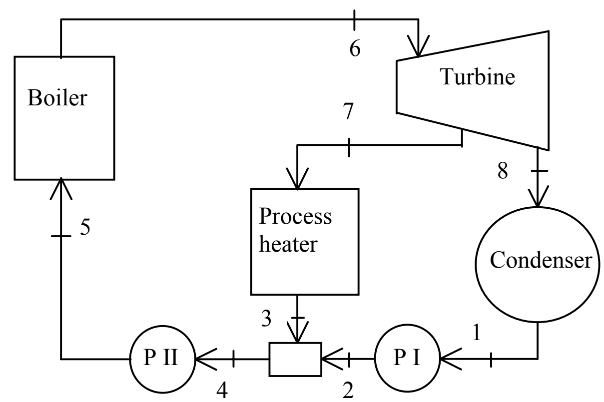
10-67 A cogeneration plant is to generate power and process heat. Part of the steam extracted from the turbine at a relatively high pressure is used for process heating. The net power produced and the utilization factor of the plant are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible.

Analysis From the steam tables (Tables A-4, A-5, and A-6),

$$h_1 = h_{f\ @\ 10\ \text{kPa}} = 191.81\ \text{kJ/kg}$$
$$v_1 = v_{f\ @\ 10\ \text{kPa}} = 0.00101\ \text{m}^3/\text{kg}$$



$$w_{\text{pI,in}} = v_1(P_2 - P_1) = (0.00101\ \text{m}^3/\text{kg})(600 - 10\ \text{kPa})\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right) = 0.60\ \text{kJ/kg}$$

$$h_2 = h_1 + w_{\text{pI,in}} = 191.81 + 0.60 = 192.41\ \text{kJ/kg}$$

$$h_3 = h_{f\ @\ 0.6\ \text{MPa}} = 670.38\ \text{kJ/kg}$$

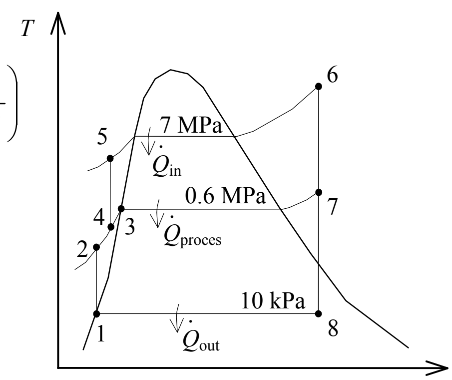
Mixing chamber:

$$\dot{E}_{\text{in}} - \dot{E}_{\text{out}} = \Delta\dot{E}_{\text{system}}^{\nearrow 0\ \text{(steady)}} = 0 \longrightarrow \dot{E}_{\text{in}} = \dot{E}_{\text{out}}$$

$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e \longrightarrow \dot{m}_4 h_4 = \dot{m}_2 h_2 + \dot{m}_3 h_3$$

or, $$h_4 = \frac{\dot{m}_2 h_2 + \dot{m}_3 h_3}{\dot{m}_4} = \frac{(22.50)(192.41) + (7.50)(670.38)}{30} = 311.90\ \text{kJ/kg}$$

$$v_4 \cong v_{f\ @\ h_f = 311.90\ \text{kJ/kg}} = 0.001026\ \text{m}^3/\text{kg}$$



$$w_{p\text{II,in}} = v_4(P_5 - P_4) = (0.001026\ \text{m}^3/\text{kg})(7000 - 600\ \text{kPa})\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right) = 6.57\ \text{kJ/kg}$$

$$h_5 = h_4 + w_{p\text{II,in}} = 311.90 + 6.57 = 318.47\ \text{kJ/kg}$$

$$\left.\begin{array}{l} P_6 = 7\ \text{MPa} \\ T_6 = 500°\text{C} \end{array}\right\} \begin{array}{l} h_6 = 3411.4\ \text{kJ/kg} \\ s_6 = 6.8000\ \text{kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_7 = 0.6\ \text{MPa} \\ s_7 = s_6 \end{array}\right\} h_7 = 2774.6\ \text{kJ/kg}$$

$$\left.\begin{array}{l} P_8 = 10\ \text{kPa} \\ s_8 = s_6 \end{array}\right\} \begin{array}{l} x_8 = \dfrac{s_8 - s_f}{s_{fg}} = \dfrac{6.8000 - 0.6492}{7.4996} = 0.8201 \\ h_8 = h_f + x_8 h_{fg} = 191.81 + (0.8201)(2392.1) = 2153.6\ \text{kJ/kg} \end{array}$$

Then,

$$\dot{W}_{\text{T,out}} = \dot{m}_6(h_6 - h_7) + \dot{m}_8(h_7 - h_8) = (30\ \text{kg/s})(3411.4 - 2774.6)\text{kJ/kg} + (22.5\ \text{kg/s})(2774.6 - 2153.6)\text{kJ/kg} = 33{,}077\ \text{kW}$$

$$\dot{W}_{\text{p,in}} = \dot{m}_1 w_{\text{pI,in}} + \dot{m}_4 w_{\text{pII,in}} = (22.5\ \text{kg/s})(0.60\ \text{kJ/kg}) + (30\ \text{kg/s})(6.57\ \text{kJ/kg}) = 210.6\ \text{kW}$$

$$\dot{W}_{\text{net}} = \dot{W}_{\text{T,out}} - \dot{W}_{\text{p,in}} = 33{,}077 - 210.6 = \mathbf{32{,}866\ kW}$$

Also, $$\dot{Q}_{\text{process}} = \dot{m}_7(h_7 - h_3) = (7.5\ \text{kg/s})(2774.6 - 670.38)\ \text{kJ/kg} = 15{,}782\ \text{kW}$$

$$\dot{Q}_{\text{in}} = \dot{m}_5(h_6 - h_5) = (30\ \text{kg/s})(3411.4 - 318.47) = 92{,}788\ \text{kW}$$

and

$$\varepsilon_u = \frac{\dot{W}_{\text{net}} + \dot{Q}_{\text{process}}}{\dot{Q}_{\text{in}}} = \frac{32{,}866 + 15{,}782}{92{,}788} = \mathbf{52.4\%}$$

