1
Pork 8% fat	70.0	19.2	40.6	53.5	70.7	100.8	281.5	298.3	315.9	351.4	385.3
Cod	80.3	20.1	42.2	56.1	71.5	105.0	322.6	341.0	360.2	381.2	434.3
Herring	63.8	20.1	42.2	56.1	73.2	101.2	278.2	296.2	314.2	348.9	382.4
Egg white	86.5	18.4	38.4	50.2	64.4	87.0	351.4	370.7	389.5	427.2	465.7
Egg yolk	50.0	18.4	38.9	50.6	64.8	84.5	228.4	246.4	268.2	303.7	334.3
Whole egg	74.0	18.4	38.9	52.3	66.1	85.8	308.4	328.4	349.4	387.0	441.4
Butter	16.0	16.7	35.1	45.6	58.1	74.9	139.3	157.7	179.5	228.0	264.0
Lard	0.00	14.6	31.0	40.6	51,9	64.4	82.4	107.5	125.1	151.8	195.4
White bread	35.0	17.5	35.1	46.4	66.5	109.6	125.5	137.6	150.6	174.0	201.2

Table 6.2 Thermophysical Properties of Some Foods (at ambient temperature)

	x_f (%)	α ($m^2.s^{-1}(x10^{-6})$)	ρ ($kg.m^{-3}$)	k ($kW.m^{-1}.K^{-1}$)	c_p ($kJ.kg^{-1}.K^{-1}$)
Apple juice	87.0	0.14	1000	0.559	3.86
Grape Juice	89.0	0.14	1000	0.481	3.59
Peaches`	85.1	0.14	960	0.526	3.91
Bananas	76.0	0.14	980	0.481	3.59
Potatoes	78.0	0.11	1355	0.498	3.64
Raisons	32.0	0.11	1380	0.376	2.48
Beef (5%)	74.0	0.13	1090	0.471	3.54
Chicken	75.0	0.13	1050	0.476	3.56
Pork	70.0	0.13	1030	0.456	3.49
Cod	80.3	0.12	1180	0.534	3.71
Lamb	72.0	0.13	1030	0.456	3.49
Turkey	74.0	0.13	1050	0.496	3.54
Veal	75.0	0.13	1060	0.470	3.56
Margarine	16.0	0.11	1000	0.233	2.08

Example:

Determine the total amount of heat to be removed during cooling and freezing of 10 kg of lean beef (5% fat) from an initial temperature of 20°C to a final temperature of -20°C.

Solution:

The heat to be removed is calculated from

$$Q = m(h_{20^\circ C} - h_{-20^\circ C})$$

From Table 6.1 this is

$$Q = 10 \times (368.2 - 41.4) = 3268 kJ$$

Alternatively, an empirical relationship for specific enthalpy for beef is given by

$$h = 216.9 + 2.90T + 8.25 \times 10^{-3} T^2 + 73.3 \tan^{-1}(1.76(T + 1.7))$$

Where T is the temperature in °C. Thus

$$Q = m(h_{20^oC} - h_{-20^oC}) = 10 \times (391.4 - 49.3) = 3421kJ$$

This is slightly higher value. The empirical relation which fits experimental data well is shown in Figure 6.2.

