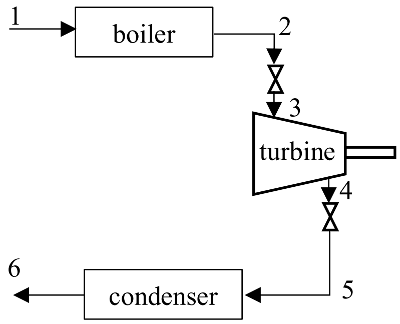
A power system is devised consisting of the components shown in the figure. The states at various points in the system are also shown in the figure. Kinetic and potential energies may be neglected at all of states.



State 1:
liquid water
p_1 = 60 bar (abs)

State 2:
p_2 = 60 bar (abs)
T_2 = 540 °C

State 3:
p_3 = 40 bar (abs)

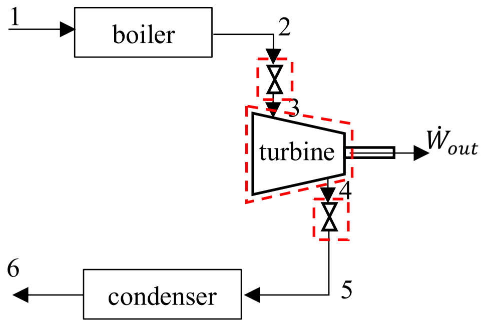
State 4:
p_4 = 5 bar (abs)
T_4 = 240 °C

State 5:
p_5 = 1 bar (abs)

State 6:
condensate
p_6 = 1 bar (abs)

a. Show the states and paths on a *T*-*s* diagram.
b. Determine the power developed by the turbine per unit mass flow rate of steam.
c. Calculate the rate of entropy production per unit mass flow rate for the valves and turbine.
d. Rank the components from those that contribute most to inefficient operation in the overall system to those that contribute the least.
e. If the goal is to increase the power developed per unit mass flow rate, which of the components (if any) might be eliminated? Explain.

SOLUTION:



Apply the 1st Law to a CV surrounding the first valve,

$$\frac{dE_{CV}}{dt} = \sum_{in} \dot{m}(h + ke + pe) - \sum_{out} \dot{m}(h + ke + pe) + \dot{Q}_{in} + \dot{W}_{out}, \quad (1)$$

where,

$$\frac{dE_{CV}}{dt} = 0 \quad \text{(assuming steady state operation)}, \quad (2)$$

$$\sum_{in} \dot{m}(h + ke + pe) - \sum_{out} \dot{m}(h + ke + pe) = \dot{m}(h_2 - h_3) \quad \text{(neglecting the KE and PE)}, \quad (3)$$

(Note that COM has been used, assuming steady state operation, to give $\dot{m} = \dot{m}_2 = \dot{m}_3$.)

$$\dot{Q}_{in} = 0 \quad \text{(assuming adiabatic operation)}, \quad (4)$$

$$\dot{W}_{out} = 0 \quad \text{(the valve is a passive device)}. \quad (5)$$

Substitute and solve for the specific enthalpy at State 3,

$$0 = \dot{m}(h_2 - h_3), \quad (6)$$

$$h_3 = h_2. \quad (7)$$

A similar analysis can be performed for the downstream valve to give,

$$h_5 = h_4. \quad (8)$$

Now apply the 1st Law to a CV surrounding the turbine,

$$\frac{dE_{CV}}{dt} = \sum_{in} \dot{m}(h + ke + pe) - \sum_{out} \dot{m}(h + ke + pe) + \dot{Q}_{in} - \dot{W}_{out}, \quad (9)$$

where,

$$\frac{dE_{CV}}{dt} = 0 \quad \text{(assuming steady state operation)}, \quad (10)$$

$$\sum_{in} \dot{m}(h + ke + pe) - \sum_{out} \dot{m}(h + ke + pe) = \dot{m}(h_3 - h_4) \quad \text{(neglecting the KE and PE)}, \quad (11)$$

$$\dot{Q}_{in} = 0 \quad \text{(assuming adiabatic operation)}, \quad (12)$$

$$\dot{W}_{out} = ?. \quad (13)$$

Substitute and solve for the turbine power per unit mass flow rate,

$$\dot{W}_{out} = \dot{m}(h_3 - h_4), \quad (14)$$

$$\frac{\dot{W}_{out}}{\dot{m}} = h_3 - h_4. \quad (15)$$

Use the given state information and the property tables to determine the specific enthalpies, temperatures, and the specific entropies.

