Appendix

Equations

Isentropic Efficiencies

$$\eta_t = 0.85 \quad \text{efficiency of turbine} \tag{1}$$

$$\eta_p = 0.95 \quad \text{efficiency of pump} \tag{2}$$

State 1

$$P_1 = 10 \ \text{[kPa]} \tag{3}$$

$$h_1 = \mathrm{h}\left(Steam, \ \mathrm{P} \ = P_1, \ \mathrm{x} = 0\right) \tag{4}$$

$$v_1 = \mathrm{v}\left(Steam, \ \mathrm{P} \ = P_1, \ \mathrm{x} = 0\right) \tag{5}$$

$$T_1 = \mathrm{T_{sat}}\left(Steam, \ \mathrm{P} = P_1\right) \tag{6}$$

Work input to the pump

$$W_{p,in} = v_1 \cdot \frac{P_2 - P_1}{\eta_p} \tag{7}$$

State 2

$$P_2 = 15000 \ \text{[kPa]} \tag{8}$$

$$h_2 = h_1 + W_{p,in} \tag{9}$$

$$T_2 = \mathrm{T}\left(Steam, \ \mathrm{P} = P_2, \ \mathrm{h} = h_2\right) \tag{10}$$

State 3

$$P_3 = P_2 \tag{11}$$

$$T_3 = 809.2 \quad \text{[K]} \tag{12}$$

$$h_3 = \mathrm{h}\left(Steam, \ \mathrm{T} = T_3, \ \mathrm{P} = P_3\right) \tag{13}$$

$$s_3 = \mathrm{s}\left(Steam, \ \mathrm{T} = T_3, \ \mathrm{P} = P_3\right) \tag{14}$$

State 4

$$P_{4s} = 2000 \ \text{[kPa]} \tag{15}$$

$$s_{4s} = s_3 \tag{16}$$

$$h_{4s} = \mathrm{h}\left(Steam, \ \mathrm{P} = P_{4s}, \ \mathrm{s} = s_{4s}\right) \tag{17}$$

$$h_4 = h_3 - \eta_t \cdot \left(h_3 - h_{4s}\right) \tag{18}$$

$$T_4 = \mathrm{T}\left(Steam, \ \mathrm{P} = P_{4s}, \ \mathrm{h} = h_4\right) \tag{19}$$

State 5

$$P_5 = P_{4s} \tag{20}$$

$$T_5 = T_3 \tag{21}$$

$$h_5 = \mathrm{h}\left(Steam,\ \mathrm{T} = T_5,\ \mathrm{P} = P_5\right) \tag{22}$$

$$s_5 = \mathrm{s}\left(Steam,\ \mathrm{T} = T_5,\ \mathrm{P} = P_5\right) \tag{23}$$

State 6

$$P_{6s} = P_1 \tag{24}$$

$$s_{6s} = s_5 \tag{25}$$

$$x_{6s} = \mathrm{x}\left(Steam,\ \mathrm{P} = P_{6s},\ \mathrm{s} = s_{6s}\right) \quad \text{At the turbine outlet} \tag{26}$$

$$h_{6s} = \mathrm{h}\left(Steam,\ \mathrm{P} = P_{6s},\ \mathrm{x} = x_{6s}\right) \tag{27}$$

$$h_6 = h_5 - \eta_t \cdot (h_5 - h_{6s}) \tag{28}$$

$$T_6 = \mathrm{T}\left(Steam,\ \mathrm{P} = P_{6s},\ \mathrm{h} = h_6\right) \tag{29}$$

Turbine output

$$W_{t,out} = (h_3 - h_4) + (h_5 - h_6) \tag{30}$$

Heat input

$$Q_{in} = (h_3 - h_2) + (h_5 - h_4) \tag{31}$$

Net work output

$$W_{net} = W_{t,out} - W_{p,in} \tag{32}$$

Mass flow rate

$$\dot{m} = 250000/w_{net} \tag{33}$$

1st law efficiency(equal to thermal efficiency)

$$\eta_{th} = W_{net}/Q_{in} \tag{34}$$

2nd Law Analysis

$$T_0 = 298\ \text{[K]} \tag{35}$$

$$T_{source} = T_3 + 100\ \text{[K]} \tag{36}$$

$$s_1 = \mathrm{s}\left(Steam,\ \mathrm{P} = P_1,\ \mathrm{x} = 0\right) \tag{37}$$

$$s_2 = \mathrm{s}\left(Steam,\ \mathrm{P}\ = P_2,\ \mathrm{h} = h_2\right) \tag{38}$$

$$s_4 = \mathrm{s}\left(Steam,\ \mathrm{P}\ = P_{4s},\ \mathrm{h}\ = h_4\right) \tag{39}$$

$$s_6 = \mathrm{s}\left(Steam,\ \mathrm{P} = P_{6s},\ \mathrm{h}\ = h_6\right) \tag{40}$$

