***Problem* 1.1**

An air stream of 0.6 kg/s is heated at constant pressure of 1.5 MPa from 620 K to 930 K. Calculate the rate: (i) the rate of work of volume change, (ii) the rate of heat addition, (iii) the rates of change in internal energy and the enthalpy of the air.

Given:

Air mass flow m = 0.6 kg/s; air pressure p = 1.5 MPa; air initial and final temperatures: T_1 = 620 K and T_2 = 930 K. For the air: gas constant R = 0.287 kJ/kgK, isentropic exponent k = 1.4, isochoric specific heat c_v = 0.718 kJ/kgK and isobaric specific heat c_p = 1005 J/kgK.

Calculate:

Rate of work of volume change W, heat input rate Q, rates of internal energy change ΔU and enthalpy change ΔH of the air. Set up the energy flow balance for the isobaric heat addition process.

The isobaric heat addition process. with an ideal gas is shown in Figure 1.1.

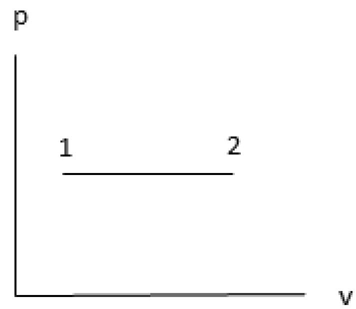

Figure 1.1. P - v diagram of an isobaric heat addition process with ideal gas

Solution:

1. Specific volume of the air at initial and final states, respectively

$v_1 = R\, v_1/p$ = 0.287 kJ/kgK * 620 K / 1500 kPa = 0. 1186 m^3/kg

$v_2 = v_1\, T_2/T_1$ = 0.1186 *780 / 520 = 0.1779 m^3/kg

2. Rate of work of volume change

$W = m\, p\, (v_2 - v_1)$ = 0.6 kg/s*1500 kPa*(0.1779 - 0.1186) m^3/kg = 53.38 kJ/s

3.Rate of heat addition

$Q = m\, c_p\, (T_2 - T_1)$ = 0.6 kg/s*1.005 kJ/kgK *(930 - 620) K = 186.93 kJ/s

4. Rates of change in internal energy and enthalpy of the air

$\Delta U = m\, c_v\, (T_2 - T_1)$ = 0.6 kg/s*0.718 kJ/kgK *(930 - 620) = 133.55 kJ/s

$\Delta H = m\, c_p\, (T_2 - T_1) = Q$ = 186.93 kJ/s.

5. Based on the first law of thermodynamics, the process energy flow balance

$Q = W + \Delta U$: 186.93 kJ/s = 53.38 kJ/s + 133.55 kJ/s.

Answer:

W = 53.38 kJ/s, Q = 186.93 kJ/s, = 186.93 kJ/s, ΔH = 186.93 kJ/s.

***Problem* 1.2**

A gas turbine compressor compresses 235 kg/s of air from p_1 = 1 bar and T_1 = 300 K to p_2 = 17 bars in an isentropic process. Calculate (i) the air final temperature, (ii) the power input to the compressor, (iii) the rates of change in internal energy and enthalpy of the air. For the air: k = 1.4, c_v = 0.718 kJ/kgK and c_p = 1.005 kJ/kgK.

Given:

Mass flow rate of the air m = 235 kg/s, initial state: p_1 = 1 bar and T_1 = 300 K, final pressure p_2 = 17 bars.

Calculate:

Air final temperature T_2, rate of compressor shaft work W_c, rates of change in internal energy and enthalpy of the air, ΔU and ΔH.

The isentropic compression process with an ideal gas is shown in Figure 1.2.