State 2: p_2 = 60 bar (abs), T_2 = 540 °C => (SHV) h_2 = 3517.7 kJ/kg, s_2 = 7.002 kJ/(kg.K),
State 3: p_3 = 40 bar (abs), h_3 = h_2 = 3517.7 kJ/kg (Eq. (7)) => (SHV) T_3 = 531.3 °C, s_3 = 7.182898 kJ/(kg.K),
State 4: p_4 = 5 bar (abs), T_4 = 240 °C => (SHV) h_4 = 2940.2 kJ/kg, s_4 = 7.232 kJ/(kg.K),
State 5: p_5 = 1 bar (abs), h_5 = h_4 = 2940.2 kJ/kg (Eq. (8)) => (SHV) T_5 = 232.7 °C, s_5 = 7.966872 kJ/(kg.K).

Using these values for the specific enthalpies, Eq. (15) gives,

$$\boxed{\frac{\dot{W}_{out}}{\dot{m}} = 578 \text{ kJ/kg}}.$$

Now evaluate the rate of entropy production per unit mass flow rate by applying the Entropy Equation. Start with the CV surrounding the upstream valve,

$$\frac{dS_{CV}}{dt} = \sum_{in} \dot{m}s - \sum_{out} \dot{m}s + \int_b \frac{\delta\dot{Q}_{in}}{T} + \dot{\sigma}, \quad (16)$$

where,

$$\frac{dS_{CV}}{dt} = 0 \quad \text{(steady state operation)}, \quad (17)$$

$$\sum_{in} \dot{m}s - \sum_{out} \dot{m}s = \dot{m}(s_2 - s_3), \quad (18)$$

$$\int_b \frac{\delta\dot{Q}_{in}}{T} = 0 \quad \text{(adiabatic process assumed)}, \quad (19)$$

$$\dot{\sigma} = ?. \quad (20)$$

Substitute and re-arrange,

$$\dot{\sigma} = \dot{m}(s_3 - s_2), \quad (21)$$

$$\frac{\dot{\sigma}}{\dot{m}} = s_3 - s_2. \quad (22)$$

Similar analyses can be performed for the turbine and downstream valves to give,

$$\text{turbine: } \frac{\dot{\sigma}}{\dot{m}} = s_4 - s_3. \quad (23)$$

$$\text{downstream valve: } \frac{\dot{\sigma}}{\dot{m}} = s_5 - s_4. \quad (24)$$

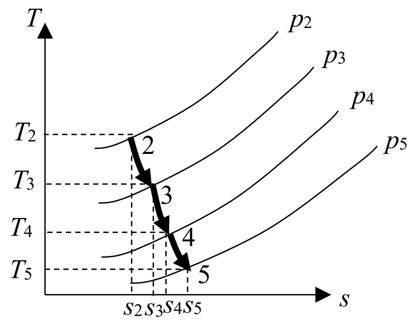
Using the previously determine values for the specific entropies,

$$\boxed{\text{upstream valve: } \frac{\dot{\sigma}}{\dot{m}} = 0.18090 \text{ kJ/K}},$$

$$\boxed{\text{turbine: } \frac{\dot{\sigma}}{\dot{m}} = 0.04910 \text{ kJ/K}},$$

$$\boxed{\text{downstream valve: } \frac{\dot{\sigma}}{\dot{m}} = 0.73487 \text{ kJ/K}}.$$

The downstream valve has the largest internal irreversibility while the turbine has the least. Only one of the valves is required to control the flow rate. Thus, it makes sense to remove the downstream valve since it produces the largest irreversibility and will contribute the most to the inefficiency of the system.


T
p2
p3
p4
p5
T2
T3
T4
T5
2
3
4
5
s2 s3 s4 s5
s