HEAT TRANSFER WITH CHANGE OF PHASE

충남대학교
CHUNGNAM NATIONAL UNIVERSITY

Introduction

•**This chapter deals with energy transport when a change of phase is involved.**

•**After you have studied this chapter, you should be able to**

1. Explain the process of gradual freezing of a biomaterial over a temperature range, as opposed to one fixed temperature.

2. Explain the process of freezing in a cellular tissue and how the success of freezing depends on the rate of freezing.

3. Describe the changes in thermal and physical properties of biomaterials during freezing.

4. Calculate the time to freeze a plant of an animal tissue of given size.

Freezing and Thawing

•**Freezing and thawing is one of the most promising methods of preserving biological material.**

“Cryopreservation”

•**Freezing is one of the most common methods of preserving large quantities of food materials.**

“Frozen foods”

•**Freezing is sometimes used to purposely destroy living material.**

“Cryosurgery”

Freezing of Pure Water

Freezing Process

- **Several steps are involved in the freezing of pure water.**

Supercooling

↓

Nucleation

↓

Crystal growth

↓

Crystal maturation

Freezing of Pure Water

Property Changes During Freezing

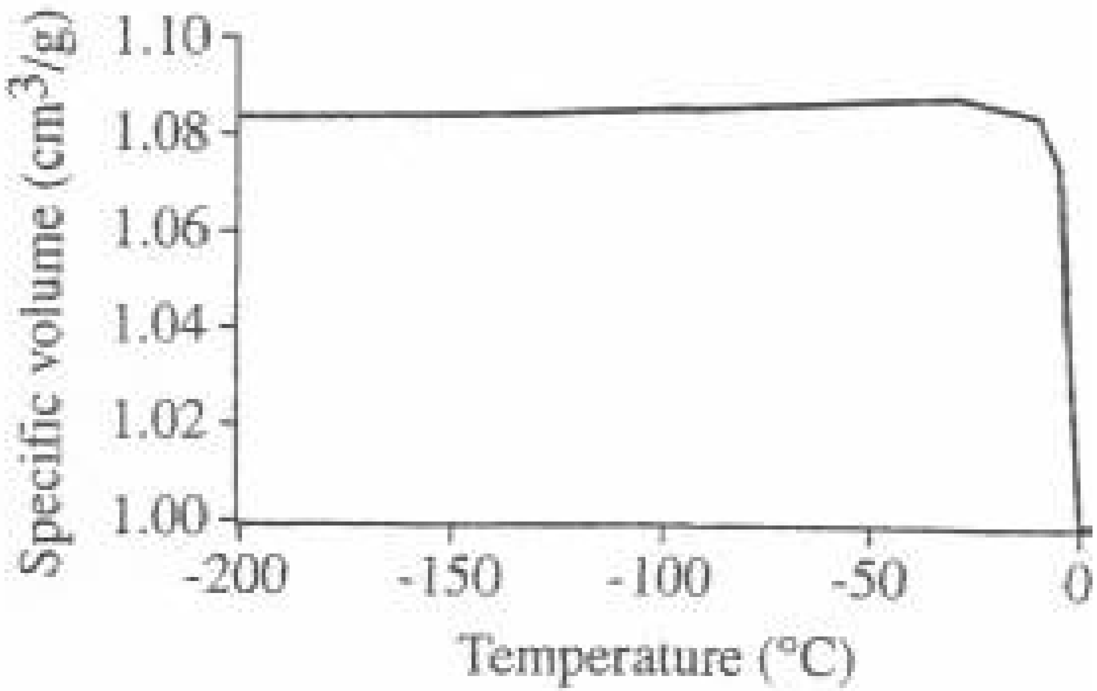


Figure 1. Increase in specific volume of water during freezing.

