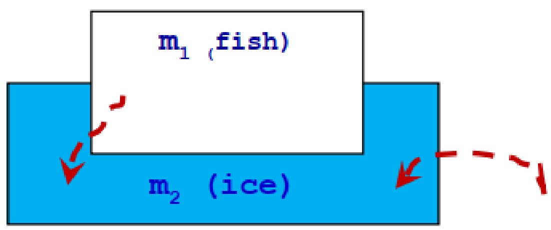
Energy Balances with Reaction

Materials and Energy Balances

1. Ice is used to cool the herring from 20 oC to 3 °C. The container with clean fish is inserted into an insulated container with ice at -10 °C. Ice will absorb 20 % of heat from the surroundings and 80 % of heat from the fish. Mean specific heat of ice is 2.06 kJ/kgK and it melts at 0 °C with latent heat of melting 333 kJ/kg. Assume 3/4 of ice melts during the cooling process. Calculate the amount of ice necessary to cool 50 kg of fish. Mean specific heat of herring is 2.97 kJ/kgK.



Solution

- Heat to be removed from herring:

$$H_1 = m_1 C_{p1}(T_1 - T_2)$$
$$= 50 \times 2.97 \times (20 - 3)$$
$$= 2524\ kJ$$

- This represents 80 % of the total heat taken by ice: $0.8\ H_{ice} = H_1$

$$H_{ice} = \frac{2524}{0.8} = 3155.625\ kJ$$

- Heat balance on the ice: the mass m2 of ice is first warming from -10 to 0 degrees, then ¾ of it is melting:

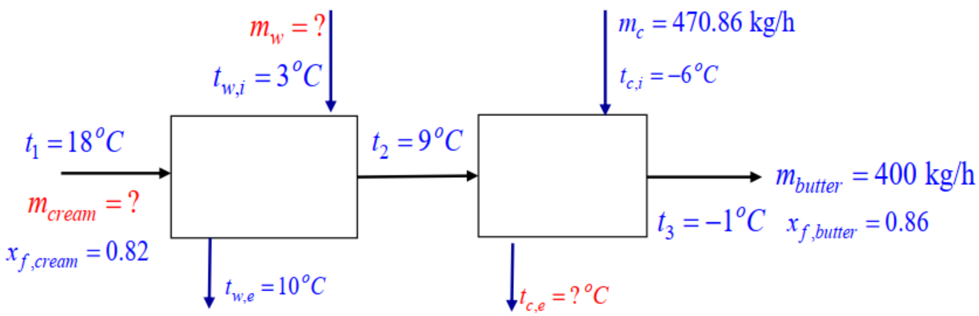
$$H_{ice} = m_{ice} C_{p\ ice}(T_4 - T_3) + \frac{3}{4} m_{ice}\ h_f$$

$$H_{ice} = m_{ice}\left(2.06 \times (0 - (-10)) + \frac{3}{4} \times 333\right)$$

$$3155 = m_{ice} \times 270.35$$

$$m_{ice} = 11.67\ kg$$

2. 400 kg/h of butter with 86 % (w/w) fat content is produced in a continuous process using cream with 82 % fat content. The cream is initially cooled from 18 oC to 9 °C in a jacketed vessel where water flows counter-currently. The inlet and outlet temperatures of the cooling water are 3 °C and 10 °C, respectively. The cream is further cooled to -1 °C using a coolant entering at -6 °C. The mass flow rate of the coolant is 470.86 kg/h and its mean specific heat is 3.15 kJ/kgK. The mean specific heat of the cream is 3.18 kJ/kgK. Calculate the mass flow rate of the cream in the cooling sections, the mass flow rate of the cooling water in the first section and the exit temperature of the coolant from the second section.