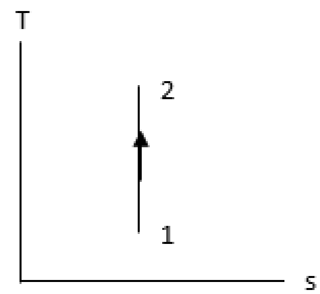

Figure 1.2. T – s diagram of an isentropic compression process with ideal gas

Solution:

1. Air final temperature

   $T_2 = T_1 (p_2 / p_1)^{(k-1)/k} = 300*(17/1)^{(1.4-1)/1.4} = 674$ K
2. Power input to the compressor, i.e., rate of the compressor shaft work

   $W_c = m\, c_p (T_1 – T_2) = 235*1.005*(300 - 674) = -163516$ kJ/s
3. Rates of change in internal energy and enthalpy of the air

   $\Delta U = m\, c_v (T_2 – T_1) = 235*0.718*(674 - 300) = 116820$ kJ/s

   $\Delta H = m\, c_p (T_2 – T_1) = 235*1.005* (674 - 300) = 163516$ kJ/s
4. Energy flow balance for the process per unit time

   For the isentropic process $Q = 0$ and $W_c = -\Delta H$: -163516 = - 163516.

Answer: T_2 = 674 K, W_c = -163516 kJ/s, ΔU = 116820 kJ/s and ΔH = 163516 kJ/s.

***Problem* 1.3**

An arbitrary heat engine is operating with the average heat addition and heat rejection temperatures $T_{in,1}$ and $T_{out,1}$ of 600 K and 360 K, respectively The thermal efficiency of the cycle should be increased by 25% (i) by increasing the heat addition temperature or (ii) by decreasing the heat rejection temperature. Determine the required temperatures (i) $T_{in,2}$ and (ii) $T_{out,2}$.

Given:

Heat addition and heat rejection temperatures $T_{in,1}$ = 600 K and $T_{out,1}$ = 360 K. Thermal efficiency of the cycle should be increased by 25% by changing these temperatures.

Calculate:

Required temperatures (i) $T_{in,2}$ and (ii) $T_{out,2}$.

Refer to Figure 1.4 in the book "Advanced Energy Systems", 2nd ed.

Solution:

1. Initial thermal efficiency of the cycle

   $\eta_{th,1} = 1 – T_{out,1}/ T_{in,1} = 1 - 360/600 = 0.4$

2. Thermal efficiency is increasing from $\eta_{th,1}$ = 0.4 to $\eta_{th,2}$ = 0.5
(i) If the heat addition temperature increases from $T_{in,1}$ of 600 K to

$T_{in,2} = T_{out,1}/(1- \eta_{th,2}) = 360/(1-0.5) = 720$ K or

(ii) If the heat rejection temperature decreases from $T_{out,1}$ of 360 K to

$T_{out,2} = T_{in,1}*(1- \eta_{th,2}) = 600/(1-0.5) = 300$ K.

Hence, the cycle thermal efficiency η_{th} increases if the temperature difference $T_1 - T_2$ increases. *Answer:* $T_{in,2}$ = 720 K and $T_{out,2}$ = 300 K.

***Problem* 1.4**

A steam turbine is operating at a steam flow rate of 550 kg/s with an enthalpy of live steam h_1 of 3670 kJ/kg and enthalpy of exhaust steam h_2 of 2010 kJ/kg. The condensate enthalpy h_c at the condenser outlet is 140 kJ/kg. Calculate (i) the power output of the steam turbine, (ii) the rate of heat rejection in the condenser, and (iii) the required cooling water flow in the condenser, where its temperature increases by ΔT_{cw} = 11 K. Specific heat of the water is 4.19 kJ/kgK.

Given:

Steam flow rate m = 550 kg/s. Enthalpies of live steam h_1 = 3670 kJ/kg, exhaust steam h_2 = 2010 kJ/kg and condensate h_c = 140 kJ/kg. Temperature of cooling water increases in condenser by ΔT_{cw} = 11 K.

Calculate:

Turbine power output P_t, heat rejection rate in the condenser Q_c, cooling water requirements m_{cw}.