Freezing of Pure Water

Property Changes During Freezing

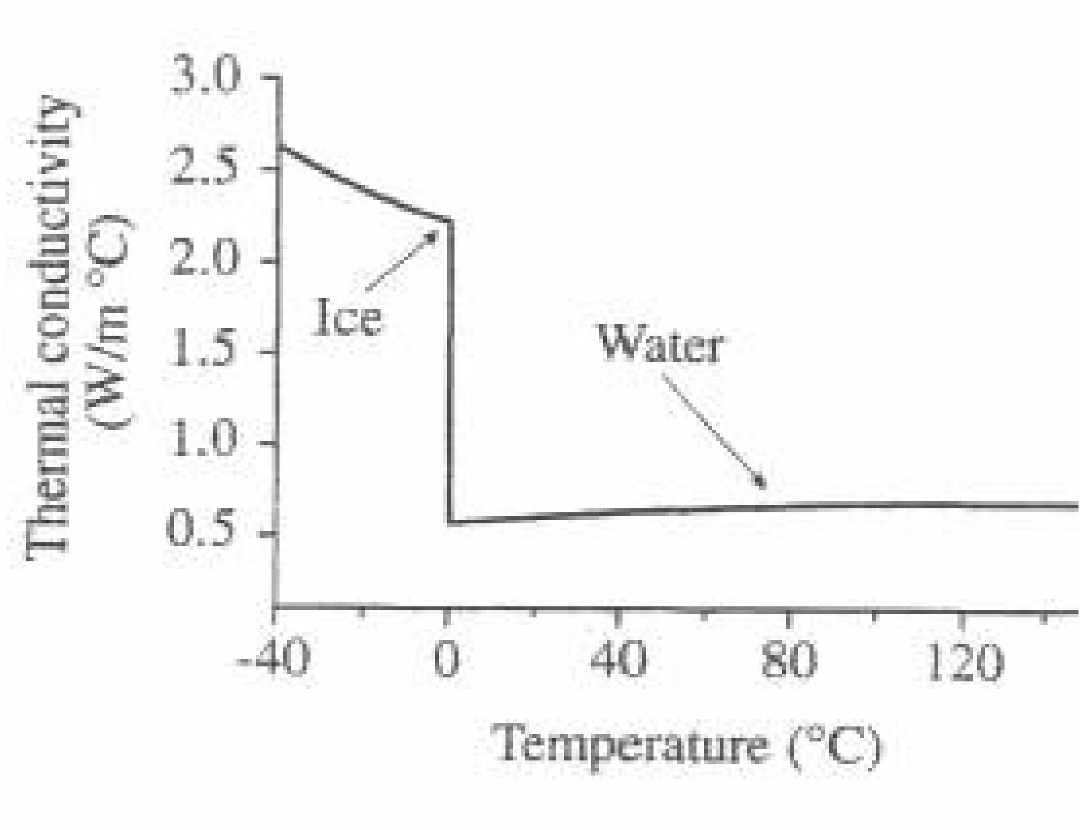


Figure 2. Changes in thermal conductivity with temperature showing large increase in thermal conductivity for ice over water.

