280.372 Process Cooling

Lecture 3

Prediction of freezing time of food

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Learning Outcomes

- Knowledge of refrigerated facilities features and the areas of importance to ensure efficient operation.

To estimate:

- Heat load in cool stores → Lecture 1
- Heat transfer in cooling → Lecture 2
- Freezing times for food products → Lecture 3
- Cooling times for food products → Lecture 4

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Freezing of food

- *The preservation of food by freezing has become a major industry in developed countries*
- *Controlling the temperature of food across the whole supply chain is vital to extend shelf life*

FACTS:

- All food deteriorates in quality over a period of time
- Freezing can reduce the speed at which this occurs and prevent or limit microbial growth not detrimentally affecting quality

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Consequences of underproduction of food freezing time

- At temperatures below 0'C there is a significant reduction in **growth rates for microorganisms** and in the corresponding deterioration of the product due to microbial activity.
- Temperature influence applies to most other reactions that might normally occur in the product, such as **enzymatic and oxidative reactions**
- The formation of **ice crystals** within the product changes the availability of water to participate in reactions. As the temperature is reduced and more water is converted to a solid state, **less water is available to support deteriorative reactions**

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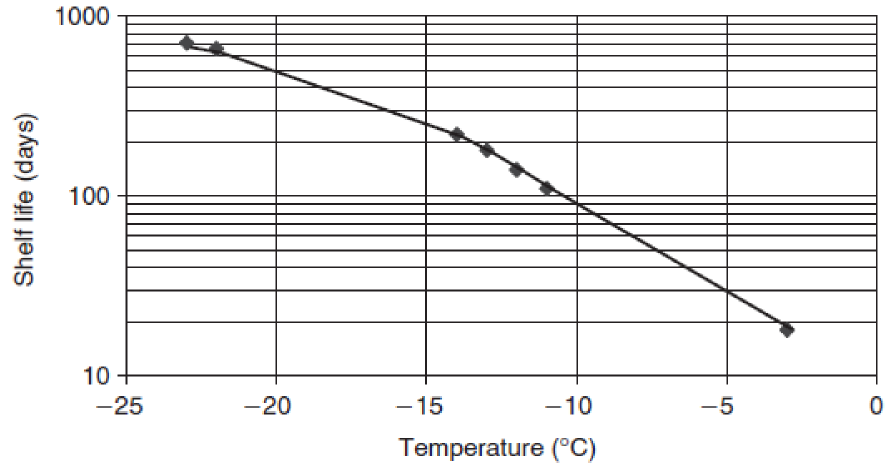
Quality Changes in Foods during Frozen Storage



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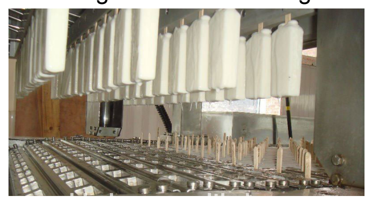
Cooling processes	Temperature Reduction T ↘	Temperature Control T = const
Above Freezing	**Chiller** 	**Cool Store** 
Below Freezing	**Freezer** 	**Cold Store** 

What are the advantages of pre-cooling and pre-freezing before food enters coldroom or coldstore?

e.g. Postharvest
(1 hour = 1 day Shel life)

e.g. Ice cream making



e.g. Export – load to ship

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Reducing Product Temperature

Aim
to reduce product temperature as fast as possible to a specific temperature

- Increase heat transfer coefficient
- Increase temperature difference
- Try to achieve cooling consistency

Design decisions
- Cooling mode
- Cooling medium and application

Chiller/freezer types characterized by the cooling medium

- Air Blast Chillers/Freezers

- Liquid Chillers/Freezers
  - chilled liquid bath
  - chilled liquid spray

Hydro cooler

- Cryogenic freezers

- Plate freezers (conduction)

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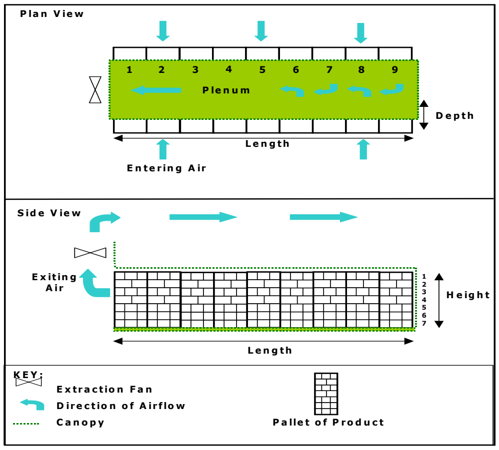
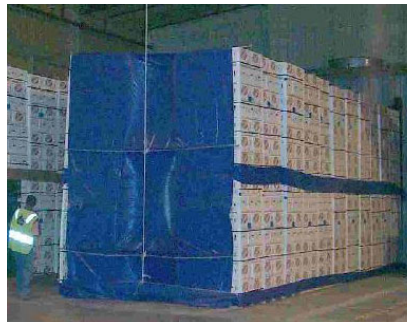
Air