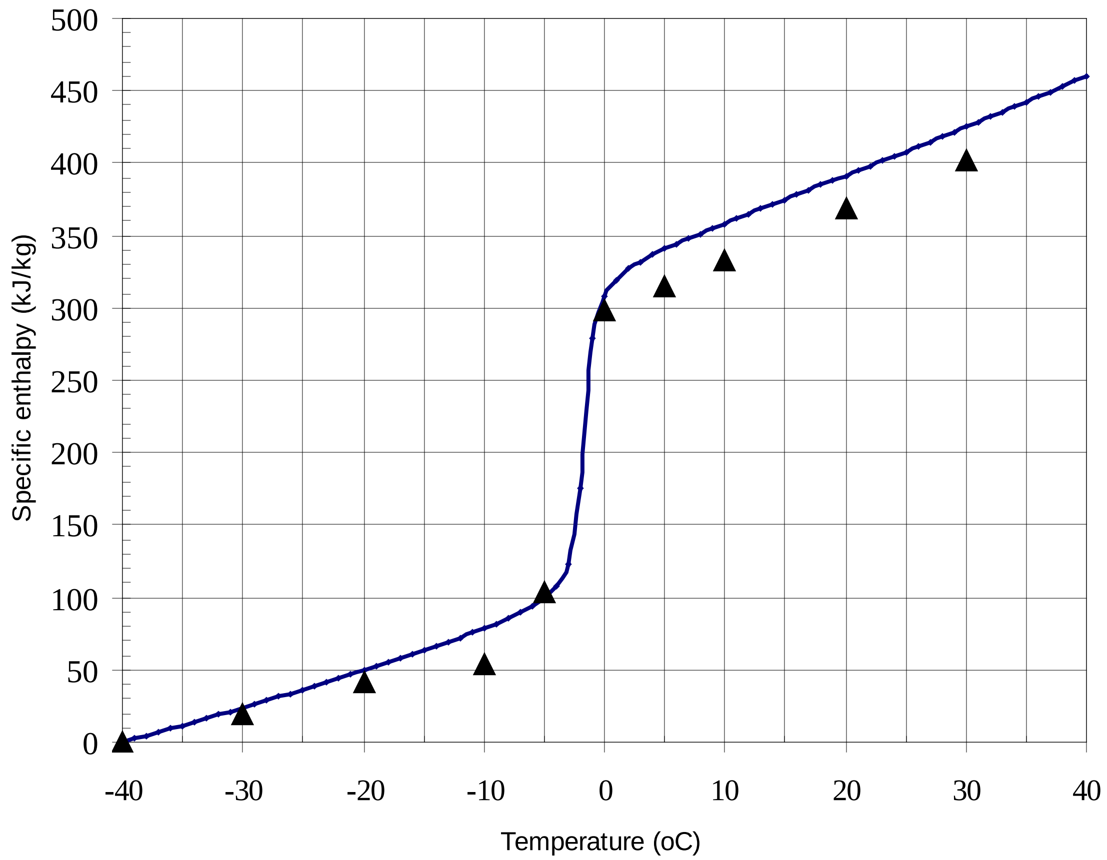

Figure 6.2 Specific Enthalpy of Lean Beef

Pre-cooling

The rate of heat loss from a body of food during the pre-cooling period by convection is given by

$$-mc_p \frac{dT}{dt} = hA(T - T_o)$$

Where T_o is the temperature of the cooling medium. The time taken to cool the food from an initial temperature, T_1, down to the freezing point, T_2, can be determined by rearranging the equation to

$$\int_0^t dt = \frac{-mc_p}{hA}\int_{T_i}^{T_2}\frac{dT}{T-T_o}$$

Completing the integration to gives

$$t = \frac{mc_p}{hA}\ln\left(\frac{T_1-T_o}{T_2-T_o}\right)$$

Example:

A 5 kg block of cod with a moisture content of 80.3% w/w is to be frozen in air at -20°C. The surface area of the block is 0.2 m^2 and the heat transfer coefficient is 30 $W.m^{-2}.K^{-1}$. Determine the time for the block to reach its freezing point of -2°C.

Solution:

Using data in Table 6.2, the time for the block to reach its freezing point is therefore determined from

$$t = \frac{mc_p}{hA}\ln\left(\frac{T_1 - T_o}{T_2 - T_o}\right) = \frac{5 \times 3710}{30 \times 0.2}\ln\left(\frac{5 - -20}{-2 - -20}\right) = 1016s$$

or about 17 minutes.

6.1.1 Quick-Freezing

As an advance on cold air storage, "quick-freezing" was developed the result of the early pioneering work of Clarence Birdseye in the 1930s in which he noticed how the Eskimos of Arctic Canada kept food in the intense cold of the open air for several months and yet were able to eat it as fresh when it was thawed. It was found that food that is frozen quickly and kept at a sufficiently low temperature loses little flavour or textural properties and can still be fresh many months later.

When food is frozen slowly, large ice crystals form in the cells of the food. The crystals rupture the cell walls as they grow. When the food is thawed the water drains away carrying salts and other minerals with it. The food consequently loses it flavour and value. In the "quick-freeze" method the ice crystals are formed much more quickly and are much smaller. All the moisture in the food freezes before the crystals have had time to reach a size sufficient to rupture the cell walls. When the food is thawed no moisture is lost.

6.1.2 Freezing Kinetics

Formulae are available for estimating the effective freezing time, although calculations involving unsteady state heat transfer with a change of phase are not always straightforward. Such formulae are usually based on the assumptions that the body to be frozen is initially at a uniform temperature and is cooled by a constant temperature medium. It is also assumed that the body has a constant thermal conductivity and the specific heat are different for the frozen and unfrozen states, has a constant density that does not vary with temperature or alter during the freezing process and that there is a definite freezing point at which all the latent heat of fusion is liberated.

If the body to be frozen is initially at its freezing point and that there is no pre-cooling period, hence no heat flows in the unfrozen material, the calculation of its freezing time is comparatively simple. Further simplification occurs if the material at the thermal centre at the end of the freezing process is assumed to be frozen, but still at its freezing point. The freezing time calculated on these assumptions may be termed the calculated freezing time. The effective freezing time can be estimated from the calculated freezing time by applying corrections to allow any pre- and post-cooling.

Formulae for the calculated freezing times can be simplified by making use of three dimensionless groups. Two of these, the Biot (Bi) and Fourier (Fo) numbers, are commonly used for unsteady state heat transfer and are given by:

$$Bi = \frac{hl}{k}$$

and

$$Fo = \frac{\alpha t}{l^2}$$

where h is the surface heat transfer coefficient at the surface of the body, l is the characteristic dimension of the body, k is the thermal conductivity of the frozen body and α is the thermal diffusivity of the body given by:

$$\alpha = \frac{k}{\rho c_p}$$

where ρ is the density and c_p is the specific heat of the food.

It is often important to determine the temperature at the centre of a body in the final stages of heating and cooling. When a solid body changes temperature from T_1 to T_0 it is convenient to express the temperature, T, of a point within it at time t during the change as a dimensionless temperature, V, as

$$V = \frac{T - T_o}{T_1 - T_o}$$

Clearly V will have an initial value of 1.0 and will tend to zero as the change progresses. Formulae for V are conveniently expressed in the terms of the Bi and Fo numbers. Expressions giving V as a function of time are available but are cumbersome. Charts are available for determining V at certain points in slabs, rods, cylinders, spheres and brick-shaped bodies.