Freezing of Pure Water

Property Changes During Freezing

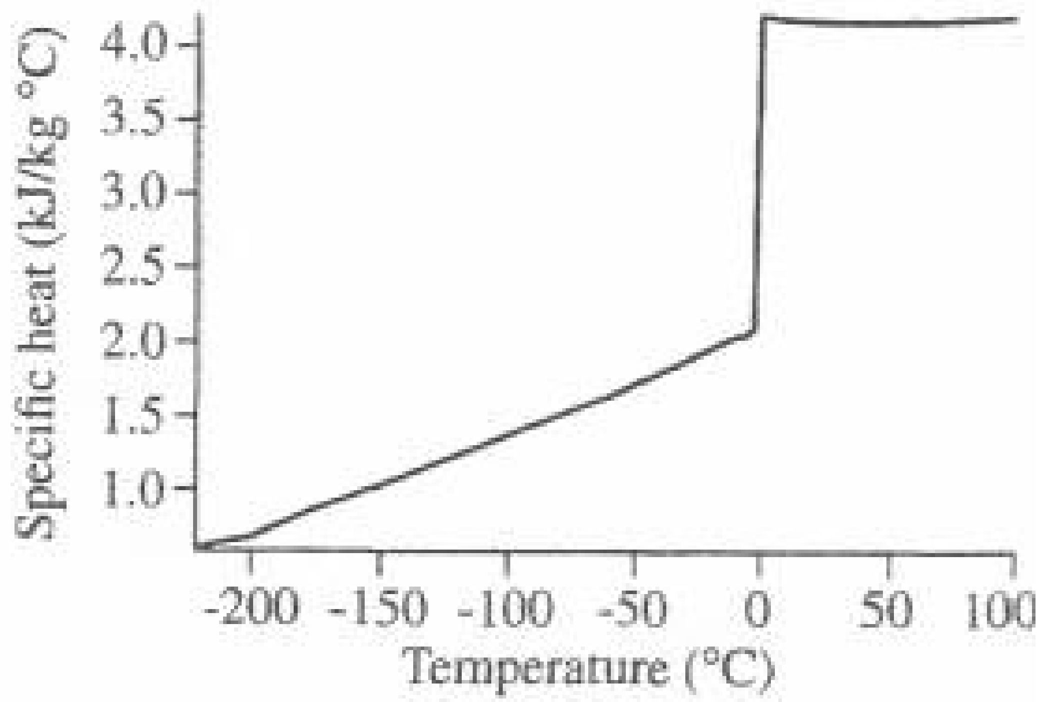


Figure 3. Specific heat of water and ice as a function of temperature.

