LECUTRE -34: Heat flow in furnaces and exchangers

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Exercise-1

a) Regenerator receives hot flue gases at 1400°C and cold air at 25 °C, the flue gases leave at 750 °C and the air is preheated to 1100°C. As estimated 15% of the heat given up by the flue gases is heat lost to the regenerator surroundings, and the rest (85%) is recovered in the preheated air. It may be assumed for estimating purposes that \( C_P = 0.3 \) for flue gases and \( C_P = 0.25 \) for air, independent of temperature. Estimate over all thermal efficiency, efficiency limit, and relative efficiency for this heat exchange operation.

\[
\text{Solution:}
\]

\[
\text{a)} \quad \text{Heat balance: reference temperature } 25°C
\]
\[
\frac{m_a C_p_a (1100 - 25)}{m_f C_p_f (1400 - 750)} = 0.85 \times \frac{m_a C_p_a}{m_f C_p_f} = 0.514
\]

Overall thermal efficiency \( = 40.18\% \).

Efficiency limit \( = 51.4\% \).

Relative efficiency \( = 79.4\% \).

b) Suppose now that the depth of the regenerator is increased to 2.5 times in such a way to double the heat exchange area while keeping constant the over-all heat transfer coefficient \( U \) \( \frac{\text{Btu}}{\text{hr ft}^2 \text{°F}} \). The quantities and entering temperatures of the flue gases and air will be kept the same. Heat losses are same as that in a). Estimate for the enlarged regenerator (a) air preheat temperature, (b) over-all thermal efficiency and relative thermal efficiency

\[
\ln \left[ \frac{T_{h_2} - 25}{1400 - T_{c_2}} \right] = 2.5 \times \ln \left[ \frac{750 - 25}{1400 - 1100} \right]
\]
\[ T_{h2} - 25 = 12698 - 9.07T_{c2} \]  

(1)

Heat balance for the enlarged regenerator:

\[ m_a C_{Pa} (T_{c2} - 25) = 0.85 m_f C_{pf} (1400 - T_{h2}) \]  

(2)

In equation 2, \( T_{c2} \) and \( T_{h2} \) are air and flue gas temperature at the exit of the regenerator.

Or \[ 0.605 T_{c2} - 15.11 = 1400 - T_{h2} \]  

(3)

By solving 1 and 3

We get \( T_{c2} = 1335.8^\circ C \) and \( T_{h2} = 557^\circ C \).

Overall thermal efficiency = 49%.

Relative efficiency = 96%.

**Exercise-2**

Hot exhaust gases at 1250 kg/h are flowing at 480\(^\circ\)C through a heat exchanger and are cooled to 180\(^\circ\)C by water flowing initially at 20\(^\circ\)C. The specific heat of water is 1 kcal/kg × \(^\circ\)C and that of exhaust gas is 0.27 kcal/kg × \(^\circ\)C. The overall heat transfer coefficient is 125 kcal/hr × m\(^2\) × \(^\circ\)C and the flow rate of water is 1550 kg/hr. **Calculate surface area required when**

a) Exhaust gas and water flow counter-current  
b) Exhaust gas and water flow co-current.

**Solution:**

**Figure 34.1:** A) Counter-Current and B) Co-Current flow of water and gas

We have to find temperature of water at exit.

Heat given by exhaust gas = heat taken by water

\[ 1250 \times 0.27 \times 300 = 1500 \times 1(T - 20) \]
\[ T = 85^\circ C. \]
\[ q = UA_0 \frac{(T_{h1} - T_{c1}) - (T_{h2} - T_{c2})}{\ln \left( \frac{(T_{h1} - T_{c1})}{(T_{h2} - T_{c2})} \right)} \]

For counter current
\[ 1250 \times 0.27 \times 300 = 125 \times A_0 \frac{(480 - 85) - (180 - 20)}{\ln \left( \frac{480}{180} \right)} \]

\[ A_0 = 3.11 \text{ m}^2 \]

For co-current, one can calculate
\[ A_0 = 3.51 \text{ m}^2 \]

We note that in a counter current heat exchanger, area required for heat transfer is lower than that required for co-current heat exchanger. In this example heat exchange area for counter-current heat exchanger is 10% lower than that required for co-current one. It is due to the efficient contact between heat exchanging fluids, exchanging heat in counter-current.