In calculating the Biot and Fourier numbers, the characteristic dimension is the shortest distance from the thermal centre to the surface of the body being frozen. The calculated freezing time and the thermal constants used are those for the frozen material. Figures 6.3, 6.4 and 6.5 are used to determine the temperature of a food found from the dimensionless temperature, V, and Fourier number.

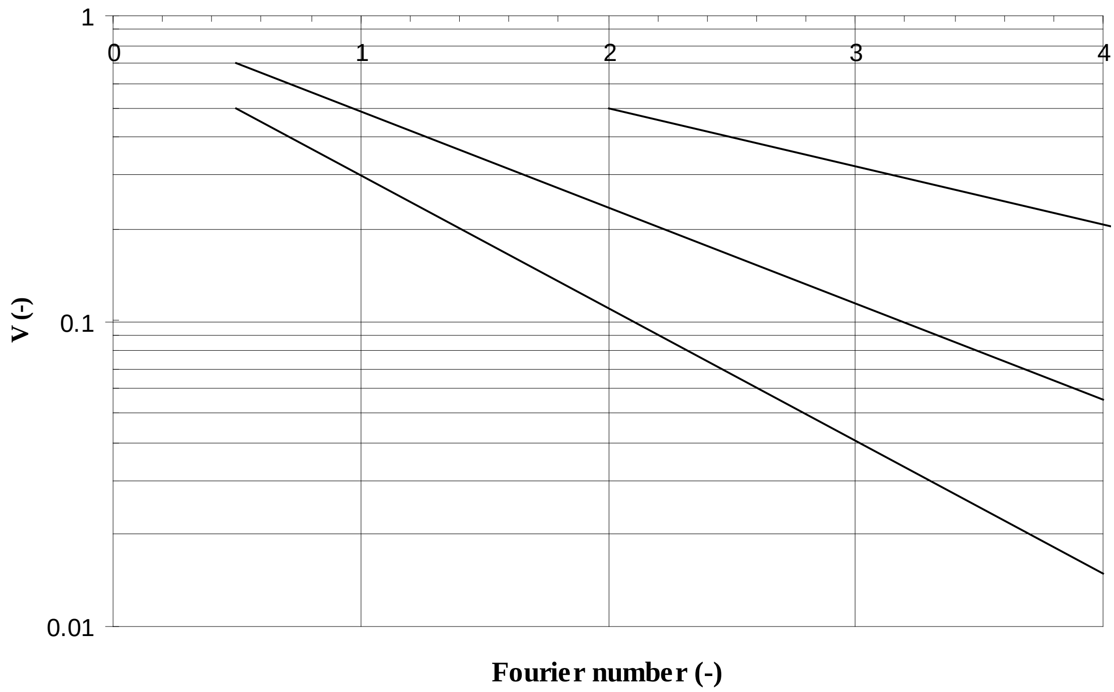

Figure 6.3 Temperature for the centre of an infinite slab. The lines are for 1/Bi=0.5, 1.0 and 2.0

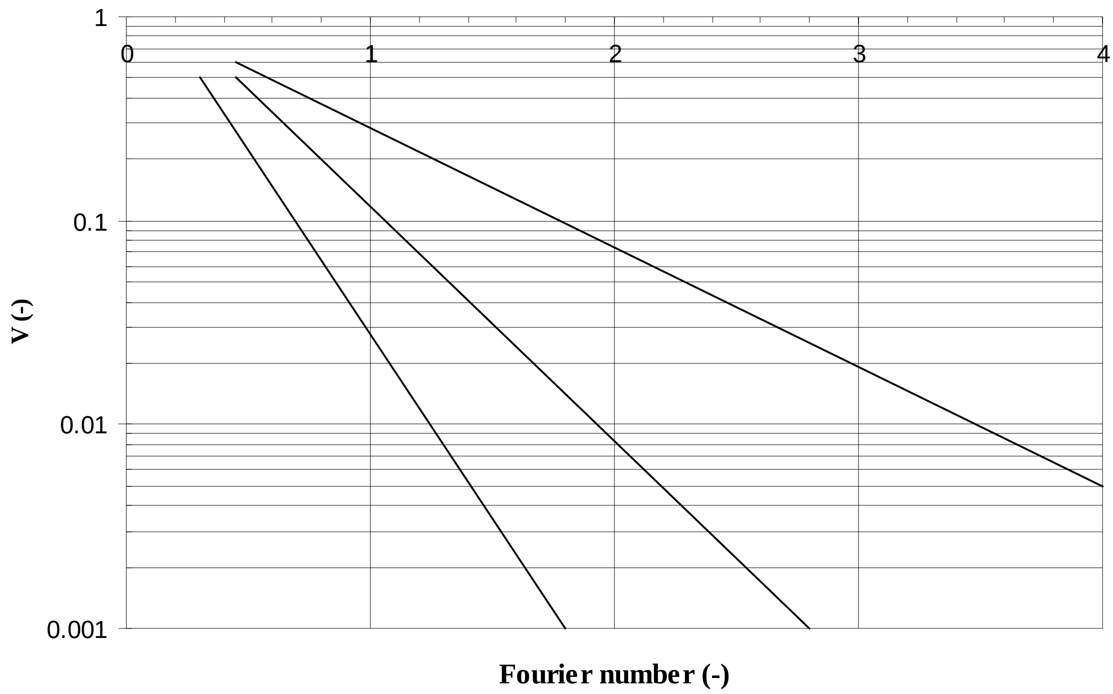

Figure 6.4 Temperature for the centre of a sphere. The lines are for 1/Bi=0.5, 1.0, and 2.0