Freezing of Pure Water

Property Changes During Freezing

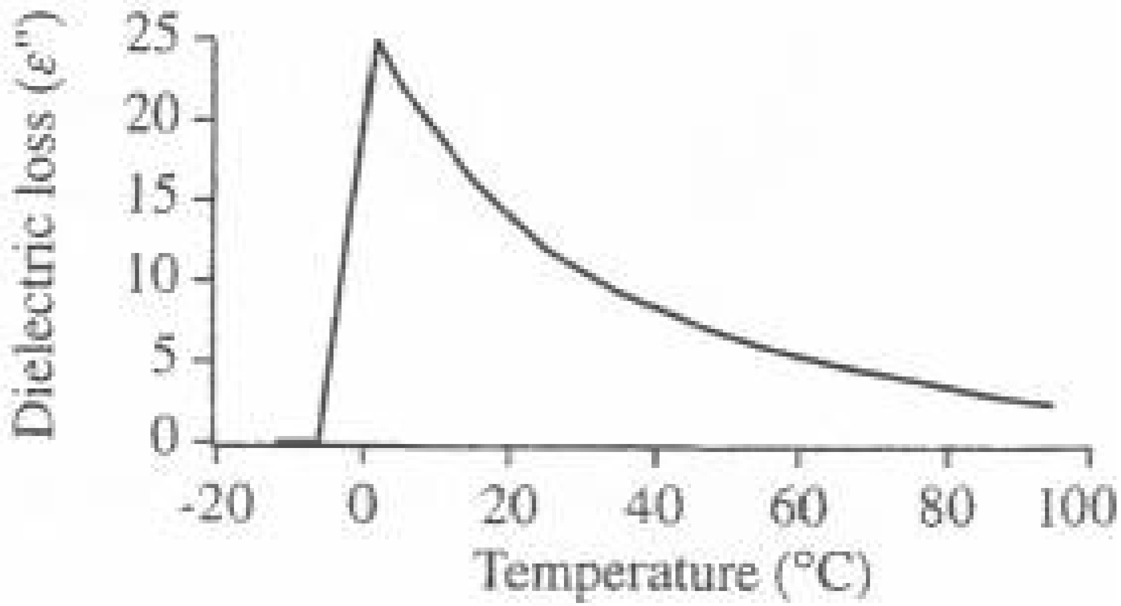


Figure 4. Dielectric loss of water and ice at a microwave frequency of 2450Mhz

Freezing of Solutions and Biomaterials

Solutions

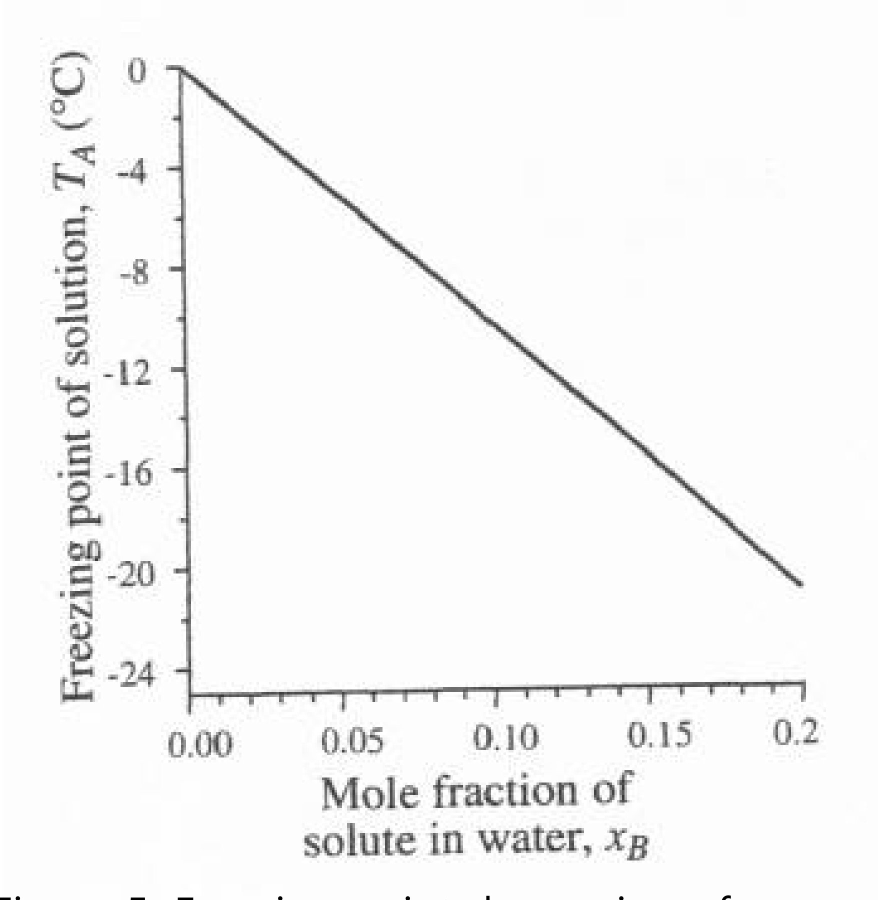


Figure 5. Freezing point depression of an aqueous solution as a function of concentration.

$$\frac{\Delta H_f}{R_g}\left[\frac{1}{T_{A0}}-\frac{1}{T_A}\right]=\ln x_A \quad (7.1)$$

$$\frac{\Delta H_f}{R_g}\left[\frac{T_A-T_{A0}}{T_{A0}T_A}\right]=\ln(1-x_B) \quad (7.2)$$

$$\frac{\Delta H_f}{R_g}\frac{\Delta T_f}{T_{A0}^2}=x_B \quad (7.3)$$

Freezing of Solutions and Biomaterials

Solutions

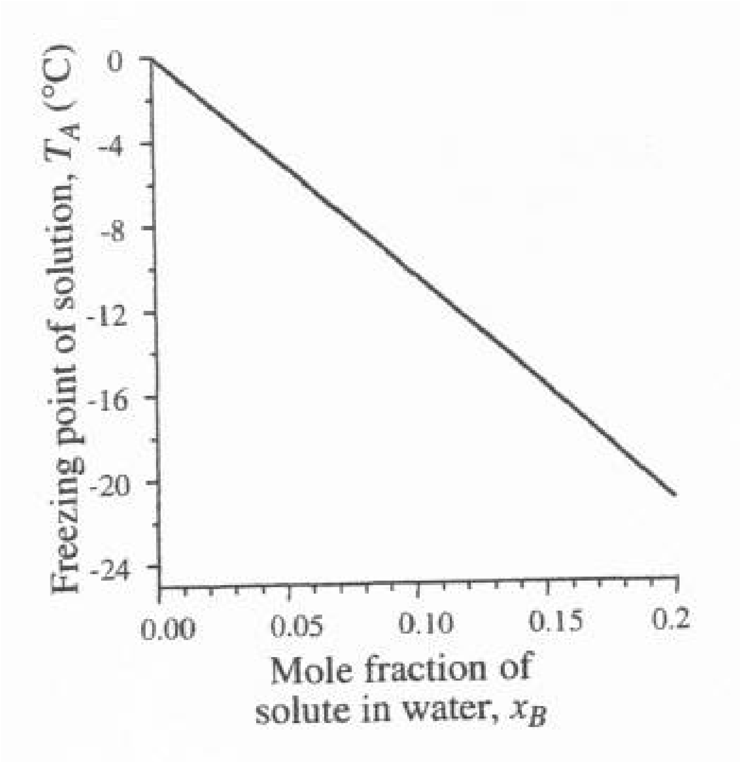


Figure 5. Freezing point depression of an aqueous solution as a function of concentration.