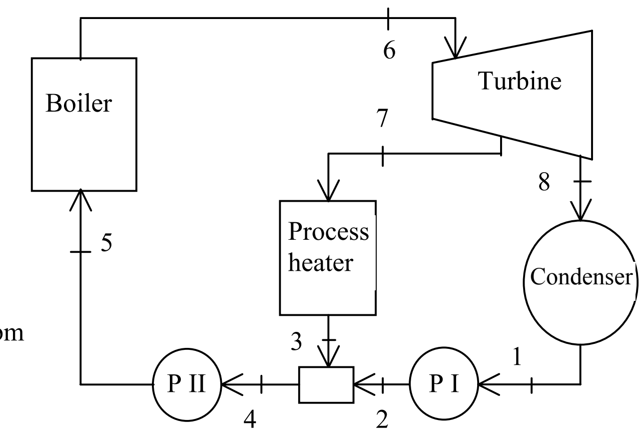
10-68E A large food-processing plant requires steam at a relatively high pressure, which is extracted from the turbine of a cogeneration plant. The rate of heat transfer to the boiler and the power output of the cogeneration plant are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible.

Analysis

(*a*) From the steam tables (Tables A-4E, A-5E, and A-6E),

$$h_1 = h_{f\ @\ 2\text{ psia}} = 94.02\text{ Btu/lbm}$$
$$\boldsymbol{v}_1 = \boldsymbol{v}_{f\ @\ 2\text{ psia}} = 0.01623\ \text{ft}^3\text{/lbm}$$



$$\begin{aligned} w_{\text{pI,in}} &= \boldsymbol{v}_1(P_2 - P_1)/\eta_p \\ &= \frac{1}{0.86}(0.01623\ \text{ft}^3\text{/lbm})(80-2)\text{psia} \\ &\quad \times\left(\frac{1\text{ Btu}}{5.4039\ \text{psia}\cdot\text{ft}^3}\right) \\ &= 0.27\text{ Btu/lbm} \end{aligned}$$

$$h_2 = h_1 + w_{\text{pI,in}} = 94.02 + 0.27 = 94.29\text{ Btu/lbm}$$

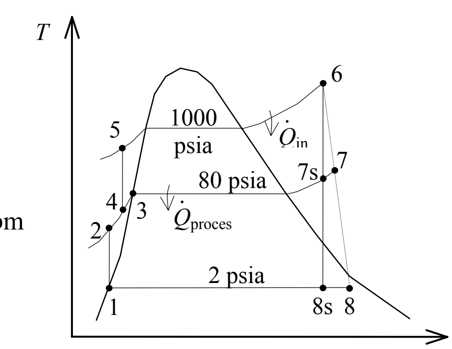
$$h_3 = h_{f\ @\ 80\text{ psia}} = 282.13\text{ Btu/lbm}$$

Mixing chamber:

$$\dot{E}_{\text{in}} - \dot{E}_{\text{out}} = \Delta\dot{E}_{\text{system}}{}^{\nearrow 0\text{ (steady)}} = 0$$

$$\dot{E}_{\text{in}} = \dot{E}_{\text{out}}$$

$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e \longrightarrow \dot{m}_4 h_4 = \dot{m}_2 h_2 + \dot{m}_3 h_3$$



or,

$$h_4 = \frac{\dot{m}_2 h_2 + \dot{m}_3 h_3}{\dot{m}_4} = \frac{(3)(94.29)+(2)(282.13)}{5} = 169.43\text{ Btu/lbm}$$

$$\boldsymbol{v}_4 \cong \boldsymbol{v}_{f\ @\ h_f = 169.43\text{ Btu/lbm}} = 0.01664\ \text{ft}^3\text{/lbm}$$

$$\begin{aligned} w_{\text{pII,in}} &= \boldsymbol{v}_4(P_5 - P_4)/\eta_p \\ &= (0.01664\ \text{ft}^3\text{/lbm})(1000-80\text{ psia})\left(\frac{1\text{ Btu}}{5.4039\ \text{psia}\cdot\text{ft}^3}\right)/(0.86) \\ &= 3.29\text{ Btu/lbm} \end{aligned}$$

$$h_5 = h_4 + w_{pII,\text{in}} = 169.43 + 3.29 = 172.72\text{ Btu/lbm}$$

$$\left.\begin{aligned} P_6 &= 1000\text{ psia} \\ T_6 &= 1000°\text{F} \end{aligned}\right\}\ \begin{aligned} h_6 &= 1506.2\text{ Btu/lbm} \\ s_6 &= 1.6535\text{ Btu/lbm}\cdot\text{R} \end{aligned}$$

$$\left.\begin{aligned} P_{7s} &= 80\text{ psia} \\ s_{7s} &= s_6 \end{aligned}\right\}\ h_{7s} = 1209.0\text{ Btu/lbm}$$

$$\left.\begin{aligned} P_{8s} &= 2\text{ psia} \\ s_{8s} &= s_6 \end{aligned}\right\}\ \begin{aligned} x_{8s} &= \frac{s_{8s} - s_f}{s_{fg}} = \frac{1.6535 - 0.17499}{1.74444} = 0.8475 \\ h_{8s} &= h_f + x_{8s} h_{fg} = 94.02 + (0.8475)(1021.7) = 959.98\text{ Btu/lbm} \end{aligned}$$

Then, $\dot{Q}_{\text{in}} = \dot{m}_5(h_6 - h_5) = (5\text{ lbm/s})(1506.2 - 172.72)\text{Btu/lbm} = \mathbf{6667\ Btu/s}$

(*b*)

$$\begin{aligned} \dot{W}_{\text{T,out}} &= \eta_T \dot{W}_{T,s} = \eta_T\left[\dot{m}_6(h_6 - h_{7s}) + \dot{m}_8(h_{7s} - h_{8s})\right] \\ &= (0.86)\left[(5\text{ lbm/s})(1506.2 - 1209.0)\text{ Btu/lbm} + (3\text{ lbm/s})(1209.0 - 959.98)\text{ Btu/lbm}\right] \\ &= 1921\text{ Btu/s} = \mathbf{2026\ kW} \end{aligned}$$

10-69 A cogeneration plant has two modes of operation. In the first mode, all the steam leaving the turbine at a relatively high pressure is routed to the process heater. In the second mode, 60 percent of the steam is routed to the process heater and remaining is expanded to the condenser pressure. The power produced and the rate at which process heat is supplied in the first mode, and the power produced and the rate of process heat supplied in the second mode are to be determined.