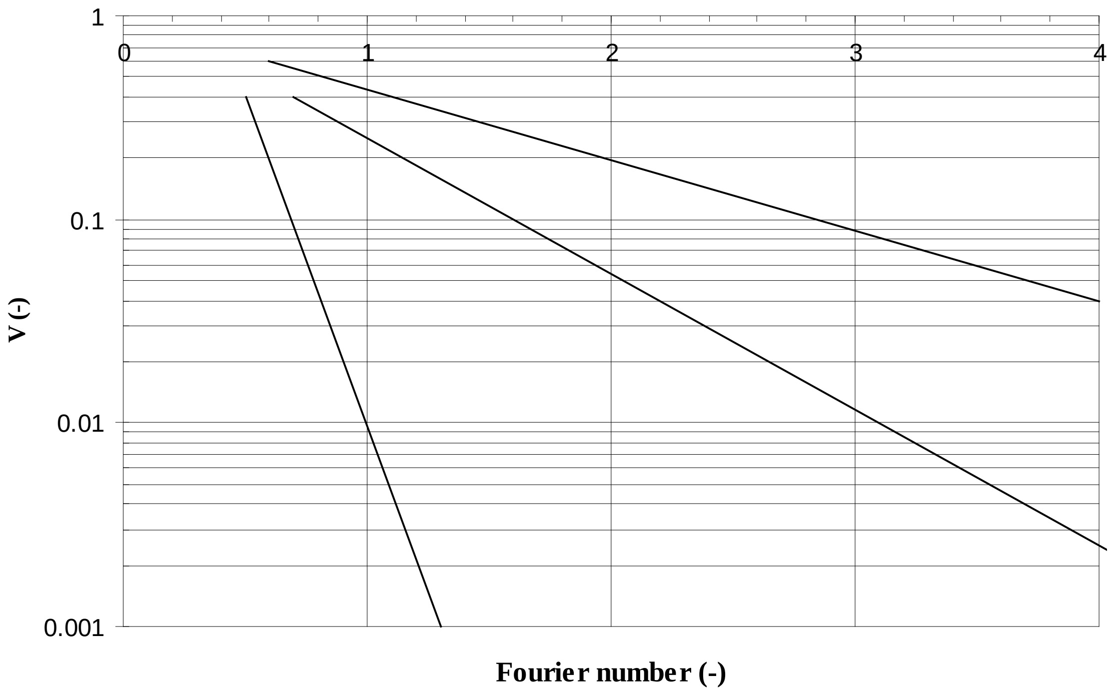

Figure 6.5 Temperature for the centre of a cylinder. The lines are for 1/Bi=0.5, 1.0, and 2.0

6.2 Freezing of a Slab

To determine the time taken to freeze a semi-infinite slab of food, assume that the foodstuff is a finite slab of thickness *2l* with a heat transfer coefficient at both surfaces as shown. The slab is considered to be semi-infinite since the width far exceeds the thickness so end effects are not needed to be taken into consideration.

Now assume also that the slab is already at its freezing point and that the material does not change in density and a phase change takes place at a specific phase transition temperature. Consider one face of the slab where a thickness dx is frozen in time dt.

The rate of heat release unit area, q, (flux) at the freezing front is therefore

$$q = \rho\lambda \frac{dx}{dt}$$

The rate of heat transfer by conduction per unit area through the frozen layer is given by

$$q = \frac{k}{x}(T_o - T_1)$$

where k is the thermal conductivity of the frozen foodstuff and x is the thickness of ice formed at the surface. Thus

$$\frac{k}{x}(T_o - T_1) = \rho\lambda \frac{dx}{dt}$$

The rate of convection from the surface per unit area is given by

$$q = h(T_1 - T_2)$$

So

$$h(T_1 - T_2) = \rho\lambda \frac{dx}{dt}$$

Rearranging the two equations

$$T_1 - T_2 = \frac{\rho\lambda}{h}\frac{dx}{dt}$$

$$T_0 - T_1 = \frac{\rho\lambda x}{k}\frac{dx}{dt}$$

Addition gives

$$T_0 - T_2 = \frac{\rho\lambda}{h}\frac{dx}{dt} + \frac{\rho\lambda x}{k}\frac{dx}{dt}$$

Therefore

$$\frac{\Delta T}{\rho\lambda}dt = \frac{dx}{h} + \frac{xdx}{k}$$

where ΔT is the difference in temperature between the freezing medium and the freezing point of the foodstuff. Integrating over the half-thickness of the slab

$$\frac{\Delta T}{\rho\lambda}\int_0^t dt = \int_0^l \frac{dx}{h} + \int_0^l \frac{xdx}{k}$$

gives

$$t = \frac{\rho\lambda}{\Delta T}\left(\frac{l}{h} + \frac{l^2}{2k}\right)$$

which can further be written as

$$t = \frac{\rho\lambda l^2}{k\Delta T}\left(\frac{k}{hl} + \frac{1}{2}\right)$$

Multiplying both sides by $k/\rho c_p l^2$ gives

$$\frac{kt}{\rho c_p \Delta T} = \frac{\lambda}{c_p \Delta\theta}\left(\frac{k}{hl} + \frac{1}{2}\right)$$