$$\Delta T_f = \frac{R_g T_{A0}^2 M_A M}{\Delta H_f}$$

(7.4)

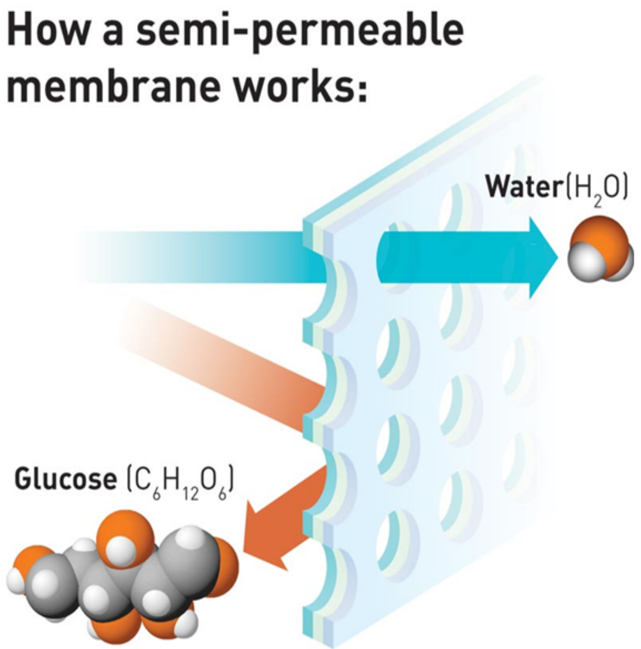
$$\Delta T_f = K_f M$$

(7.5)

Freezing of Solutions and Biomaterials

Cellular Tissues

During tissue freezing, the most fundamental physical change taking place is the transport of water across a cell's semi-permeable membrane.



Ice forms in the extracellular fluid first.

↓

The remaining extracellular fluid becomes more concentrated.

↓

This difference develops osmotic pressure.

↓

water flows out of the cell.

7.3 Freezing of Solutions and Biomaterials

Cooling Rates and Success of Freezing

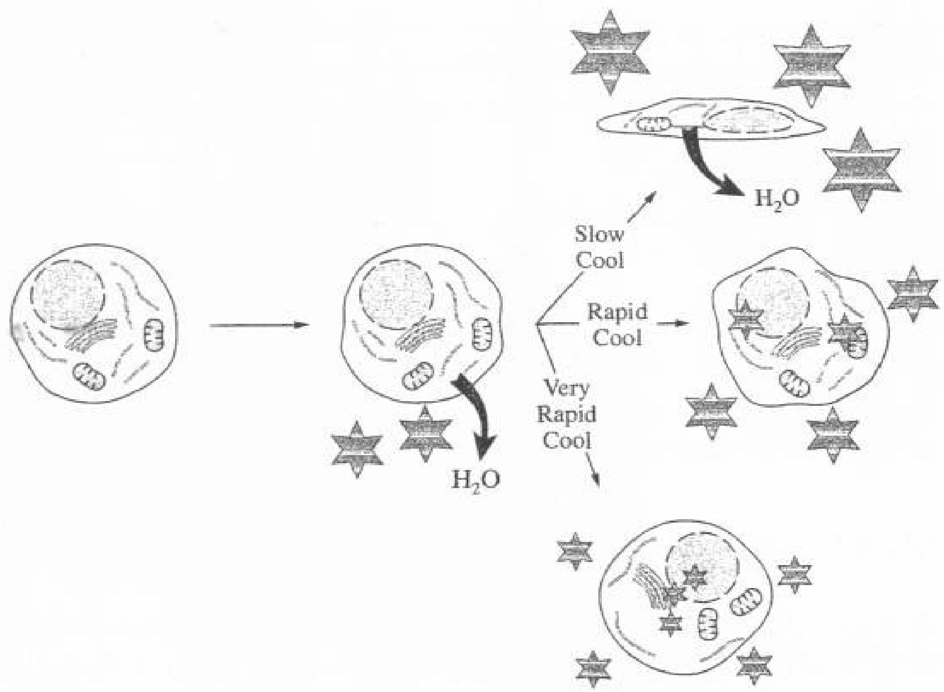


Figure 6. Schematic showing possibilities during cell freezing. Faster freezing reduces the transport of water out of the cell.