Solution:

1. Power output of the steam turbine

$P_t = m\,(h_1 - h_2)$ = 550 kg/s * (3670-2010) kJ/kg = 913 MW

2. Rate of heat rejection in the condenser

$Q_c = m\,(h_2 - h_c)$ = 550 kg/s * (2010-140) kJ/kg = 1028.5 MJ/s

3. Flow rate of the cooling water

$m_{cw} = Q_c / (c_p\, \Delta T_{cw})$ = 1028500 kJ/s / (4.19 kJ/kgK * 11 K) = 22315 kg/s = 80330 t/h.

Answer:

P_t = 913 MW, Q_c = 1028.5 MJ/s, m_{cw} = 22315 kg/s = 80330 t/h.

***Problem* 1.5**

A two-layer 24 m^2 plane wall consists of a 250 mm thick inner concrete layer with thermal conductivity k_1 of 2 W/m K and a 80 mm thick outer insulation with k_2 of 0.04 W/m K. The temperatures of wall inner and outer surfaces are: t_1 = 28°C and t_3 = -9°C. Calculate (i) the rate of heat transfer and (ii) the temperature t_2 of the wall intermediate surface.

Given:

Wall surface area A = 24 m^2, thickness of inner aNEWnd outer layers δ_1 = 250 mm and δ_2 = 80 mm, their thermal conductivity k_1 = 2 W/m K and k_2 = 0.04 W/m K. Temperatures of inner and outer surfaces t_1 = 28°C and t_3 = -9°C.

Calculate:

Rate of heat transfer Q and temperature of the wall intermediate surface t_2.
Refer to Figure 1.6 in the book “Advanced Energy Systems”, 2nd ed.

Solution:

1.Thermal resistance of the 2-layer wall

$R_w = R_1 + R_2 = \delta_1 / k_1 + \delta_2 / k_2 = 0.25/2 + 0.08/0.04 = 0.125 + 2 = 2.125$ m^{2}K/W

2. Rate of heat transfer

   $Q = A (t_1 - t_3) / R_w = 24*[28 – (-12)] / 2.125 = 417.9$ W

3. Temperature of the wall intermediate surface

   $t_2 = t_1 - R_1 Q / A = 28 – 0.125*417.9 / 24 = 25.82°C$

Answer:

Q = 417.9 W and t_2 = 25.82°C.

***Problem* 1.6**

Water flows at a velocity of 1.2 m/s in a tube with a diameter of 50 mm and a length L of 16 m. The mean temperature of water is 30°C and that of tube surface is 39°C. Calculate (i) the heat transfer coefficient and (ii) the rate of heat transfer from tube to the fluid. Physical properties of water at 30°C are: k = 0.614 W/mK, $\nu = 0.801*10^{-6}$ m^2/s, Pr = 5.43.

Given:

Water velocity u = 1.2 m/s, tube diameter d = 50 mm and length L = 16 m. Water and tube surface temperatures: t_f = 30°C and t_w = 39°C. Properties of water at 30°C: k = 0.614 W/mK, $\nu = 0.801*10^{-6}$ m^2/s, Pr = 5.43.

Calculate:

Heat transfer coefficient h and rate of heat transfer Q.

Solution:

1. Reynolds number $Re = u\, d/v$

   $Re = u\, d/v = 1.2*0.05 / (0.801*10^{-6}) = 74906$.

   As Re>10,000, the fluid flow is turbulent.

2. Nusselt number

   $Nu = 0.023\, Re^{0.8}\, Pr^{0.4} = 0.023* (74906)^{0.8}*5.43^{0.4} = 359$

3. Heat transfer coefficient

   $h = \text{Nu}\, k/d = 359*0.614/0.05 = 4408$ W/(m^{2}K)

4. Rate of heat transfer

   $Q = \pi\, d\, L\, h\, (t_w - t_f) = \pi\ 0.05*16*4408*(39-30) = 99706$ W.