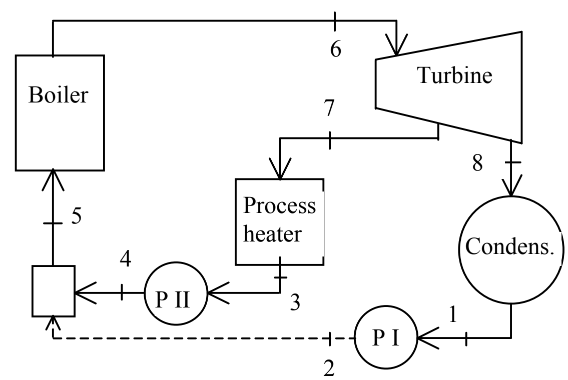
Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible.

Analysis (*a*) From the steam tables (Tables A-4, A-5, and A-6),

$$h_1 = h_{f\,@\,20\text{ kPa}} = 251.42\text{ kJ/kg}$$
$$v_1 = v_{f\,@\,20\text{ kPa}} = 0.001017\text{ m}^3\text{/kg}$$

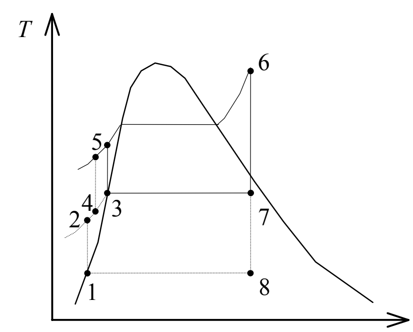
$$\begin{aligned} w_{\text{pI,in}} &= v_1(P_2 - P_1) \\ &= (0.001017\text{ m}^3\text{/kg})(10{,}000 - 20\text{ kPa})\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right) \\ &= 10.15\text{ kJ/kg} \end{aligned}$$

$$h_2 = h_1 + w_{\text{pI,in}} = 251.42 + 10.15 = 261.57\text{ kJ/kg}$$
$$h_3 = h_{f\,@\,0.5\text{ MPa}} = 640.09\text{ kJ/kg}$$
$$v_3 = v_{f\,@\,0.5\text{ MPa}} = 0.001093\text{ m}^3\text{/kg}$$



$$\begin{aligned} w_{\text{pII,in}} &= v_3(P_4 - P_3) \\ &= (0.001093\text{ m}^3\text{/kg})(10{,}000 - 500\text{ kPa})\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right) \\ &= 10.38\text{ kJ/kg} \end{aligned}$$

$$h_4 = h_3 + w_{\text{pII,in}} = 640.09 + 10.38 = 650.47\text{ kJ/kg}$$



Mixing chamber:

$$\dot{E}_{\text{in}} - \dot{E}_{\text{out}} = \Delta\dot{E}_{\text{system}}^{\nearrow 0\text{ (steady)}} = 0 \rightarrow \dot{E}_{\text{in}} = \dot{E}_{\text{out}}$$
$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e \longrightarrow \dot{m}_5 h_5 = \dot{m}_2 h_2 + \dot{m}_4 h_4$$

or, $$h_5 = \frac{\dot{m}_2 h_2 + \dot{m}_4 h_4}{\dot{m}_5} = \frac{(2)(261.57) + (3)(650.47)}{5} = 494.91\text{ kJ/kg}$$

$$\left.\begin{aligned} P_6 &= 10\text{ MPa} \\ T_6 &= 450°\text{C} \end{aligned}\right\} \begin{aligned} h_6 &= 3242.4\text{ kJ/kg} \\ s_6 &= 6.4219\text{ kJ/kg}\cdot\text{K} \end{aligned}$$

$$\left.\begin{aligned} P_7 &= 0.5\text{ MPa} \\ s_7 &= s_6 \end{aligned}\right\} \begin{aligned} x_7 &= \frac{s_7 - s_f}{s_{fg}} = \frac{6.4219 - 1.8604}{4.9603} = 0.9196 \\ h_7 &= h_f + x_7 h_{fg} = 640.09 + (0.9196)(2108.0) = 2578.6\text{ kJ/kg} \end{aligned}$$

$$\left.\begin{aligned} P_8 &= 20\text{ kPa} \\ s_8 &= s_6 \end{aligned}\right\} \begin{aligned} x_8 &= \frac{s_8 - s_f}{s_{fg}} = \frac{6.4219 - 0.8320}{7.0752} = 0.7901 \\ h_8 &= h_f + x_8 h_{fg} = 251.42 + (0.7901)(2357.5) = 2114.0\text{ kJ/kg} \end{aligned}$$

When the entire steam is routed to the process heater,

$$\dot{W}_{\text{T,out}} = \dot{m}_6(h_6 - h_7) = (5\text{ kg/s})(3242.4 - 2578.6)\text{kJ/kg} = \mathbf{3319\ kW}$$
$$\dot{Q}_{\text{process}} = \dot{m}_7(h_7 - h_3) = (5\text{ kg/s})(2578.6 - 640.09)\text{kJ/kg} = \mathbf{9693\ kW}$$

(*b*) When only 60% of the steam is routed to the process heater,

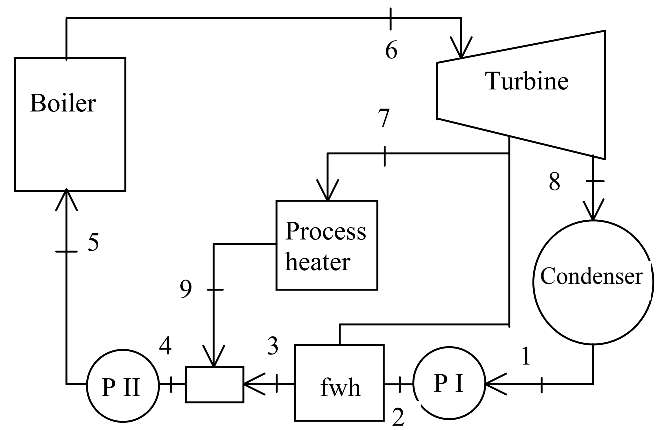
$$\begin{aligned} \dot{W}_{\text{T,out}} &= \dot{m}_6(h_6 - h_7) + \dot{m}_8(h_7 - h_8) \\ &= (5\text{ kg/s})(3242.4 - 2578.6)\text{ kJ/kg} + (2\text{ kg/s})(2578.6 - 2114.0)\text{ kJ/kg} \\ &= \mathbf{4248\ kW} \end{aligned}$$

$$\dot{Q}_{\text{process}} = \dot{m}_7(h_7 - h_3) = (3\text{ kg/s})(2578.6 - 640.09)\text{ kJ/kg} = \mathbf{5816\ kW}$$

10-70 A cogeneration plant modified with regeneration is to generate power and process heat. The mass flow rate of steam through the boiler for a net power output of 15 MW is to be determined.

Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible.

Analysis

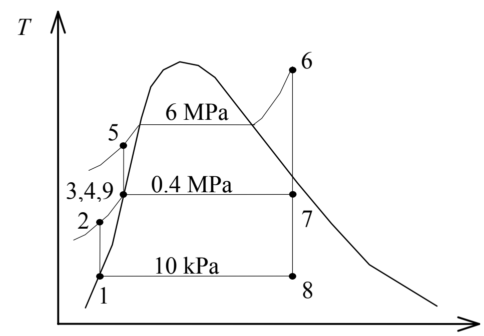


From the steam tables (Tables A-4, A-5, and A-6),

$$h_1 = h_{f\ @\ 10\text{ kPa}} = 191.81\text{ kJ/kg}$$
$$v_1 = v_{f\ @\ 10\text{ kPa}} = 0.00101\ \text{m}^3/\text{kg}$$

$$\begin{aligned} w_{\text{pI,in}} &= v_1(P_2 - P_1) \\ &= \left(0.00101\ \text{m}^3/\text{kg}\right)\left(400 - 10\text{ kPa}\right)\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right) \\ &= 0.39\text{ kJ/kg} \end{aligned}$$

$$h_2 = h_1 + w_{\text{pI,in}} = 191.81 + 0.39 = 192.20\text{ kJ/kg}$$
$$h_3 = h_4 = h_9 = h_{f\ @\ 0.4\text{ MPa}} = 604.66\text{ kJ/kg}$$
$$v_4 = v_{f\ @\ 0.4\text{ MPa}} = 0.001084\ \text{m}^3/\text{kg}$$



$$\begin{aligned} w_{\text{pII,in}} &= v_4(P_5 - P_4) \\ &= \left(0.001084\ \text{m}^3/\text{kg}\right)\left(6000 - 400\text{ kPa}\right)\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right) \\ &= 6.07\text{ kJ/kg} \end{aligned}$$

$$h_5 = h_4 + w_{\text{pII,in}} = 604.66 + 6.07 = 610.73\text{ kJ/kg}$$

$$\left.\begin{aligned} P_6 &= 6\text{ MPa} \\ T_6 &= 450°\text{C} \end{aligned}\right\} \begin{aligned} h_6 &= 3302.9\text{ kJ/kg} \\ s_6 &= 6.7219\text{ kJ/kg}\cdot\text{K} \end{aligned}$$

$$\left.\begin{aligned} P_7 &= 0.4\text{ MPa} \\ s_7 &= s_6 \end{aligned}\right\} \begin{aligned} x_7 &= \frac{s_7 - s_f}{s_{fg}} = \frac{6.7219 - 1.7765}{5.1191} = 0.9661 \\ h_7 &= h_f + x_7 h_{fg} = 604.66 + (0.9661)(2133.4) = 2665.7\text{ kJ/kg} \end{aligned}$$

$$\left.\begin{aligned} P_8 &= 10\text{ kPa} \\ s_8 &= s_6 \end{aligned}\right\} \begin{aligned} x_8 &= \frac{s_8 - s_f}{s_{fg}} = \frac{6.7219 - 0.6492}{7.4996} = 0.8097 \\ h_8 &= h_f + x_8 h_{fg} = 191.81 + (0.8097)(2392.1) = 2128.7\text{ kJ/kg} \end{aligned}$$

Then, per kg of steam flowing through the boiler, we have

$$\begin{aligned} w_{\text{T,out}} &= (h_6 - h_7) + 0.4(h_7 - h_8) \\ &= (3302.9 - 2665.7)\text{ kJ/kg} + (0.4)(2665.7 - 2128.7)\text{ kJ/kg} \\ &= 852.0\text{ kJ/kg} \end{aligned}$$

$$\begin{aligned} w_{\text{p,in}} &= 0.4 w_{\text{pI,in}} + w_{\text{pII,in}} \\ &= (0.4)(0.39\text{ kJ/kg}) + (6.07\text{ kJ/kg}) \\ &= 6.23\text{ kJ/kg} \end{aligned}$$

$$w_{\text{net}} = w_{\text{T,out}} - w_{\text{p,in}} = 852.0 - 6.23 = 845.8\text{ kJ/kg}$$

Thus,

$$\dot{m} = \frac{\dot{W}_{\text{net}}}{w_{\text{net}}} = \frac{15{,}000\text{ kJ/s}}{845.8\text{ kJ/kg}} = \mathbf{17.73\ kg/s}$$

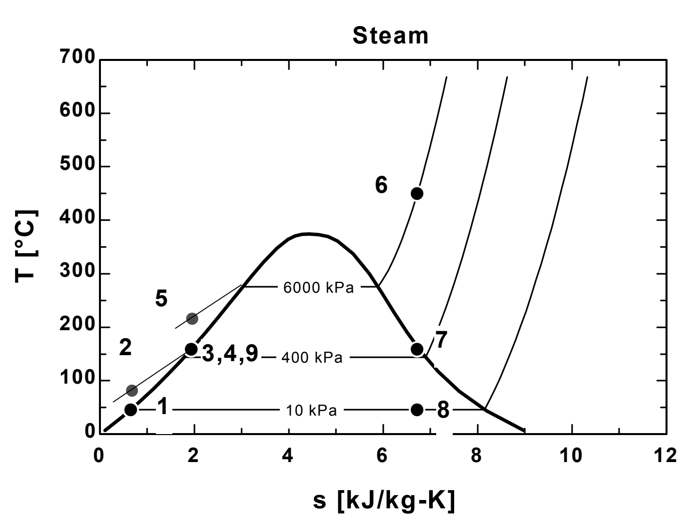
10-71 EES Problem 10-70 is reconsidered. The effect of the extraction pressure for removing steam from the turbine to be used for the process heater and open feedwater heater on the required mass flow rate is to be investigated.