Temperature Profiles and Freezing Time

Freezing Time for an Infinite Slab of Pure Liquid

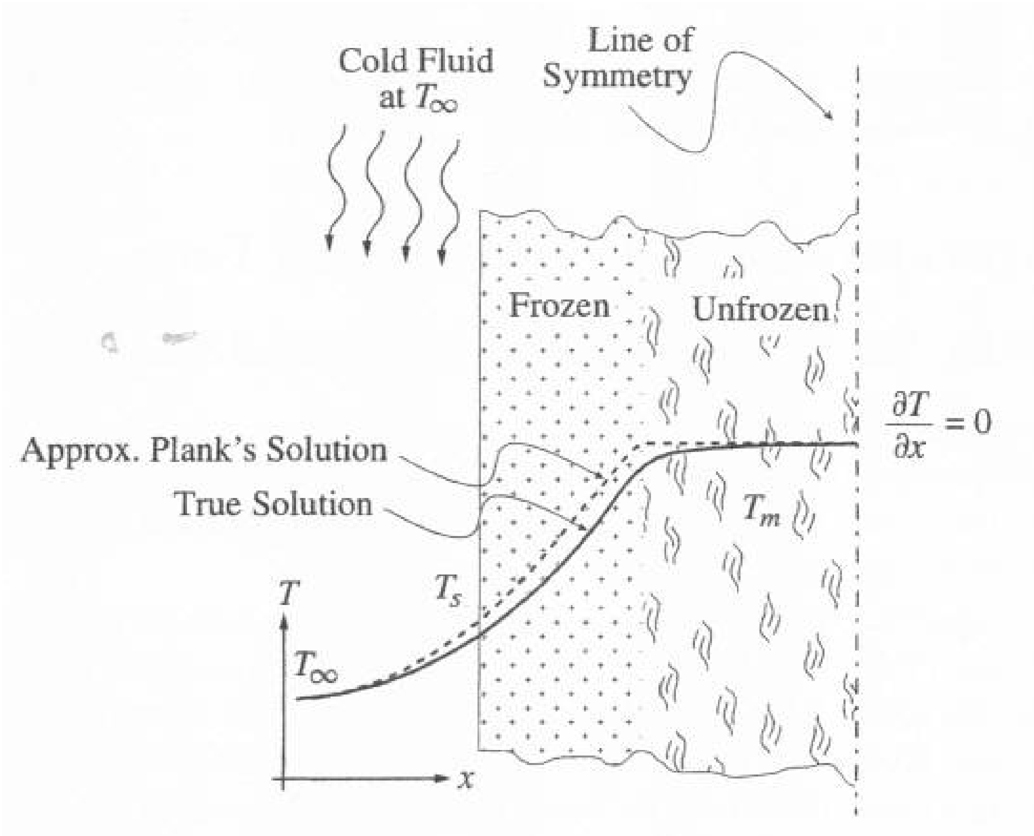


Figure 7. Freezing of a pure liquid showing two distinct regions, frozen and unfrozen.

Temperature Profiles and Freezing Time

Freezing Time for an Infinite Slab of Pure Liquid

$$q = kA\frac{T_m - T_s}{x}$$

$$q = \Delta H_f A \rho \frac{dx}{dt}$$

$$\rightarrow \Delta H_f A \rho \frac{dx}{dt} = kA\frac{T_m - T_s}{x}$$

When the freezing is completed, $t_{slab} = \frac{\Delta H_f \rho}{k(T_m - T_s)}\frac{L^2}{2}$

A more common boundary condition : $t_F = \frac{\Delta H_f \rho}{T_m - T_\infty}\left[\frac{L^2}{2k} + \frac{L}{h}\right]$