$$C_{P,c} = 3.15 \frac{kJ}{kgK};\ C_{P,cream} = 3.18 \frac{kJ}{kgK};$$

$$\left.\begin{array}{l} C_{P,w}\left(at\ 10\ ^{o}C\right) = 4.1949 \dfrac{kJ}{kgK} \\ C_{P,w}\left(at\ 3\ ^{o}C\right) = 4.2104 \dfrac{kJ}{kgK} \end{array}\right\} \Rightarrow C_{P,w} = 4.2026 \frac{kJ}{kgK}$$

Solution

To calculate m_{cream} the mass balance of the fat is written:

$$m_{cream} \cdot x_{f,cream} = m_{butter} \cdot x_{f,butter}$$

$$m_{cream} = \frac{m_{butter} \cdot x_{f,butter}}{x_{f,cream}} = \frac{400 \cdot 0.86}{0.82} = 419.51 \text{ kg/h}$$

Heat balance for first cooler:

$$m_{cream} \cdot C_{P,cream} \cdot (t_1 - t_2) = m_w \cdot C_{P,w} \cdot (t_{w,i} - t_{w,e})$$

$$m_w = \frac{m_{cream} \cdot C_{P,cream} \cdot (t_1 - t_2)}{C_{P,w} \cdot (t_{w,i} - t_{w,e})}$$

$$m_w = \frac{419.51 \frac{kg}{h} \cdot 3.18 \frac{kJ}{kgK} \cdot (18-9)K}{4.2026 \frac{kJ}{kgK} \cdot (10-3)K} = 408.13 \text{ kg/h}$$

Heat balance for second cooler:

$$m_{cream} \cdot C_{P,cream} \cdot (t_2 - t_3) = m_c \cdot C_{P,c} \cdot (t_{c,e} - t_{c,i})$$

$$t_{c,e} = \frac{m_{cream} \cdot C_{P,cream} \cdot (t_2 - t_3)}{m_c \cdot C_{P,c}} + t_{c,i}$$

$$t_{c,e} = \frac{419.51 \cdot 3.18 \cdot (9 - (-1))}{470.86 \cdot 3.15} + (-6) = 2.99 \ ^oC$$

3. Oil fuel containing 83% C and 17% H_2 is burnt in a furnace using preheated air, the preheat being supplied by the waste gases. The dry flue gas had the following composition: 12% CO_2, 4.4% O_2, 83.6% N_2. Calculate the temperature of the air leaving the preheater if it enters at 15°C and the hot gas inlet and outlet temperatures are 365°C and 110°C respectively.

Specific heat of flue gas = 1.05 kJ/kg K.

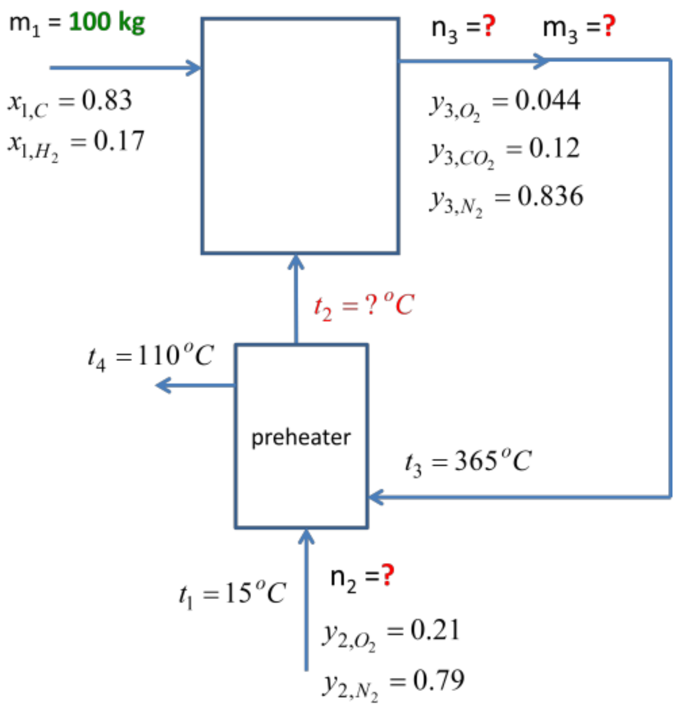
Specific heat of air = 1.003 kJ/kg K.