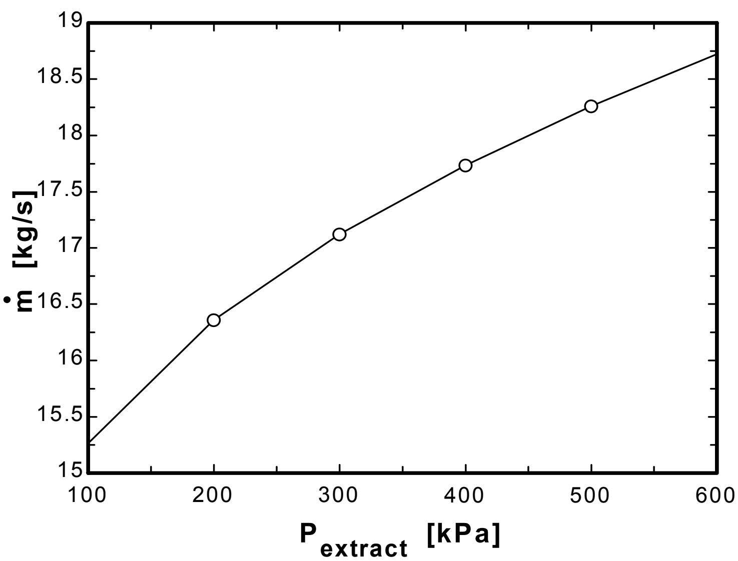
Analysis The problem is solved using EES, and the solution is given below.

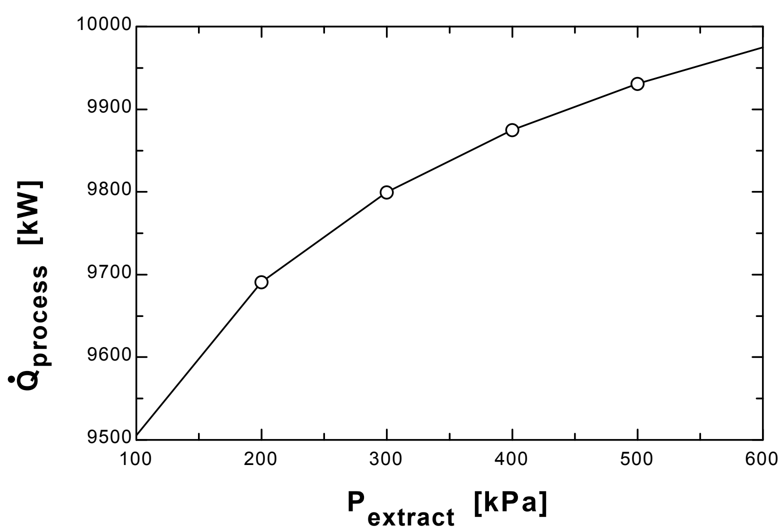
```
"Input Data"
y = 0.6 "fraction of steam extracted from turbine for feedwater heater and process heater"
P[6] = 6000 [kPa]
T[6] = 450 [C]
P_extract=400 [kPa]
P[7] = P_extract
P_cond=10 [kPa]
P[8] = P_cond
W_dot_net=15 [MW]*Convert(MW, kW)
Eta_turb= 100/100 "Turbine isentropic efficiency"
Eta_pump = 100/100 "Pump isentropic efficiency"
P[1] = P[8]
P[2]=P[7]
P[3]=P[7]
P[4] = P[7]
P[5]=P[6]
P[9] = P[7]

"Condenser exit pump  or Pump 1 analysis"
Fluid$='Steam_IAPWS'

h[1]=enthalpy(Fluid$,P=P[1],x=0)    {Sat'd liquid}
v1=volume(Fluid$,P=P[1],x=0)
s[1]=entropy(Fluid$,P=P[1],x=0)
T[1]=temperature(Fluid$,P=P[1],x=0)
w_pump1_s=v1*(P[2]-P[1])"SSSF isentropic pump work assuming constant specific volume"
w_pump1=w_pump1_s/Eta_pump "Definition of pump efficiency"
h[1]+w_pump1= h[2]  "Steady-flow conservation of energy"
s[2]=entropy(Fluid$,P=P[2],h=h[2])
T[2]=temperature(Fluid$,P=P[2],h=h[2])

"Open Feedwater Heater analysis:"
z*h[7]  + (1- y)*h[2] = (1- y + z)*h[3] "Steady-flow conservation of energy"
h[3]=enthalpy(Fluid$,P=P[3],x=0)
T[3]=temperature(Fluid$,P=P[3],x=0) "Condensate leaves heater as sat. liquid at P[3]"
s[3]=entropy(Fluid$,P=P[3],x=0)

"Process heater analysis:"
(y - z)*h[7]  = q_process + (y - z)*h[9] "Steady-flow conservation of energy"
Q_dot_process = m_dot*(y - z)*q_process"[kW]"
h[9]=enthalpy(Fluid$,P=P[9],x=0)
T[9]=temperature(Fluid$,P=P[9],x=0) "Condensate leaves heater as sat. liquid at P[3]"
s[9]=entropy(Fluid$,P=P[9],x=0)

"Mixing chamber at 3, 4, and 9:"
(y-z)*h[9]  + (1-y+z)*h[3] = 1*h[4] "Steady-flow conservation of energy"
T[4]=temperature(Fluid$,P=P[4],h=h[4]) "Condensate leaves heater as sat. liquid at P[3]"
```