Process 1-2

$$X_{destroyed,12} = T_0 \cdot (s_2 - s_1) \tag{41}$$

Process 2-3

$$X_{destroyed,23} = T_0 \cdot \left(s_3 - s_2 - \frac{h_3 - h_2}{T_{source}} \right) \tag{42}$$

Process 3-4

$$X_{destroyed,34} = T_0 \cdot (s_4 - s_3) \tag{43}$$

Process 4-5

$$X_{destroyed,45} = T_0 \cdot \left(s_5 - s_4 + \frac{h_5 - h_4}{T_{source}} \right) \tag{44}$$

Process 5-6

$$X_{destroyed,56} = T_0 \cdot (s_6 - s_5) \tag{45}$$

Process 6-1

$$X_{destroyed,61} = T_0 \cdot \left(s_1 - s_6 + \frac{h_6 - h_1}{T_0} \right) \tag{46}$$

Exergy destruction associated with the combined pumping and heat addition process

$$X_{destruction,combined} = T_0 \cdot (s_3 - s_1 + s_5 - s_4 + q_{in}/T_{source}) \tag{47}$$

$$X_{recovered} = W_{t,out} \tag{48}$$

$$\eta_{II} = X_{recovered}/X_{destruction,combined} \tag{49}$$

Solution

$\boldsymbol{\eta_{II} = 0.4459}$	$\eta_p = 0.95$
$\eta_t = 0.85$	$\boldsymbol{\eta_{th} = 0.377}$
$h_1 = 191.8$ [kJ/kg]	$h_2 = 207.8$ [kJ/kg]
$h_3 = 3411$ [kJ/kg]	$h_4 = 2947$ [kJ/kg]
$h_{4s} = 2865$ [kJ/kg]	$h_5 = 3547$ [kJ/kg]
$h_6 = 2561$ [kJ/kg]	$h_{6s} = 2387$ [kJ/kg]
$\dot{m} = 174.4$ [kg/s]	$P_1 = 10$ [kPa]
$P_2 = 15000$ [kPa]	$P_3 = 15000$ [kPa]
$P_{4s} = 2000$ [kPa]	$P_5 = 2000$ [kPa]
$P_{6s} = 10$ [kPa]	$Q_{in} = 3803$ [kJ/kg]
$s_1 = 0.6493$ [kJ/kg-K]	$s_2 = 0.6519$ [kJ/kg-K]
$s_3 = 6.474$ [kJ/kg-K]	$s_4 = 6.629$ [kJ/kg-K]
$s_{4s} = 6.474$ [kJ/kg-K]	$s_5 = 7.533$ [kJ/kg-K]
$s_6 = 8.078$ [kJ/kg-K]	$s_{6s} = 7.533$ [kJ/kg-K]
$T_0 = 298$ [K]	$T_1 = 319$ [K]
$T_2 = 319.7$ [K]	$T_3 = 809.2$ [K]
$T_4 = 541.4$ [K]	$T_5 = 809.2$ [K]
$T_6 = 319$ [K]	$T_{source} = 909.2$ [K]

$v_1 = 0.00101$ $[\mathrm{m}^3/\mathrm{kg}]$

$W_{p,in} = 15.94$ $[\mathrm{kJ/kg}]$

$x_{6s} = 0.9179$

$X_{destroyed,23} = 685$ $[\mathrm{K}]$

$X_{destroyed,45} = 465.9$ $[\mathrm{K}]$

$X_{destroyed,61} = 155.8$ $[\mathrm{kJ/kg}]$

$X_{recovered} = 1450$ $[\mathrm{kJ/kg}]$

$W_{net} = 1434$ $[\mathrm{kJ/kg}]$

$W_{t,out} = 1450$ $[\mathrm{kJ/kg}]$

$X_{destroyed,12} = 0.7878$ $[\mathrm{kJ/kg}]$

$X_{destroyed,34} = 46.44$ $[\mathrm{kJ/kg}]$

$X_{destroyed,56} = 162.6$ $[\mathrm{kJ/kg}]$

$X_{destruction,combined} = 3251$ $[\mathrm{K}]$

Results

1st Law Efficiency = 37.7%
2nd Law Efficiency = 44.59%

T-s Diagram of the System

Equations

$$s_1 = 0.6493 \text{ [kJ/kg-K]} \quad (1)$$

$$s_2 = 0.6519 \text{ [kJ/kg-K]} \quad (2)$$

$$s_3 = 6.474 \text{ [kJ/kg-K]} \quad (3)$$

$$s_4 = 6.629 \text{ [kJ/kg-K]} \quad (4)$$

$$s_5 = 7.533 \text{ [kJ/kg-K]} \quad (5)$$

$$s_6 = 8.078 \text{ [kJ/kg-K]} \quad (6)$$

$$T_1 = 319 \text{ [K]} \quad (7)$$

$$T_2 = 319.7 \text{ [K]} \quad (8)$$

$$T_3 = 809.2 \text{ [K]} \quad (9)$$

$$T_4 = 541.4 \text{ [K]} \quad (10)$$

$$T_5 = 809.2\text{[K]} \quad (11)$$

$$T_6 = 319 \text{ [K]} \quad (12)$$