Answer: h = 4408 W/(m^{2}K), Q = 99706 W.

***Problem* 1.7**

Calculate the net rate of energy exchange by thermal radiation in a system consisting of two large parallel plane surfaces 1 and 2 with a surface area of A = 4 m^2 each, temperatures T_1 of 550 K and T_2 of 430 K, and emissivities ε_1 of 0.3 and ε_2 of 0.8. Assume that the distance between the two plane surfaces is small compared to their dimensions.

Given:

Two parallel grey planes. Plane surface area A = 4 m^2, temperatures T_1 = 550 K and T_2 = 430 K, and emissivities ε_1 of 0.3 and ε_2 of 0.8

Calculate:

Net rate Q_{12} of energy exchange by thermal radiation. Refer to Figure 1.8a in the book “Advanced Energy Systems”, 2nd ed.

Solution:

1. Effective emissivity of the system

   $\varepsilon_{eff} = (1/\varepsilon_1 + 1/\varepsilon_2 - 1)^{-1} = (1/0.3 + 1/0.8 - 1)^{-1} = 0.279$

2. Net rate of radiation energy exchange between planes 1 and 2

$Q_{12} = \varepsilon_{eff} A \, \sigma \, (T_1^4 - T_2^4) = 0.279*4*5.67*10^{-8}$ W/(m^{2}K^4) * (550^4 - 430^4) K^4

Q_{12} = 3628 W

Answer:

Q_{12} = 3628 W.

***Problem* 1.8**

Calculate the net rate of energy exchange by thermal radiation between a grey convex body 1 and its grey enclosure 2. The surface area of the convex body is A_1 of 0.8 m^2, its temperature T_1 is 410 K and emissivity ε_1 is 0.6. The enclosure has a surface area A_2 of 1.6 m^2, temperature T_2 of 330 K and emissivity ε_2 of 0.9.

Given:

Grey convex body 1: A_1 of 0.8 m^2, T_1 is 410 K, ε_1 is 0.6

Grey enclosure 2: A_2 of 1.6 m^2, T_2 of 330 K and ε_2 of 0.9

Calculate:

Net rate Q_{12} of energy exchange by thermal radiation. Refer to Figure 1.8b in the book "Advanced Energy Systems", 2nd ed.

Solution:

1. Effective emissivity of the system

$\varepsilon_{eff} = [1/\varepsilon_1 + (1/\varepsilon_2 - 1) A_1 / A_2]^{-1} = [(1/0.6 + 1/0.9 - 1)*0.8/1.6]^{-1} = 0.581$

2. Net rate of energy exchange by thermal radiation between body and its enclosure

$Q_{12} = \varepsilon_{eff} A_1 \, \sigma \, (T_1^4 - T_2^4) = 0.581*0.8$ m^2 $*5.67*10^{-8}$ W/(m^{2}K^4) * (410^4 - 330^4) K^4

Q_{12} = 432.2 W.

Answer:

Q_{12} = 432.2 W.

***Problem* 1.9**

For a counter-flow water-water heat exchanger, the mass flow rate s of hot and cold fluids are m_h = 0.24 kg/s and m_c = 0.2 kg/s, the overall heat transfer coefficient is U = 1700 W/m^{2}K, the hot fluid temperatures are t_{hi} = 66°C (inlet), t_{he} = 48°C (exit) and hot fluid inlet temperature is t_{ci} = 19°C. The specific heat of hot and cold fluids c_p is 4.19 kJ/kgK. Calculate (i) the heat transfer rate, (ii) the exit temperature of cold fluid, and (iii) the heat transfer surface area.

Given:

Counter-flow heat exchanger. Overall heat transfer coefficient is U = 1700 W/m^{2}K.

Hot fluid: m_h = 0.24 kg/s, t_{hi} = 66°C, t_{he} = 48°C. Cold fluid: m_c = 0.2 kg/s, t_{ci} = 19°C.