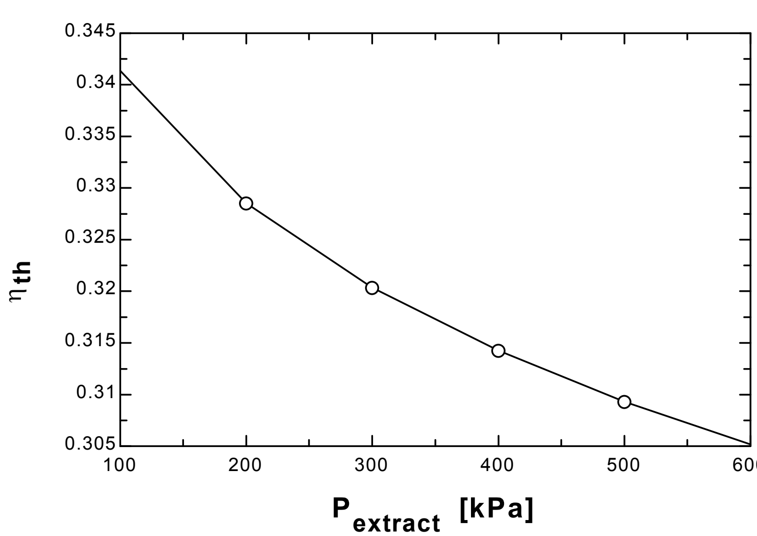
```
s[4]=entropy(Fluid$,P=P[4],h=h[4])

"Boiler condensate pump  or Pump 2 analysis"
v4=volume(Fluid$,P=P[4],x=0)
w_pump2_s=v4*(P[5]-P[4])"SSSF isentropic pump work assuming constant specific volume"
w_pump2=w_pump2_s/Eta_pump "Definition of pump efficiency"
h[4]+w_pump2= h[5]  "Steady-flow conservation of energy"
s[5]=entropy(Fluid$,P=P[5],h=h[5])
T[5]=temperature(Fluid$,P=P[5],h=h[5])

"Boiler analysis"
q_in + h[5]=h[6]"SSSF conservation of energy for the Boiler"
h[6]=enthalpy(Fluid$, T=T[6], P=P[6])
s[6]=entropy(Fluid$, T=T[6], P=P[6])

"Turbine analysis"
ss[7]=s[6]
hs[7]=enthalpy(Fluid$,s=ss[7],P=P[7])
Ts[7]=temperature(Fluid$,s=ss[7],P=P[7])
h[7]=h[6]-Eta_turb*(h[6]-hs[7])"Definition of turbine efficiency for high pressure stages"
T[7]=temperature(Fluid$,P=P[7],h=h[7])
s[7]=entropy(Fluid$,P=P[7],h=h[7])
ss[8]=s[7]
hs[8]=enthalpy(Fluid$,s=ss[8],P=P[8])
Ts[8]=temperature(Fluid$,s=ss[8],P=P[8])
h[8]=h[7]-Eta_turb*(h[7]-hs[8])"Definition of turbine efficiency for low pressure stages"
T[8]=temperature(Fluid$,P=P[8],h=h[8])
s[8]=entropy(Fluid$,P=P[8],h=h[8])
h[6] =y*h[7] + (1- y)*h[8] + w_turb "SSSF conservation of energy for turbine"

"Condenser analysis"
(1- y)*h[8]=q_out+(1- y)*h[1]"SSSF First Law for the Condenser"

"Cycle Statistics"
w_net=w_turb - ((1- y)*w_pump1+ w_pump2)
Eta_th=w_net/q_in
W_dot_net = m_dot * w_net
```

$P_{extract}$ [kPa]	η_{th}	m [kg/s]	$Q_{process}$ [kW]
100	0.3413	15.26	9508
200	0.3284	16.36	9696
300	0.3203	17.12	9806
400	0.3142	17.74	9882
500	0.3092	18.26	9939
600	0.305	18.72	9984




19
18.5
18
17.5
17
16.5
16
15.5
15
100
200
300
400
500
600
ṁ [kg/s]
P extract [kPa]


10000
9900
9800
9700
9600
9500
100
200
300
400
500
600
Q̇ process [kW]
P extract [kPa]


0.345
0.34
0.335
0.33
0.325
0.32
0.315
0.31
0.305
100
200
300
400
500
600
η th
P extract [kPa]

10-72E A cogeneration plant is to generate power while meeting the process steam requirements for a certain industrial application. The net power produced, the rate of process heat supply, and the utilization factor of this plant are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible.

Analysis

(*a*) From the steam tables (Tables A-4E, A-5E, and A-6E),

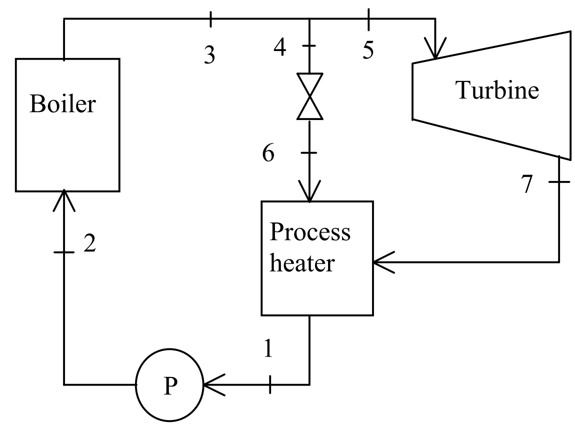
$$h_1 \cong h_{f\ @\ 240°F} = 208.49 \text{ Btu/lbm}$$
$$h_2 \cong h_1$$

$$\left.\begin{array}{l} P_3 = 600 \text{ psia} \\ T_3 = 800°F \end{array}\right\} \begin{array}{l} h_3 = 1408.0 \text{ Btu/lbm} \\ s_3 = s_5 = s_7 = 1.6348 \text{ Btu/lbm}\cdot\text{R} \end{array}$$

$$h_3 = h_4 = h_5 = h_6$$

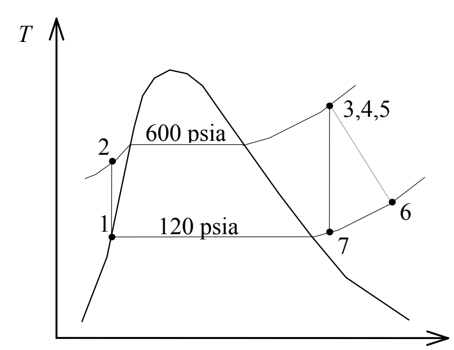
$$\left.\begin{array}{l} P_7 = 120 \text{ psia} \\ s_7 = s_3 \end{array}\right\} h_7 = 1229.5 \text{ Btu/lbm}$$

$$\begin{aligned} \dot{W}_{net} &= \dot{m}_5(h_5 - h_7) \\ &= (12 \text{ lbm/s})(1408.0 - 1229.5) \text{ Btu/lbm} \\ &= 2142 \text{ Btu/s} = \mathbf{2260\ kW} \end{aligned}$$