That is, in dimensionless form:

$$Fo = Ko\left(\frac{1}{Bi} + \frac{1}{2}\right)$$

This is known as the Plank equation after originally being proposed by R.Z. Plank in 1913 in which Ko is the Kossovitch number, given as

$$Ko = \frac{\lambda}{c_p \Delta T}$$

Example:

Sliced pork is quick frozen in a continuous blast freezer using chilled air. The air with a mass flow of 20 kg. $m^{-2}.s^{-1}$ is passed through a stack of trays at -34°C in a duct of mean hydraulic diameter of 0.1m. Assuming that the pork slices, which have a slab of thickness 1.0 cm, are considered to be infinite in each direction perpendicular to the heat flow, that steady state conditions exist in the blast freezer and that heat is extracted equally from both sides of the slab, calculate the freezing time using the following data:

Pork:		Air	
Density	1030 kg.m^{-3}	Viscosity	1.6x10^{-5} kg.m^{-1}.s^{-1}
Thermal conductivity	0.456 W.m^{-1}.K^{-1}	Specific heat	1005 J.kg^{-1}.K^{-1}
Latent heat of fusion	2.3x10^{5} J.kg^{-1}	Thermal conductivity	0.0242 W.m^{-1}.K^{-1}
Freezing point	-2^{o}C		

Solution:

The heat transfer coefficient is obtained from the Dittus-Boelter equation for turbulent flow

$$Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4}$$

Where the Reynolds number is given by

$$\mathrm{Re} = \frac{Gd_m}{\mu} = \frac{20 \times 0.1}{1.6 \times 10^{-5}} = 125{,}000$$

and the Prandtl number is given by

$$\mathrm{Pr} = \frac{c_p \mu}{k} = \frac{1005 \times 1.6 \times 10^{-5}}{0.0242} = 0.66$$

Nusselt number is therefore

$$Nu = \frac{hd_m}{k} = \frac{h \times 0.1}{0.0242} = 0.023 \times 125000^{0.8} \times 0.66^{0.4} = 232.8$$

Solving gives a heat transfer coefficient of 56.3 W.m^{-2},K^{-1}. The freezing time for an infinite slab is therefore

$$t = \frac{\rho \lambda l^2}{k \Delta T}\left(\frac{k}{hl} + \frac{1}{2}\right) = \frac{1030 \times 2.3 \times 10^5 \times 0.005^2}{0.456 \times 32} \times \left(\frac{0.456}{56.3 \times 0.005} + \frac{1}{2}\right) = 860s$$

or about 14½ minutes.

6.3 General Case for Freezing

The Plank equation can be developed from first principles for other geometries such as cylinders and spheres. Plank's work may by summarised in the dimensionless form

$$\frac{Fo}{Ko} = D\left(\frac{1}{Bi} + G\right)$$

where the constants *D* and *G* are determined by the geometry of the body being frozen. *G* takes the value ½ for the infinite slab, infinite cylinder and sphere. The constant *D* is given by

$$D = \frac{V}{al}$$

where V is the volume of the body and a is the area of its cooled surface. For the infinite slab, infinite cylinder and sphere D takes the values 1, ½ and ⅓, respectively.

In practical applications it is often difficult to decide on an appropriate value for the heat transfer coefficient, h. For the blast freezing of unpacked food heat transfer coefficients can be calculated from standard formulae.

Example:

Determine the geometric constant D for the freezing of spherical shaped foods such as peas.

Solution:

The geometric index is given by

$$D = \frac{V}{al} = \frac{\frac{4}{3}\pi r^3}{4\pi r^2 \times r} = \frac{1}{3}$$

6.4 Chilling

The chilling of foods is a process by which the temperature of a food is reduced to a desired holding temperature just above the freezing point and is usually in the range of -2°C to 2°C. The effect of chilling is to slow the rate of deterioration and reactions that are temperature dependent. The chilling of food therefore extends shelf-life.

The rate of chilling is governed by the laws of (unsteady state) heat transfer. To determine the rate of chilling, it is necessary to evaluate the surface heat transfer coefficient, the resistance offered to heat flow by any packing material and the unsteady state conduction.

Although the shape and geometry of most foods are not regular, they often approximate to the shape of slabs, bricks, spheres and cylinders.

Example:

Plot the variation of thermal conductivity for carrots if below the freezing point of -1oC the conductivity can be given by

$$k = 1.26 - 0.0011T + 0.8624/T$$

and above the freezing point, is given by

$$k = 0.551 + 0.0011T$$

Solution:

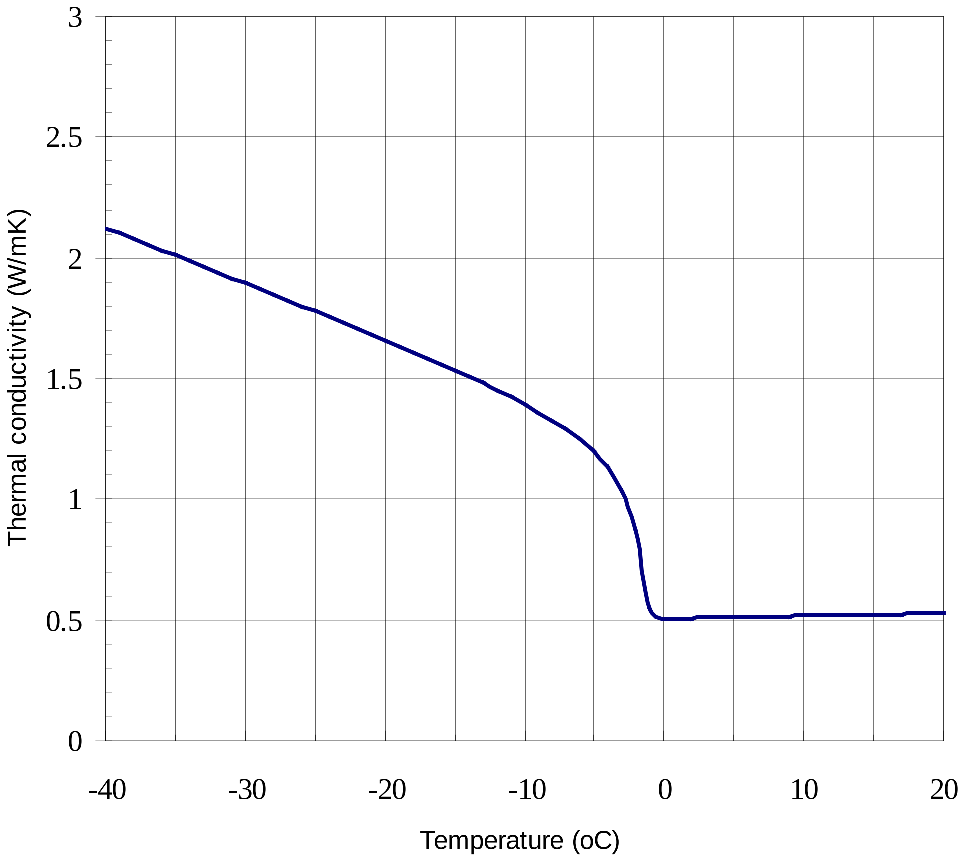

Figure 6.6 Thermal conductivity of carrots

Note the rapid decline towards the freezing point. This trend is typical for most foods.

Example:

Determine the time taken to chill apples with a diameter of 7 cm and initial temperature of 25°C to a core temperature of 5°C using air at a temperature of -1°C. The surface heat transfer coefficient is 30 W.m^{-2}.K^{-1}. The density of the apples is 920 kg.m^{-3} and their specific heat is 3.6 kJ.kg^{-1}.K^{-1} and thermal conductivity is 0.5 W.m^{-1}.K^{-1}.

Solution

The Biot number is

$$Bi = \frac{hr}{k} = \frac{30 \times 0.035}{0.5} = 2.1$$

The reciprocal is therefore

$$\frac{1}{Bi} = \frac{1}{2.1} = 0.48$$

The dimensionless temperature is

$$\frac{T - T_o}{T_1 - T_o} = \frac{5-(-1)}{25-(-1)} = 0.23$$

From Figure 6.4, the Fourier number is

$$Fo = 0.46 = \frac{kt}{\rho c_p r^2}$$

Rearranging

$$t = \frac{\rho c_p r^2 Fo}{k} = \frac{930 \times 3600 \times 0.035^2 \times 0.46}{0.5} = 3773s$$

or about 1 hour and 3 minutes. It is worth noting that a complete analysis should take into account the mass transfer from the surface of the food in which moistures is drawn from the surface effectively drying the food.

Example:

Rectangular blocks of food 2 cm high, 5 cm deep and 8 cm broad are to be frozen in a continuous blast-freezing tunnel on a belt 1.5 m wide. The blocks are to be placed on the belt, which offers negligible resistance to heat flow to the face in contact with it. The blocks are to be placed so that the 8 cm breadth is across the belt while the 5 cm depth is along the belt in the direction of travel.

Three forms of placement are possible, with the blocks being packed together in a slab, lined up across the belt in bars 5cm apart, or individually spaced 5cm apart as shown below in Figure 6.7:

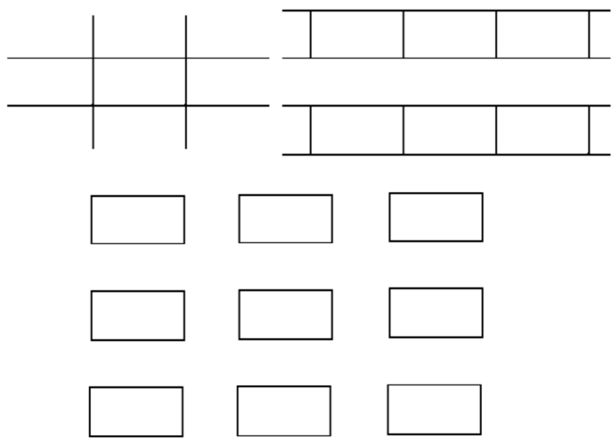

Figure 6.7 Possible arrangements of food on a belt

Assuming that the heat transfer coefficient at every exposed face is the same and is not influenced by the arrangement, determine which arrangement will give the highest plant throughput. The second geometric coefficient in Plank's equation, G, may be assumed to be equal to ½ in each case.