Temperature Profiles and Freezing Time

Freezing Time for Biomaterials

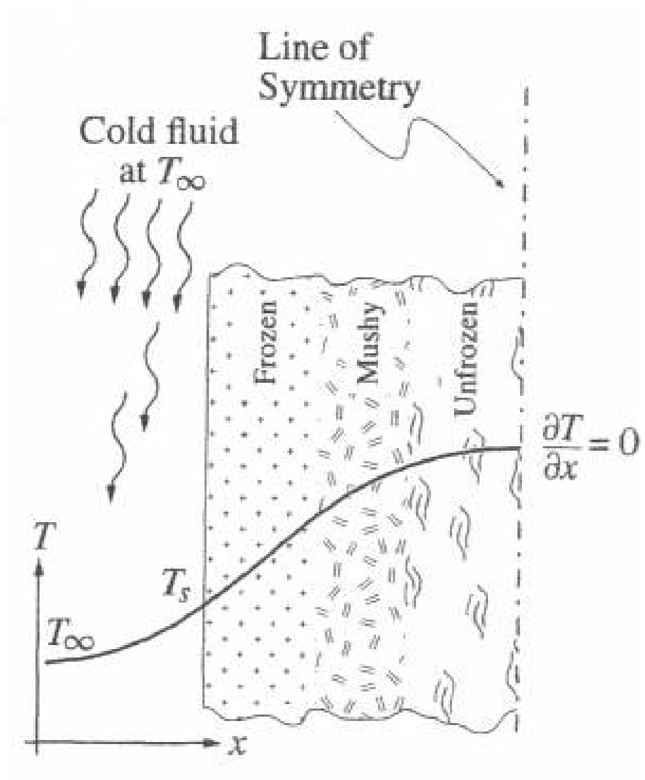


Figure 8. Freezing of a biological material a partially frozen or mushy zone.