☹ Low thermal conductivity (k=0.024 W/mK)
☹ Low heat transfer coefficients (forced convection h=10-1000 W/m^{2}K)
☹ Causes product drying
☺ Cheap
☺ Low temperatures possible
☹ Requires defrost for refrig. system
☺ Ease of accesibility to product

Apple Pre-cooler





Vertical Air Pre-cooler

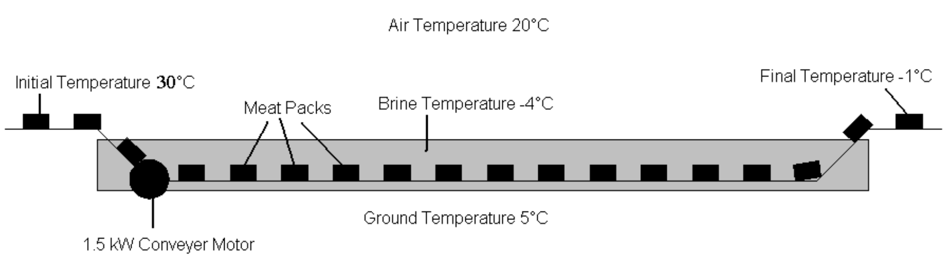
Liquids

- 😐 Average thermal conductivity (water k=0.6 W/mK)
- 😐 Good heat transfer coefficients (forced convection h=10 -10 000 W/m^2K)

- **Water / Ice Slurries**
  - ☺ Cheap
  - ☹ Limited temperature reduction
  - ☹ May be source of microbial contamination

- **Brines / Glycol**
  - ☹ Additional costs
  - ☺ Reduced temperatures
  - ☹ May be source of chemical contamination

Dog Roll Chiller



Hydro-cooler

Cooling in a bath

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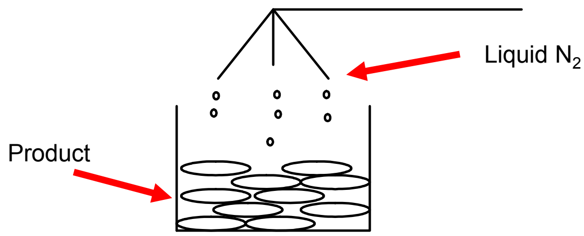
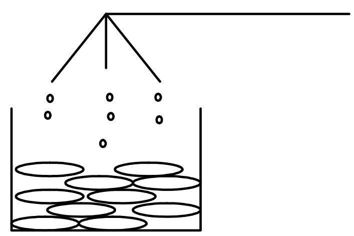
Ice slurry

Cryogenics

- ☺ Very fast freezing
  - Boiling point of liquid nitrogen -195’C
- ☹ Very expensive
- ☺ Minimal capital required
- ☺ Ability to match variable requirements



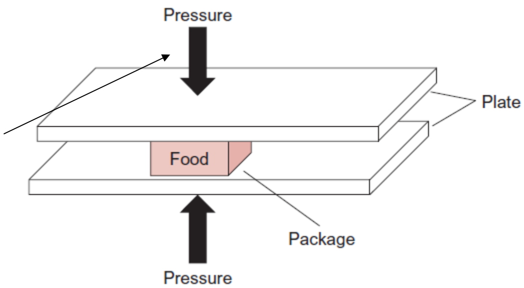
Cryogenic Freezing



Solid (Conduction)

- ☺ Excellent heat transfer coefficients
  Thermal conductivity (k≈ 100 W/m K)
- 😐 Requires flat product surfaces
- 😐 Usually batch processing

Heat transfer through the barrier (plate and package) can be enhanced by using pressure to reduce resistance to heat transfer across the barrier as illustrated



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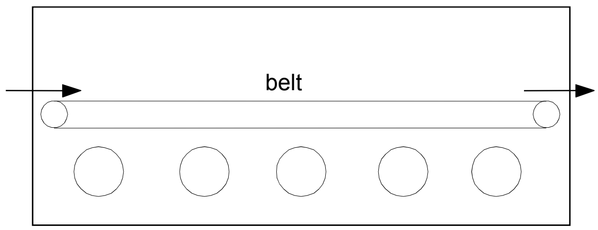
Batch Processing or continuous