Solution:

In each case the time for freezing for a slab is given by

$$t = \frac{D\rho\lambda l^2}{k\Delta T}\left(\frac{k}{hl} + \frac{1}{2}\right)$$

Thus for the three cases, the time is proportional to the geometric index, D. So

$$D_1 = \frac{V}{al} = \frac{2\times5\times8}{2\times5\times8\times1} = 1.000$$
$$D_2 = \frac{V}{al} = \frac{2\times5\times8}{2\times(5\times8+2\times8)\times1} = 0.714$$
$$D_1 = \frac{V}{al} = \frac{2\times5\times8}{2\times(5\times8+2\times8+5\times2)\times1} = 0.606$$

This shows that the individual blocks freezing 39% quicker than those closely packed. However, the number of blocks spread over the belt (taking a 1.0 length of belt) is

$$N_1 = 18\times20 = 360$$
$$N_1 = 18\times10 = 180$$
$$N_1 = 12\times10 = 120$$

The relative throughput is therefore

$$\frac{N_1}{D_1}:\frac{N_2}{D_2}:\frac{N_3}{D_3} = \frac{360}{1}:\frac{180}{0.714}:\frac{110}{0.606} = 360:252:181$$

The best arrangement is therefore to compress the blocks together in spite of the slower freezing time.

Example:

Sliced potato fries 1cm by 1cm with a mean length of 6cm are individually quick frozen in a blast freezer operating at -30°C and with a heat transfer coefficient of 120 $W.m^{-1}.K^{-1}$. If the fries are already at their freezing point determine the expected freezing time.

Data:

Conductivity of potato	0.498 $W.m^{-1}.K^{-1}$
Density of potato	1055 $kg.m^{-3}$
Freezing point of potato	-1°C
Latent heat of fusion	$2.7x10^5$ $J.kg^{-1}$.

Solution:

The geometric index used in the Plank equation is

$$D = \frac{V}{al} = \frac{0.01 \times 0.01 \times 0.06}{(2 \times 0.01 \times 0.01 + 4 \times 0.06 \times 0.01) \times 0.005} = 0.46$$

The freezing of the fry is therefore

$$t = \frac{D\rho\lambda l^2}{k\Delta T}\left(\frac{k}{hl}+\frac{1}{2}\right) = \frac{0.46\times 1055\times 2.7\times 10^5\times 0.005^2}{0.498\times 29}\left(\frac{0.498}{120\times 0.005}+\frac{1}{2}\right) = 302s$$

The fries take approximately 5 minutes to freeze.

Example:

Show from first principles that the heat transfer for the freezing of an infinite cylinder can be expressed in the dimensionless form:

$$Fo = \frac{Ko}{2}\left(\frac{1}{Bi}+\frac{1}{2}\right)$$

Solution:

Assume that the foodstuff is a semi-infinite cylinder of radius R with heat transfer at the surfaces. Assume also that the foodstuff is at its freezing point and that the material does not change in density and a phase change takes place at a specific phase transition temperature. The rate of heat release unit area, *q*, (flux) at the freezing front at radius *r* is therefore

$$q = \rho\lambda 2\pi r\frac{dr}{dt}$$

The rate of heat transfer by conduction per unit area through the frozen layer is given by

$$q = \frac{2\pi k(\theta_o - \theta_1)}{\ln\left(\frac{R}{r}\right)}$$

where k is the thermal conductivity of the frozen foodstuff and r is the radius of the ice front. Thus

$$\frac{2\pi k(\theta_o - \theta_1)}{\ln\left(\frac{R}{r}\right)} = \rho\lambda 2\pi r r \frac{dr}{dt}$$

The rate of convection from the surface per unit area is given by

$$q = 2\pi Rh(\theta_1 - \theta_2)$$

Thus

$$2\pi Rh(\theta_1 - \theta_2) = \rho\lambda 2\pi r \frac{dr}{dt}$$

Rearranging the two equations

$$\theta_1 - \theta_2 = \frac{\rho\lambda r}{Rh}\frac{dr}{dt}$$

$$\theta_0 - \theta_1 = \frac{\rho\lambda r}{k}\ln\left(\frac{R}{r}\right)\frac{dr}{dt}$$

Addition and rearranging gives

$$\frac{\Delta\theta}{\rho\lambda}dt = \frac{rdr}{Rh} + \frac{\ln Rrdr}{k} - \frac{\ln r.rdr}{k}$$

where $\Delta\theta$ is the difference in temperature between the freezing medium and the freezing point of the foodstuff. Integrating over the radius of the cylinder

$$\frac{\Delta\theta}{\rho\lambda}\int_{o}^{t} dt = \int_{0}^{R}\frac{rdr}{Rh} + \int_{0}^{R}\frac{\ln Rrdr}{k} - \int_{0}^{R}\frac{\ln r.rdt}{k}$$

gives

$$t = \frac{\rho\lambda}{\Delta\theta}\left(\frac{R^2}{2Rh} + \frac{\ln RR^2}{2k} - \frac{\ln RR^2}{2k} + \frac{R^2}{4k}\right)$$

which can be reduced to

$$t = \frac{\rho\lambda}{\Delta\theta}\left(\frac{R}{2h} + \frac{R^2}{4k}\right)$$

or further

$$t = \frac{\rho \lambda R^2}{2k\Delta\theta}\left(\frac{k}{hR} + \frac{1}{2}\right)$$

Rearranging, the freezing time, *t*, is

$$\frac{kt}{\rho c_p R^2} = \frac{k\rho\lambda R^2}{2k\rho c_p R^2 \Delta\theta}\left(\frac{k}{hR} + \frac{1}{2}\right)$$

In dimensionless form using the Fourier number

$$Fo = \frac{Ko}{2}\left(\frac{1}{Bi} + \frac{1}{2}\right)$$

Example:

After production of the meat into skins, sausages are immediately frozen in a blast freezer for storage and transportation purposes. The sausages have a diameter of 2 cm and are made from lean meat with a moisture content of 55% and density of 1120 kg.m^{-3}. The sausages have a thermal conductivity, *k*, of 0.6 W.m^{-1}.K^{-1} and the blast freezer operates at a temperature of -18°C and provides a surface heat transfer coefficient of 120 W.m^{-2}.K^{-1}. blast freezer. If the sausages enter the blast freezer at their freezing point of -2°C, determine their freezing time.