Calculate:

Heat flow rate Q, exit temperature of cold fluid t_{ce} and heat transfer surface area A. Refer to Figures 1.9a and b in the book "Advanced Energy Systems", 2nd ed.

Solution:

1. Heat transfer rate

$Q = m_h c_p (t_{hi} - t_{he})$ = 0.24 kg/s *4.19 kJ/kgK* (66 - 48) K = 18.1 kJ/s

2. Exit temperature of the cold fluid

$t_{ce} = t_{ci} + Q / (m_c c_p)$ = 19°C + 18.1 kJ/s / (0.2 kg/s *4.19 kJ/kgK) = 40.6°C

3. Mean temperature difference between hot and cold fluids (approximately)
   $\Delta T_m = [(t_{hi} - t_{ce}) + (t_{he} - t_{ci})]/2 = [(66 - 40.6) + (48 - 19)]/2 = 27.2$ K
4. Heat transfer surface area of the heat exchanger
   $A = Q / (U \Delta T_m)$ = 18.1 kJ/s / (1.7 kW/ m^2K *27.2 K) = 0.391 m^2

Answer:

Q = 18.1 kJ/s, t_{ce} = 40.6°C, A = 0.391 m^2.

***Problem* 1.10**

Water flows with a velocity of 1.3 m/s in a 25 m long hydraulically smooth pipe with a diameter of 40 mm. The water temperature is 20°C. A pump is used to raise the water pressure by 3 bars. Calculate (i) the volumetric flow rate of water, (ii) the pressure loss in the pipe, and (iii) the power required to drive the pump if its efficiency is 0.86.

Physical properties of water at 20°C: Density ρ = 998 kg/m^3, kinematic viscosity ν = 1.004*10^{-6} m^2/s.

Given: pipe d = 40 mm and L = 25 m, velocity u = 1.3 m/s, Δp_p = 3 bars,

Calculate: Water flow rate Q, pressure loss in the pipe Δp_{loss}, and power to drive the pump P_p.

Solution:

1. Volumetric flow rate of water
   $Q = u A = u \pi d^2/4 = 1.3 * \pi * 0.04^2/4 = 0.001634$ m^3/s
1. Reynolds number
   Re = $u\, d / \nu$ = 1.3*0.04 / (1.004*10^{-6}) = 51793.
   As Re > 10^4, the water flow is turbulent.
2. The friction factor for turbulent flow with Re < 10^5 is given by
   $\lambda = 0.3164 / Re^{0.25} = 0.3164/51793^{0.25} = 0.021$
3. Pressure loss in the pipe due to friction
   $\Delta p_{loss} = \lambda (L/d) \rho u^2 / 2 = 0.021 *(25 /0.04)*998*1.3^2/2 = 11068$ Pa
4. Power required to drive the pump
   $P_p = Q (\Delta p_p + \Delta p_{loss})/ \eta_p$ = 0.001634 m^3/s *(3*10^5 + 11068) Pa / 0.86 = 591 W.

Answer:

Q = 0.001634 m^3/s, Δp_{loss} = 11068 Pa, P_p = 591 W.

***Problem* 2.1**

A bituminous coal has the following composition (in % by mass): carbon 80%, hydrogen 5%, oxygen 4%, ash 5% and moisture 6%.

Calculate: (a) the stoichiometric and actual air-fuel ratios for a 10% excess air in kg/kg, (b) the volumes of the constituents of the products of combustion, and (c) the mole fractions of the products of combustion. Ignore the air humidity, i.e. ω = 0.

Given:

Coal ultimate analysis (in % by mass): C = 80%, H = 5%, O = 4%, A = 5%, M = 6%.

Excess air ratio λ = 1.1.

Calculate:

Stoichiometric and actual air-fuel ratios f_{st} and f_a, mole fractions of the products of combustion r_i.

Refer to Figure 2.1 in the book “Advanced Energy Systems”, 2nd ed.