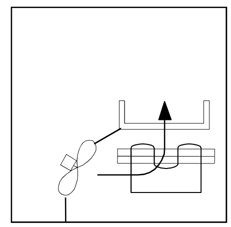
Batch	Continuous
Favoured for small volumes	Favoured for large volumes
Uneven heating	Uneven heat load removal
Labour and cost of loading	Conveying costs

Batch blast freezer

Continuous tunnel freezers - Belt type



Side



End

Pre-freezing of food in industry

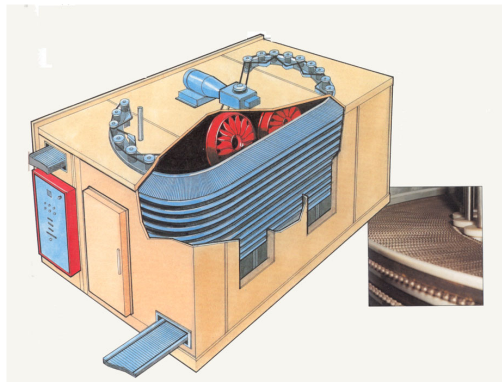
Types of freezers used:

Direct contact

Spiral Air Blast Freezer

Fluidized bed Freezer

Immersion Freezer



The factor most limiting the throughput of a freezer is the product **residence time** needed for freezing.

Reducing this time allows better use of the invested capital.

Freezing times depend on the following factors:

- Product size, measured as the half-thickness of product (use "radius" from "thermal centre" to surface on shortest route), R(m
- Shape of the product, indexed by the equivalent heat transfer dimensionality, E
- Required final product temperature, θ_{out}(°C)
- Surface heat transfer coefficient, h_e (W/m²K)
- Cooling medium temperature, θ_a(°C)
- Product initial temperature, θ_{in}(°C)

Thermal properties of the product:

- Thermal conductivity of unfrozen material k_l (W/mK)
- Thermal conductivity of frozen material k_s (W/mK)
- Specific heat capacity of unfrozen material c_l (J/kgK)
- Specific heat capacity of frozen material c_s (J/kgK)
- Density ρ (kg/m ³)
- Apparent latent heat of freezing Δh_f

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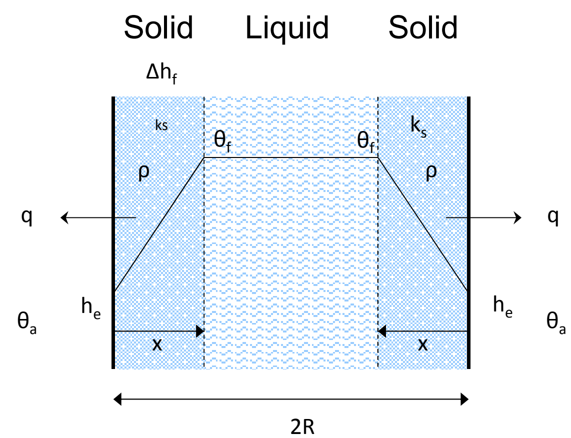
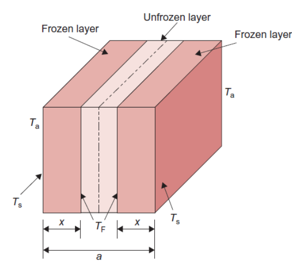
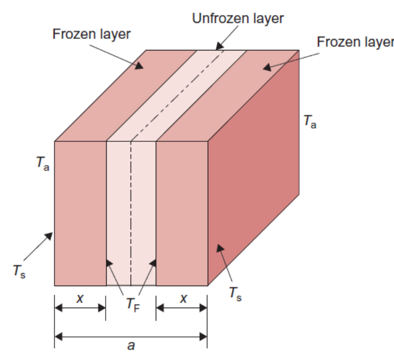
Freezing of Immobilised Water Cooled from Two Sides



http://rpaulsingh.com/animations/plankeqn.html



Plank's Equation



Freezing time

$$t_f = \frac{\rho \Delta h_f}{(\theta_f - \theta_a)} \left(\frac{R}{h_e} + \frac{R^2}{2k_s} \right)$$

t_f = freezing time
ρ = density of product
Δh_f = apparent latent heat of freezing
θ_f = product freezing temp.
θ_a = cooling medium temp.
R = product size, measured as the "shortest" half-thickness of product
h_e = surface heat transfer coefficient
k_s = thermal conductivity of frozen material