(*b*)
$$\begin{aligned} \dot{Q}_{process} &= \sum \dot{m}_i h_i - \sum \dot{m}_e h_e \\ &= \dot{m}_6 h_6 + \dot{m}_7 h_7 - \dot{m}_1 h_1 - \\ &= (6)(1408.0) + (12)(1229.5) - (18)(208.49) \\ &= \mathbf{19{,}450\ Btu/s} \end{aligned}$$

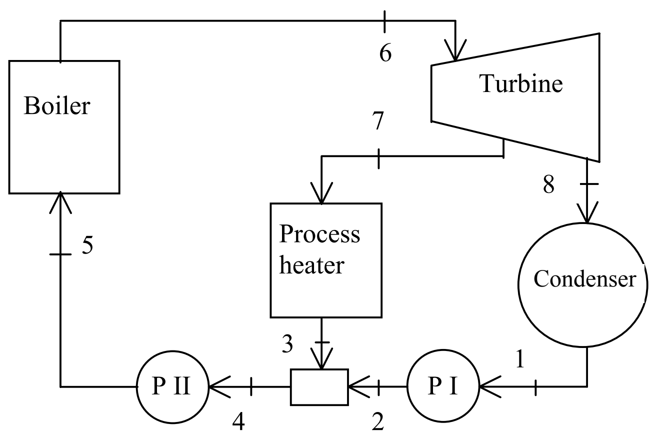
$$\begin{aligned} \dot{Q}_{process} &= \sum \dot{m}_e h_e - \sum \dot{m}_i h_i = \dot{m}_1 h_1 - \dot{m}_6 h_6 - \dot{m}_7 h_7 \\ &= (18)(208.49) - (6)(1408.0) - (12)(1229.5) \\ &= \mathbf{-19{,}450\ Btu/s} \end{aligned}$$

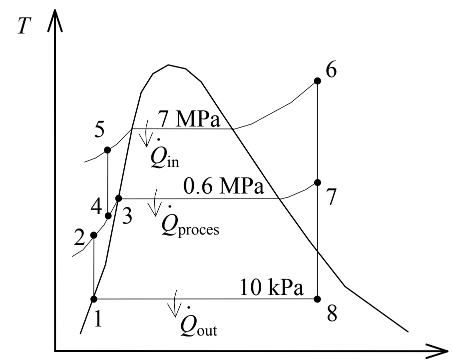


(*c*) $\varepsilon_u = \mathbf{1}$ since all the energy is utilized.

10-73 A cogeneration plant is to generate power and process heat. Part of the steam extracted from the turbine at a relatively high pressure is used for process heating. The mass flow rate of steam that must be supplied by the boiler, the net power produced, and the utilization factor of the plant are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible.





Analysis From the steam tables (Tables A-4, A-5, and A-6),

$$h_1 = h_{f\ @\ 10\ \text{kPa}} = 191.81\ \text{kJ/kg}$$
$$\boldsymbol{v}_1 = \boldsymbol{v}_{f\ @\ 10\ \text{kPa}} = 0.00101\ \ \text{m}^3/\text{kg}$$

$$\begin{aligned} w_{\text{pI,in}} &= \boldsymbol{v}_1(P_2 - P_1) \\ &= (0.00101\ \ \text{m}^3/\text{kg})(600 - 10\ \text{kPa})\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right) \\ &= 0.596\ \text{kJ/kg} \end{aligned}$$

$$h_2 = h_1 + w_{\text{pI,in}} = 191.81 + 0.596 = 192.40\ \text{kJ/kg}$$

$$h_3 = h_{f\ @\ 0.6\ \text{MPa}} = 670.38\ \text{kJ/kg}$$

Mixing chamber:

$$\dot{m}_3 h_3 + \dot{m}_2 h_2 = \dot{m}_4 h_4$$

$$(0.25)(670.38\ \text{kJ/kg}) + (0.75)(192.40\ \text{kJ/kg})) = (1)h_4 \longrightarrow h_4 = 311.90\ \text{kJ/kg}$$

$$\boldsymbol{v}_4 \cong \boldsymbol{v}_{f\ @\ h_f = 311.90\ \text{kJ/kg}} = 0.001026\ \ \text{m}^3/\text{kg}$$

$$\begin{aligned} w_{p\text{II,in}} &= \boldsymbol{v}_4(P_5 - P_4) \\ &= (0.001026\ \ \text{m}^3/\text{kg})(7000 - 600\ \text{kPa})\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right) \\ &= 6.563\ \text{kJ/kg} \end{aligned}$$

$$h_5 = h_4 + w_{p\text{II,in}} = 311.90 + 6.563 = 318.47\ \text{kJ/kg}$$

$$\left.\begin{array}{l} P_6 = 7\ \text{MPa} \\ T_6 = 500°\text{C} \end{array}\right\} \begin{array}{l} h_6 = 3411.4\ \text{kJ/kg} \\ s_6 = 6.8000\ \text{kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_7 = 0.6\ \text{MPa} \\ s_7 = s_6 \end{array}\right\} h_7 = 2773.9\ \text{kJ/kg}$$

$$\left.\begin{array}{l} P_8 = 10\ \text{kPa} \\ s_8 = s_6 \end{array}\right\} h_8 = 2153.6\ \text{kJ/kg}$$

$$\dot{Q}_{\text{process}} = \dot{m}_7(h_7 - h_3)$$
$$8600\ \text{kJ/s} = \dot{m}_7(2773.9 - 670.38)\text{kJ/kg}$$
$$\dot{m}_7 = 4.088\ \text{kg/s}$$

This is one-fourth of the mass flowing through the boiler. Thus, the mass flow rate of steam that must be supplied by the boiler becomes

$$\dot{m}_6 = 4\dot{m}_7 = 4(4.088\ \text{kg/s}) = \mathbf{16.35\ kg/s}$$

(*b*) Cycle analysis:

$$\begin{aligned}\dot{W}_{\text{T,out}} &= \dot{m}_7(h_6 - h_7) + \dot{m}_8(h_6 - h_8)\\ &= (4.088\ \text{kg/s})(3411.4 - 2773.9)\text{kJ/kg} + (16.35 - 4.088\ \text{kg/s})(3411.4 - 2153.6)\text{kJ/kg}\\ &= 18{,}033\ \text{kW}\end{aligned}$$

$$\begin{aligned}\dot{W}_{\text{p,in}} &= \dot{m}_1 w_{\text{pI,in}} + \dot{m}_4 w_{\text{pII,in}}\\ &= (16.35 - 4.088\ \text{kg/s})(0.596\ \text{kJ/kg}) + (16.35\ \text{kg/s})(6.563\ \text{kJ/kg}) = 114.6\ \text{kW}\end{aligned}$$

$$\dot{W}_{\text{net}} = \dot{W}_{\text{T,out}} - \dot{W}_{\text{p,in}} = 18{,}033 - 115 = \mathbf{17{,}919\ kW}$$