Specific heat of water vapour = 2.09 kJ/kg K.

Stoichiometric equations:

$$C + O_2 \rightarrow CO_2$$

$$H_2 + 1/2O_2 \rightarrow H_2O$$



Solution

Basis: 100 kg fuel

Component	Mass m_1, kg	Molecular weight, kg/kmol	Number of moles, kmol	Stoichiometric ratio to O_2	Theoretical kmol O2 required
C	83	12	6.92	1	6.92
H2	17	2	8.5	0.5	4.25
O2		32		-1	
N2		28		0	0
H2O		18		0	0

$$\left(n_{O_2}\right)_{theoretical} = 6.92 + 4.25 = 11.17 \text{ kmol } O_2$$

$$\left(n_{O_2}\right)_{fed} = y_{2,O_2} \cdot n_2 = 0.21 \cdot n_2 = \left(n_{O_2}\right)_{theoretical} + y_{3,O_2} \cdot n_3$$

All CO_2 comes from the C burnt:

$$n_{3,CO_2} = n_{1,C} = 6.92 \text{ kmol}$$

$$n_{3,CO_2} = y_{3,CO_2} \cdot n_3 \Rightarrow 6.92 = 0.12 \cdot n_3 \rightarrow \boxed{n_3 = 57.67 \text{ kmol DFG}}$$

$$n_{3,H_2O} = n_{1,H_2} = 8.5 \text{ kmol}$$

All N_2 comes from the air fed:

$$n_{3,N_2} = n_{2,N_2} = y_{2,N_2} \cdot n_2 = 0.79 \cdot n_2 \rightarrow n_2 = \frac{48.21}{0.79} = 61.03 \text{ kmol air}$$

$$M_{air} = 0.21 \cdot M_{O_2} + 0.79 \cdot M_{N_2} = 28.9 \frac{\text{kg}}{\text{kmol}}$$

$$m_{air} = n_2 \cdot M_{air} = 61.03 \cdot 28.9 = 1763.77 \text{ kg}$$

$$M_{DFG} = y_{3,CO_2} \cdot M_{CO_2} + y_{3,O_2} \cdot M_{O_2} + y_{3,N_2} \cdot M_{N_2}$$

$$M_{DFG} = 0.12 \cdot 44 + 0.044 \cdot 32 + 0.836 \cdot 28 = 30.1 \frac{kg}{kmol}$$

$$m_{DFG} = n_3 \cdot M_{DFG} = 57.67 \cdot 30.1 = 1735.87 \text{ kg}$$

$$m_{H_2O} = n_{3,H_2O} \cdot M_{H_2O} = 8.5 \cdot 18 = 153 \text{ kg}$$

Energy balance on the preheater:

$$C_{P,DFG} = 1.05\frac{\text{kJ}}{\text{kg K}};\ C_{P,air} = 1.003\frac{\text{kJ}}{\text{kg K}};C_{P,H_2O} = 2.09\frac{\text{kJ}}{\text{kg K}}$$

$$m_{DFG} \cdot C_{P,DFG} \cdot (t_3 - t_4) + m_{H_2O} \cdot C_{P,H_2O} \cdot (t_3 - t_4) = m_{air} \cdot C_{P,air} \cdot (t_2 - t_1)$$

$$1735.87 \cdot 1.05 \cdot (365 - 110) + 153 \cdot 2.09 \cdot (365 - 110) = 1763.77 \cdot 1.003 \cdot (t_2 - 15)$$

$$546320.54 = 1769.06 \cdot (t_2 - 15) \ \rightarrow \boxed{t_2 = 323.8\ ^oC}$$