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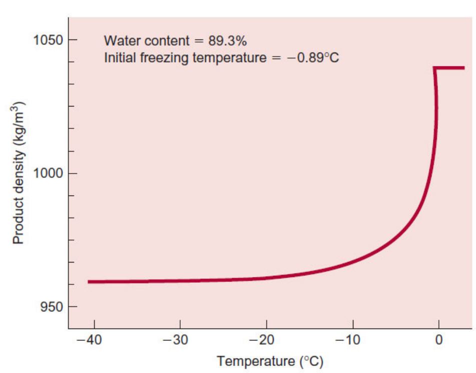
Limitations to Plank's equation

Freezing time predicted by Plank's equation is heavily underestimated (~30%) because of several assumptions (that are not true in practice):

- All food properties are constant
- The product is initially at its freezing temperature – does not take into account initial temperature
- The specific heat capacity of the frozen material is 0
- All latent heat is released at a unique temperature

Frozen food properties: Density

- Density of a frozen food will be less than the unfrozen product



Introduction to Food Engineering, 5th Edition, 2014

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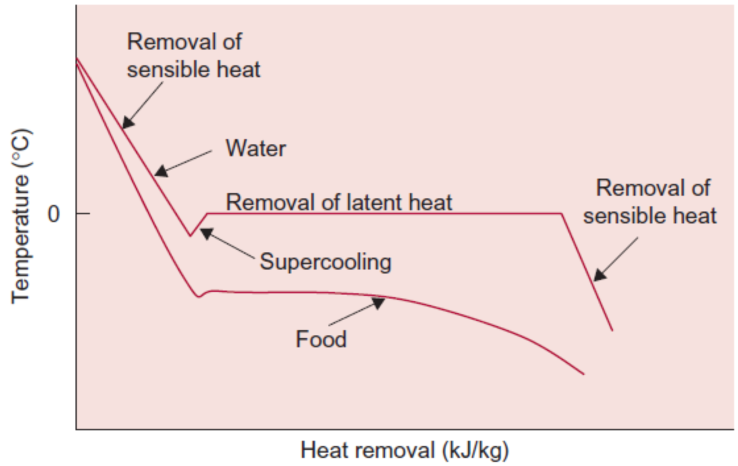
Freezing of food vs freezing of water



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Pham's equation

- This method is generally accurate to within ± 10%.
- Addition of a **shape factor** and reforming of the temperature difference and **heat to be removed** in precooling and postcooling.

Pham, T.T. (1986). Simplified equation for predicting the freezing time of foodstuffs. *J. Food Technol.*, **21**, 209-219

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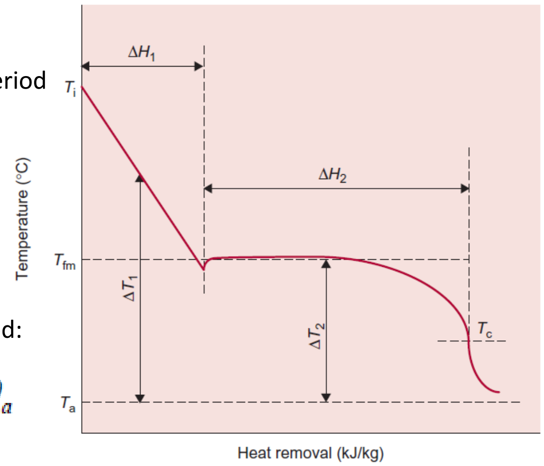
Pham's method to Predict Freezing Time

"Mean freezing temperature," θ_{fm} separates into two parts:

- one mostly for the precooling period with some phase change
- the other comprising largely the phase change and post-cooling periods

- Experimentally found θ_{fm} for food:

$$1.8 + 0.263\theta_{out} + 0.105\theta_a$$



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Pham's Modification to Plank's equation

Assumptions:

- Freezing air temperature is constant
- Initial temperature of food is uniform
- Final temperature at end of freezing is defined
- Surface of object cooled by Newton's cooling law

$$t_f = \frac{1}{E}\left(\frac{\Delta H_1}{\Delta\theta_1} + \frac{\Delta H_2}{\Delta\theta_2}\right)\left(\frac{R}{h_e} + \frac{R^2}{2k_s}\right)$$

NOTE:

- Enthalpies of precooling and post-cooling included
- Shape included (finite dimensions object)

Learn how to use Pham's Modified Plank's Equation to solve the Freezing Time Problem from Tutorial problem

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