1. With sketches, compare the differences during freezing of water, solution and food.

2. Figure 1 shows the schematic of the mechanical vapour compression cycle,
   (a) Explain its operating principle; [0.5]
   (b) If a standard vapour compression cycle operates with a condensing temperature of 35°C and an evaporating temperature of -10°C, draw the standard vapour compression cycle on the pressure-enthalthy diagram in Figure 2. [0.5]

3. **(a)** A 150 kg beef carcass is frozen to -20°C, if the mass fraction of water and protein are 58.21% and 17.48% respectively, and the initial freezing point is -1.7°C, what is the mass of frozen and unfrozen water at -20°C? The mass fraction of ice can be calculated by

   $$x_{ice} = \frac{1.105 x_{wo}}{1 + \dfrac{0.8765}{\ln\left(t_f - t + 1\right)}}$$ [0.4]

   (b) If the initial temperature of the carcass is 10°C, how much heat must be removed during this freezing process? The enthalpy of unfrozen and frozen foods can be calculated respectively by

   $$H = H_f + (t - t_f)(4.19 - 2.30 x_s - 0.628 x_s^3) \quad \text{(for unfrozen foods)}$$

   $$H = (t - t_r)\left[1.55 + 1.26 x_s - \frac{(x_{wo} - x_b) L_0 t_f}{t_r t}\right] \quad \text{(for frozen foods)}$$

   where t_r = reference temperature (zero enthalpy) = -40°C; H_f = enthalpy of food at initial freezing temperature, kJ/kg; L_0 = latent heat of fusion of water = 333.6 kJ/kg. (Hint: The equation for frozen foods can be used to calculate H_f). [0.6]

4. An infinite beef slab with thickness of 40 mm is to be frozen in an air blast freezer. The initial temperature of the beef is 10°C, freezing air temperature is -30°C and surface heat transfer coefficient is 40 $Wm^{-2}K^{-1}$.
   (a) Explain the physical meaning of the dimensionless numbers: Bi, Pk and Ste; [0.3]
   (b) Calculate the time required for the thermal centre of the beef to reach a temperature of -10°C. [0.7]

   The following data and equations may be used in the calculation:
   Densities of frozen and unfrozen beef are 1018 kg m^{-3} and 1075 kg m^{-3} respectively;
   Enthalpies at –10°C and at the initial freezing point –1.7°C are respectively 83.4 kJ kg^{-1} and 274.2 kJ kg^{-1};
   Specific heats of frozen and unfrozen beef are 2.11 kJ kg^{-1} K^{-1} and 3.52 kJ kg^{-1} K^{-1} respectively;
   Thermal conductivity of frozen beef is 1.66 W m^{-1} K^{-1}.

   $$\theta = \frac{\Delta H_{10}}{T_f - T_m}\left[\frac{PD}{h} + \frac{RD^2}{k_s}\right]$$

   $Bi = hD / k$; $Pk = C_l (T_i - T_f) / \Delta H$; $Ste = C_s (T_f - T_m) / \Delta H$
   P = 0.5072 + 0.2018 Pk + Ste (0.3224 Pk + 0.0105/Bi + 0.0681)
   R = 0.1684 + Ste (0.2740 Pk - 0.0135)