**Exercise-3**

A furnace is to be designed to carry out an exothermic gas solid reaction on a continuous basis. Both gaseous and solid reactants are to be fed continuously at a uniform total rate of 9.7lb/hr and at 70\(^\circ\)F. The reaction products are to be discharged continuously at 1200\(^\circ\)F. The heat of reaction of total reactants is 1050 Btu/lb. The average specific heat of the reaction products is 0.2 Btu/lb \(^\circ\)F.

The reaction chamber is a vertical Inconel cylinder, 1/3ft in diameter and 3ft high, with suitable auxiliary facilities for continuous feed and discharge. Assume that the whole Inconel cylinder is maintained at 1200\(^\circ\)F.

The Inconel cylinder will be insulated on the outside with a refractory material for which \( K = 0.3 \) and \( \varepsilon = 0.8 \). **Will a 1/6 ft layer of insulation (making total furnace diameter 2/3 ft) allow to operate furnace autogenously?** Make other reasonable assumption if necessary.

Environment temperature = 70\(^\circ\)F

Use \( h_c = 0.28(T_w - T_o)0.25 \)

**Solution:**

Heat input = \( 1050 \times 9.7 = 10185 \) Btu/hr.

Heat taken by POC = 2192 Btu/hr.

Gross available heat = 7993 Btu/hr.
This heat must be dissipated in order to maintain 1200°F furnace temperature.

Heat balance is

\[ q_{\text{cond}} = q_{\text{conv}} + q_{\text{radiation}} \]

\[
\frac{(1200-T_w)0.3\times2\pi\times3}{\ln\frac{8}{4}} = 0.28 \left( T_w - T_o \right)^{1.25} \times \pi D L + 0.173 \times 0.8 \times \pi DL \left( \frac{T_w+460}{100} \right)^4 - (5.3)^4 \]

Solution gives \( T_w = 400 \) °F.

Heat loss would be 6523Bhu/hr which is lower than 7993 Bhu/hr.

Hence \( \frac{1}{6} \) feet layer is not sufficient.

Exercise- 4

Air at 2kg/s is passing in a duct of 0.08m diameter at 300K. The wall temperature of the duct is 900K. If the air is heated to a temperature of 800K, what is the length of the duct?

Solution:

Average properties of air at \( \frac{300+800}{2} = 550 \)K.

\[ \rho_{\text{air}} = 0.6423 \frac{\text{kg}}{\text{m}^3}, \mu_{\text{air}} = 2.84 \times 10^{-5} \frac{\text{kg}}{\text{m.s}} \]

\[ K = 0.04360 \frac{\text{W}}{\text{mk}}, \text{Pr} = 0.68 \]

\[ C_p = 1039 \frac{\text{J}}{\text{kg \cdot ^\circ C}} \]

Heat balance in the small duct length dx.

\[ \frac{dT}{T_w = T} = \frac{\pi d_i h}{m C_p} dx \]

Where \( T_w \) = wall temperature, \( d_i \) internal diameter of duct, \( h \) is heat transfer coefficient \( \frac{\text{w}}{\text{m}^2 \times \text{K}}, C_p \)

specific heat, \( m \) manflow rate \( \frac{\text{kg}}{\text{s}} \).

Integration \[ \ln \frac{T_w-T_i}{T_w-T_f} = \frac{\pi d_i h}{m C_p} \times L. \]

\( T_i \) is initial temperature = 300K. at \( x = 0 \)

\( T_f \) is final temperature of air = 800K. at \( x = L \).

\[ N_4 = 0.023 \left( \frac{d v \rho}{\mu} \right)^{0.8} (N_{Pr})^{0.4}. \]
\[
\frac{h_d}{K} = 0.023 \left( \frac{0.08 \times 2 \times 4 \times 10^5}{\pi \times 0.08 \times 0.08 \times 2.846} \right)^{0.8} (0.68)^{0.4}
\]

\[ h = 741 \frac{w}{m^2K} \]

\[ \ln \left[ \frac{900-300}{900-800} \right] = \frac{\pi \times 0.08 \times 741}{2 \times 1039} \times L \]

\[ \therefore L = 20m. \]