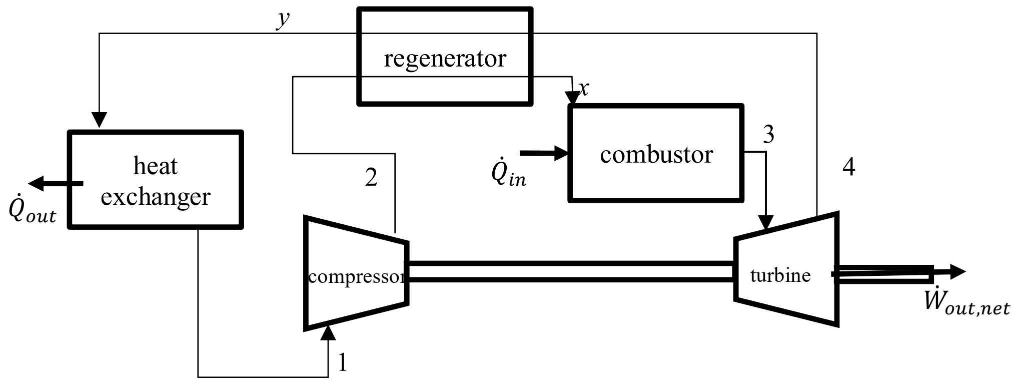
Air enters the compressor of a regenerative air-standard Brayton cycle with a volumetric flow rate of 60 m^3/s at 0.8 bar (abs) and 280 K. The compressor pressure ratio is 20 and the maximum cycle temperature is 2100 K. The compressor and turbine have isentropic efficiencies of 92% and 95%, respectively. For a regenerator effectiveness of 85%, determine:

a. the net power developed,
b. the rate of heat addition in the combustor,
c. the thermal efficiency of the cycle.

SOLUTION:



To determine the net power developed, apply the 1st Law to a CV surrounding the compressor and turbine,

$\dot{W}_{out,net} = \dot{m}(h_1 + h_3 - h_2 - h_4)$ (assuming SSSF, adiabatic, and negligible KE and PE). (1)

The rate of heat transfer in the combustor is found by applying the 1st Law to a CV surrounding the combustor,

$\dot{Q}_{in} = \dot{m}(h_3 - h_x)$ (assuming SSSF, passive device, and negligible KE and PE). (2)

Now find the properties at the various states.

State 1:

$\dot{V} = 60$ m^3/s, $p_1 = 0.8$ bar (abs) = 80 kPa (abs), $T_1 = 280$ K

=> $h_1 = 280.1$ kJ/kg and $p_r(T_1) = 1.0889$ (from the Ideal Gas Table for air)

Also, from the ideal gas law,

=> $\rho_1 = \frac{p_1}{RT_1} = 0.9955$ kg/m^3 => $\dot{m} = \rho\dot{V} = 59.731$ kg/s (3)

State 3:

$T_3 = 2100$ K,

=> $h_3 = 2377$ kJ/kg and $p_r(T_3) = 2559$ (from the Ideal Gas Table for air)

State 2:

$p_2/p_1 = 20 = p_{2s}/p_1$ and $\eta_{\text{comp,isen}} = 0.92$ (given),

$\eta_{comp,isen} = \frac{w_{in,isen}}{w_{in}} = \frac{h_{2s} - h_1}{h_2 - h_1}$ => $h_2 = h_1 + \frac{h_{2s} - h_1}{\eta_{comp,isen}}$. (4)

For an ideal gas undergoing an isentropic process,

$\frac{p_{2s}}{p_1} = \frac{p_r(T_{2s})}{p_r(T_1)}$ => $p_r(T_{2s}) = p_r(T_1)\left(\frac{p_{2s}}{p_1}\right)$, (5)

=> $p_r(T_{2s}) = 21.778$ => $T_{2s} = 649.33$ K, $h_{2s} = 659.29$ kJ/kg (IGT),

=> $h_2 = 692.26$ kJ/kg.

State 4:

$p_3/p_4 = 20 = p_3/p_{4s}$ $(= p_2/p_1)$ and $\eta_{turb,isen} = 0.95$ (given),

$$\eta_{turb,isen} = \frac{w_{out}}{w_{out,isen}} = \frac{h_3 - h_4}{h_3 - h_{4s}} \Rightarrow h_4 = h_3 - \eta_{turb,isen}(h_3 - h_{4s}). \quad (6)$$

For an ideal gas undergoing an isentropic process,

$$\frac{p_{4s}}{p_3} = \frac{p_r(T_{4s})}{p_r(T_3)} \Rightarrow p_r(T_{4s}) = p_r(T_3)\left(\frac{p_{4s}}{p_3}\right), \quad (7)$$

=> $p_r(T_{4s}) = 127.95$ => $T_{4s} = 1029.19$ K, $h_{4s} = 1079.57$ kJ/kg (IGT),

=> $h_4 = 1144.44$ kJ/kg.

State x:

From the definition of the regenerator effectiveness,

$$\eta_{reg} = \frac{h_x - h_2}{h_4 - h_2} \Rightarrow h_x = h_2 + \eta_{reg}(h_4 - h_2), \quad (8)$$

Using the previously calculated specific enthalpy values and the given $\eta_{reg} = 0.85$,

=> $h_x = 1076.61$ kJ/kg.

Using these state data, Eq. (1) gives,

$\boxed{\dot{W}_{out,net} = 49.0 \text{ MW}}$,

and Eq. (2) gives,

$\boxed{\dot{Q}_{in} = 77.7 \text{ MW}}$.

The thermal efficiency for the cycle is,

$$\boxed{\eta_{cycle} = \frac{\dot{W}_{out,net}}{\dot{Q}_{in}} = 0.631 = 63.1\%.} \quad (9)$$

Note that as η_{reg} increases, then h_x approaches h_4 and $\dot{Q}_{in}$ decreases. As a result, the thermal efficiency for the cycle would increase. In the limit of $\eta_{reg} = 100\%$, $\dot{Q}_{in,min} = 73.6$ MW and $\eta_{cycle,max} = 66.6\%$. In contrast, without the regenerator ($\eta_{reg} = 0$), then $\dot{Q}_{in,max} = 100.6$ MW and $\eta_{cycle,min} = 48.7\%$. Thus, we observe that including a regenerator can substantially improve the cycle's thermal efficiency.