Solution:

The freezing time, *t*, for semi-infinite cylindrical geometry is given by:

$$t = \frac{\rho \lambda R^2}{2k\Delta T}\left(\frac{k}{hR} + \frac{1}{2}\right)$$

For the supplied data:

$$t = \frac{1120 \times 333000 \times 0.55 \times 0.01^2}{2 \times 0.6 \times 16}\left(\frac{0.6}{120 \times 0.01} + \frac{1}{2}\right) = 1067s$$

Example:

Explain what it meant but the term “thermal centre” of a body being frozen. Discuss the interpretation of temperature measurements made at the thermal centre.

Solution:

The thermal centre is the slowest point of a food to freeze and is not necessarily the geometric centre of the food.

Example:

A slab of food of thickness 2l, is to be frozen from both sides, with heat transfer coefficient h_1 at one face and h_2 at the other ($h_1 > h_2$). Assuming the validity of Plank’s equation for freezing times, determine the displacement Δ from the geometric centre of the food at which the food finally freezes.

Solution:

The combined convection and conduction heat fluxes for both faces are

$$\frac{\Delta T}{\rho\lambda}\int_0^t dt = \int_0^{l+\Delta}\frac{dx}{h_1} + \int_0^{l+\Delta}\frac{xdx}{k}$$

and

$$\frac{\Delta T}{\rho\lambda}\int_0^t dt = \int_0^{l-\Delta}\frac{dx}{h_2} + \int_0^{l-\Delta}\frac{xdx}{k}$$

Integrating both equations gives

$$t = \frac{\rho\lambda}{\Delta T}\left(\frac{l+\Delta}{h_1} + \frac{(l+\Delta)^2}{2k}\right) = \frac{\rho\lambda}{\Delta\theta}\left(\frac{l-\Delta}{h_2} + \frac{(l-\Delta)^2}{2k}\right)$$

Expanding and ignoring small terms reduces to

$$\Delta = \frac{lk\left(h_1 - h_2\right)}{k\left(h_1 + h_2\right) + 2l(h_1 h_2)}$$

Example:

One tonne of lamb loin is to be frozen from an initial temperature of 30°C to a final temperature of -30°C. The lamb has a moisture content of 65% and the freezing point may be taken as -2°C. The specific enthalpy, h (kJ.kg^{-1}) for lamb can be given by

$$h = 217.6 + 3.24T + 0.018T^2 + 75.7\tan^{-1}(0.944(T + 2.1))$$

where T is temperature (°C).

Solution:

Using the relationship for specific enthalpy, h (kJ.kg^{-1}) for lamb:

$$h_{30^oC} = 217.6 + 3.24 \times 30 + 0.018 \times 30^2 + 75.7 \tan^{-1}(0.944(30 + 2.1)) = 468 kJ.kg^{-1}$$
$$h_{-30^oC} = 217.6 + 3.24 \times -30 + 0.018 \times -30^2 + 75.7 \tan^{-1}(0.944(-30 + 2.1)) = 16.9 kJ.kg^{-1}$$

The heat removed is therefore

$$Q = m(h_{30^oC} - h_{30^oC}) = 1000 \times (468 - 16.9) = 451.1 kJ$$

Example:

A ham burger manufacturer produces fresh burgers made from pork with 8% fat and moisture content of 70%. These are then frozen and packaged. The burger freezing process involves a continuous belt blast freezer upon which burgers 10 cm in diameter and 0.5 cm thick are frozen in rows of 10 burgers across the width of the belt. There is 10 cm between the burger centres along the length of the belt and the belt is perforated so that the freezing may be assumed to take place equally from both sides. The burgers are initially at their freezing point of -2°C and emerge from the freezer with their centres just frozen. Determine the belt speed (cm.s^{-1}) and production rate (kg.s^{-1}) if the length of the belt covered with burgers is 20 m.

Data:

Density of frozen burgers	1100 kg.m^{-3}
Air temperature	251 K
Heat transfer coefficient	120 W.m^{-2}.K^{-1}
Thermal conductivity of frozen burgers	1.3 W.m^{-1}.K^{-1}

Solution:

The burgers are assumed to be infinite slabs since their radius is considerably greater than their thickness. The time for freezing time is therefore

$$t = \frac{\rho \lambda l^2}{k \Delta T}\left(\frac{k}{hl} + \frac{1}{2}\right) = \frac{1100 \times 333000 \times 0.7 \times 0.0025^2}{1.3 \times 20}\left(\frac{1.3}{120 \times 0.0025} + \frac{1}{2}\right) = 298s$$

For a 20m belt, the belt speed is therefore 20/298=0.0067 ms^{-1}.

The mass of a burger is

$$m = \rho V = \rho \frac{\pi d^2}{4} 2l = 1100 \times \frac{3.14 \times 0.1^2}{4} \times 2 \times 0.005 = 0.043kg$$

With 100 burgers per 1.0 m length coverage of belt, the production rate is therefore

$$4.32 \times 0.067 = 0.289 kg.s^{-1}$$