Evaporation

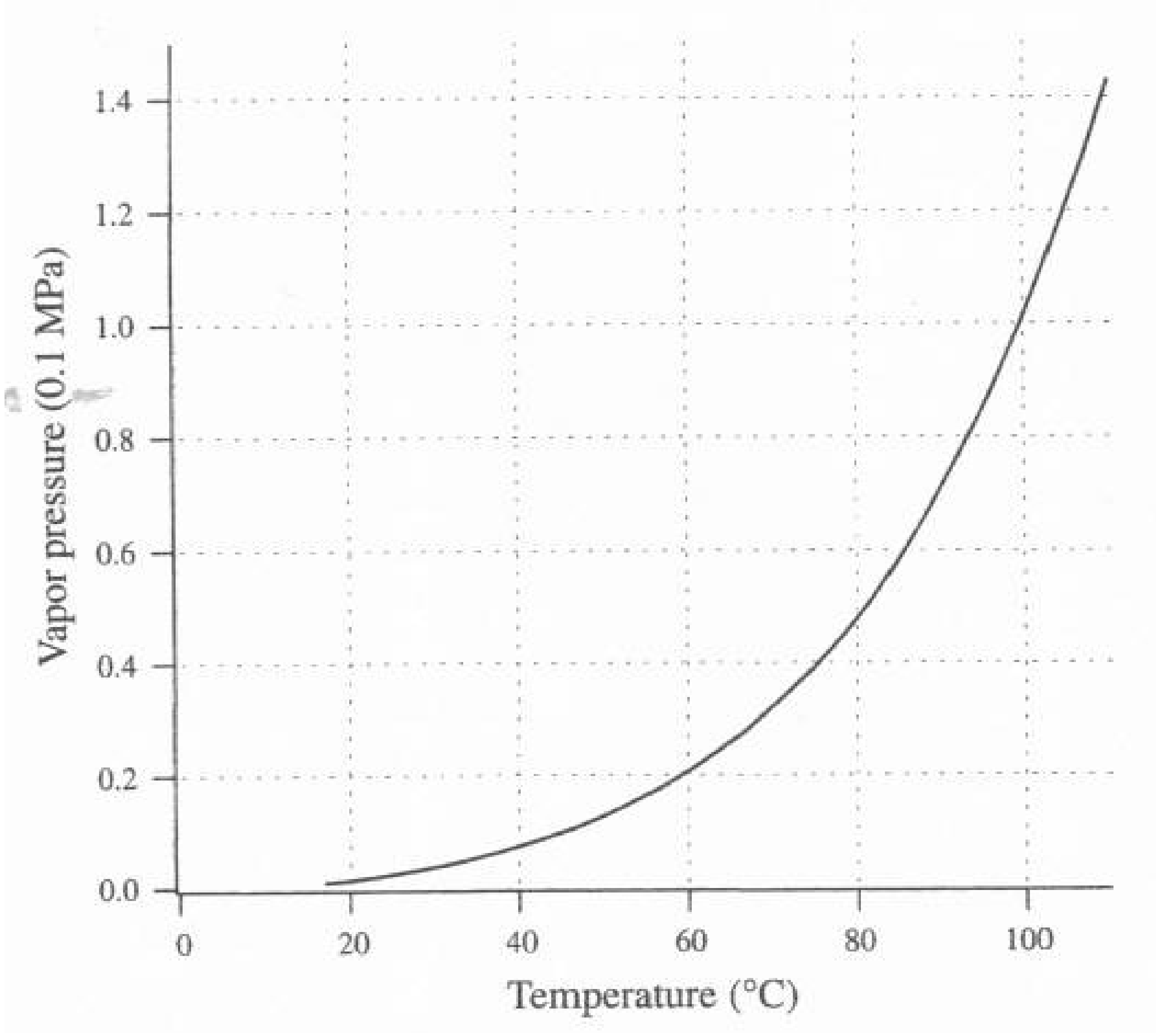


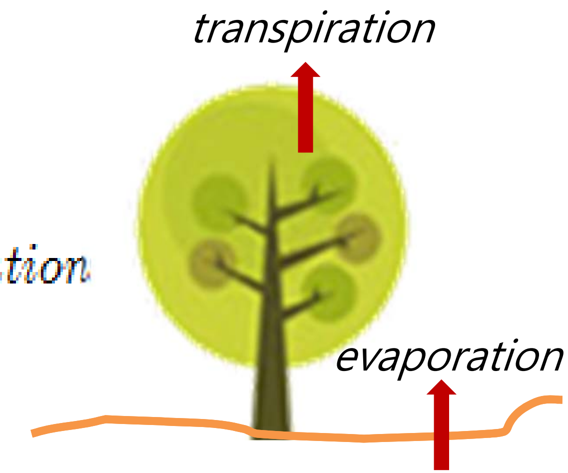
Figure 9. Vapor pressure of water at different temperature.

Evaporation

Evaporation from Wet Surfaces

$$\begin{matrix} Flux\ of \\ water\ vapor \end{matrix} = h_m (c_{sat\ at\ T} - c_{vapor\ at\ \infty}) \quad (7.15)$$

$$\begin{matrix} Flux\ of\ energy \\ from\ evaporation \end{matrix} = \Delta H_{vap} \left(\begin{matrix} Flux\ of \\ water\ vapor \end{matrix} \right) \quad (7.16)$$



- **Plant systems**

$$Evapotranspiraion = Evaporation + Transpiration$$

- **Animal systems**

Animals use panting and cutaneous evaporation.

⇒evaporative cooling processes

Evaporation

Evaporation Inside a Solid Matrix

Inside an unsaturated porous matrix, the rate of evaporation is related to temperature, amount of pore space, and permeability.

Evaporation of Solutions

Use to improve their storability or taste and to reduce bulk.

- **Evaporation** : occurring at the boiling point.
  an energy-intensive process.

- **Freeze concentration** : being separated out the ice.
  not lowered quality.

Chapter Summary

- **Freezing of Water**
  1. As water freezes, its density and specific heat decrease while its thermal conductivity increases.

- **Freezing of Solutions and Biomaterials**
  1. Water in biomaterials has dissolved solutes. When pure water freezes, concentrated solutes are lowering its freezing point.
  2. Higher cooling rates minimize the transport of intracellular water.

- **Freezing Time Calculations**
  1. Formulas for the freezing time for a slab is given by $t_F = \frac{\Delta H_f \rho}{T_m - T_\infty}\left[\frac{L^2}{2k} + \frac{L}{h}\right]$

- **Evaporation**
  1. The change of molecules from liquid to vapor state is called evaporation.
  2. Vapor pressure is the partial pressure of water vapor in equilibrium with the liquid.