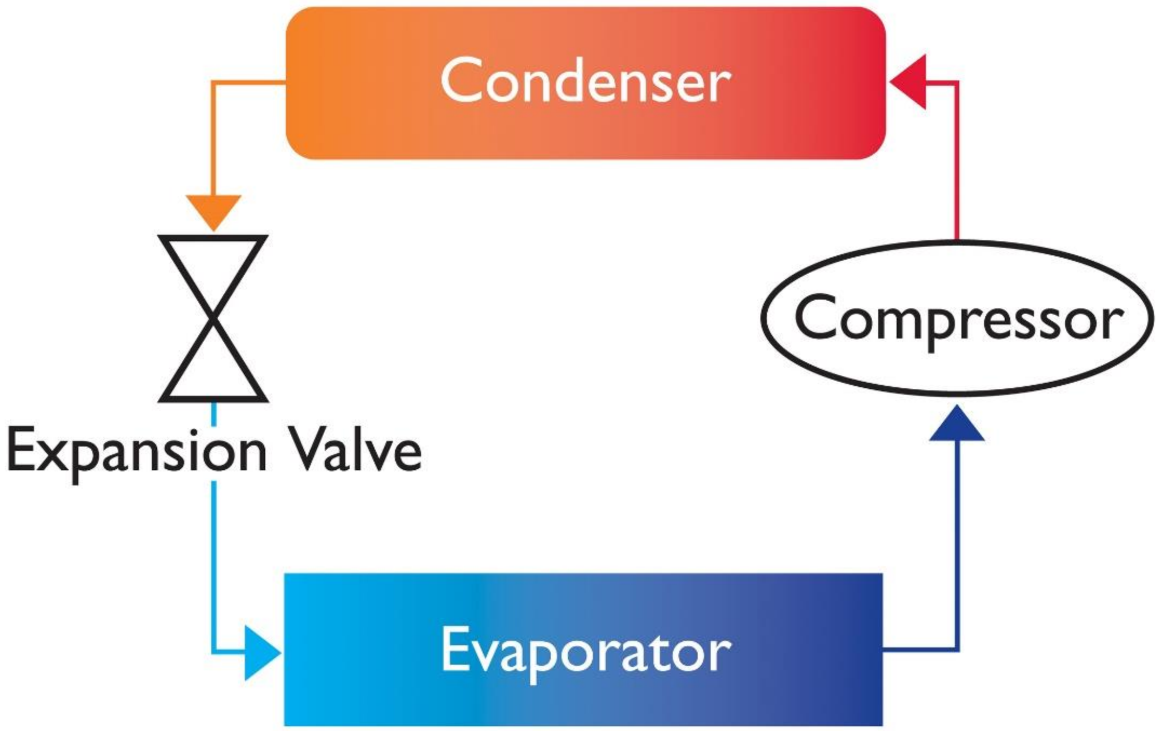

Figure 1. Mechanical vapour compression cycle.

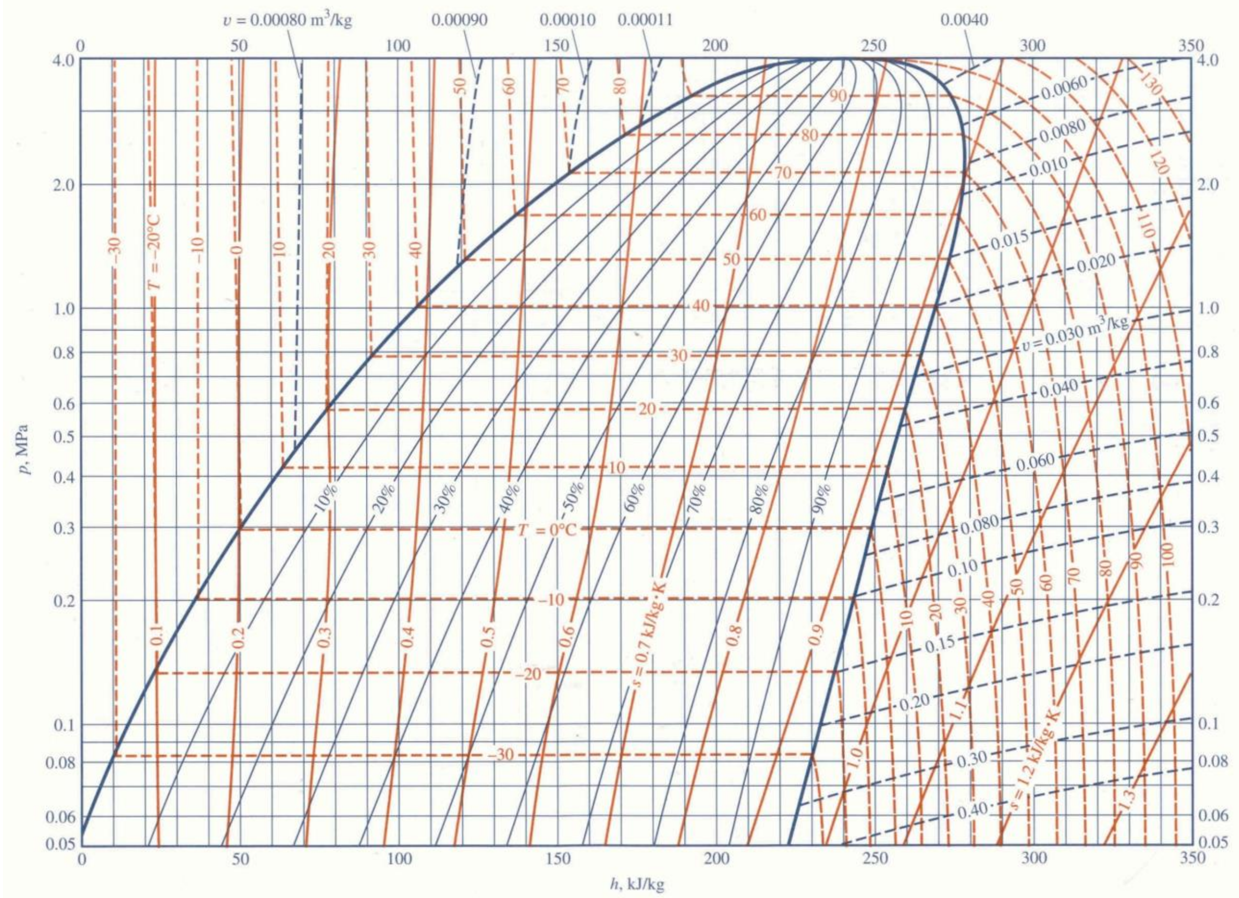

Figure 2. Pressure-enthalphy diagram for refrigerant 134a.