(*c*) Then,

$$\dot{Q}_{\text{in}} = \dot{m}_5(h_6 - h_5) = (16.35\ \text{kg/s})(3411.4 - 318.46) = 50{,}581\ \text{kW}$$

and

$$\varepsilon_u = \frac{\dot{W}_{\text{net}} + \dot{Q}_{\text{process}}}{\dot{Q}_{\text{in}}} = \frac{17{,}919 + 8600}{50{,}581} = 0.524 = \mathbf{52.4\%}$$

Combined Gas-Vapor Power Cycles

10-74C The energy source of the steam is the waste energy of the exhausted combustion gases.

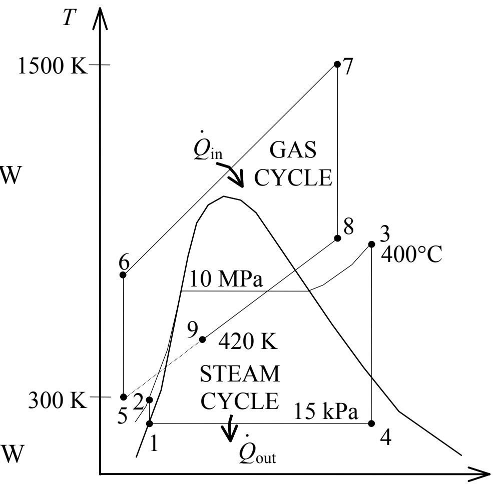
10-75C Because the combined gas-steam cycle takes advantage of the desirable characteristics of the gas cycle at high temperature, and those of steam cycle at low temperature, and combines them. The result is a cycle that is more efficient than either cycle executed operated alone.

10-76 A combined gas-steam power cycle is considered. The topping cycle is a gas-turbine cycle and the bottoming cycle is a simple ideal Rankine cycle. The mass flow rate of the steam, the net power output, and the thermal efficiency of the combined cycle are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible. **3** Air is an ideal gas with constant specific heats.

Properties The properties of air at room temperature are c_p = 1.005 kJ/kg·K and k = 1.4 (Table A-2).

Analysis (*a*) The analysis of gas cycle yields



$$T_6 = T_5\left(\frac{P_6}{P_5}\right)^{(k-1)/k} = (300\text{ K})(16)^{0.4/1.4} = 662.5\text{ K}$$

$$\dot{Q}_{\text{in}} = \dot{m}_{\text{air}}(h_7 - h_6) = \dot{m}_{\text{air}} c_p (T_7 - T_6)$$
$$= (14\text{ kg/s})(1.005\text{ kJ/kg}\cdot\text{K})(1500 - 662.5)\text{ K} = 11{,}784\text{ kW}$$

$$\dot{W}_{C,\text{gas}} = \dot{m}_{\text{air}}(h_6 - h_5) = \dot{m}_{\text{air}} c_p (T_6 - T_5)$$
$$= (14\text{ kg/s})(1.005\text{ kJ/kg}\cdot\text{K})(662.5 - 300)\text{ K} = 5100\text{ kW}$$

$$T_8 = T_7\left(\frac{P_8}{P_7}\right)^{(k-1)/k} = (1500\text{K})\left(\frac{1}{16}\right)^{0.4/1.4} = 679.3\text{ K}$$

$$\dot{W}_{T,\text{gas}} = \dot{m}_{\text{air}}(h_7 - h_8) = \dot{m}_{\text{air}} c_p (T_7 - T_8)$$
$$= (14\text{ kg/s})(1.005\text{ kJ/kg}\cdot\text{K})(1500 - 679.3)\text{ K} = 11{,}547\text{ kW}$$

$$\dot{W}_{\text{net,gas}} = \dot{W}_{T,\text{gas}} - \dot{W}_{C,\text{gas}} = 11{,}547 - 5{,}100 = 6447\text{ kW}$$

From the steam tables (Tables A-4, A-5, and A-6),

$$h_1 = h_{f\,@\,15\text{ kPa}} = 225.94\text{ kJ/kg}$$
$$\boldsymbol{v}_1 = \boldsymbol{v}_{f\,@\,15\text{ kPa}} = 0.001014\ \text{m}^3/\text{kg}$$

$$w_{\text{pI,in}} = \boldsymbol{v}_1(P_2 - P_1) = (0.001014\ \text{m}^3/\text{kg})(10{,}000 - 15\text{ kPa})\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right) = 10.12\text{ kJ/kg}$$

$$h_2 = h_1 + w_{\text{pI,in}} = 225.94 + 10.13 = 236.06\text{ kJ/kg}$$

$$\left.\begin{array}{l} P_3 = 10\text{ MPa} \\ T_3 = 400°\text{C} \end{array}\right\} \begin{array}{l} h_3 = 3097.0\text{ kJ/kg} \\ s_3 = 6.2141\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_4 = 15\text{ kPa} \\ s_4 = s_3 \end{array}\right\} \begin{array}{l} x_4 = \dfrac{s_4 - s_f}{s_{fg}} = \dfrac{6.2141 - 0.7549}{7.2522} = 0.7528 \\ h_4 = h_f + x_4 h_{fg} = 225.94 + (0.7528)(2372.3) = 2011.8\text{ kJ/kg} \end{array}$$

Noting that $\dot{Q} \cong \dot{W} \cong \Delta\text{ke} \cong \Delta\text{pe} \cong 0$ for the heat exchanger, the steady-flow energy balance equation yields

$$\dot{E}_{\text{in}} - \dot{E}_{\text{out}} = \Delta\dot{E}_{\text{system}}^{\nearrow 0\text{ (steady)}} = 0 \longrightarrow \dot{E}_{\text{in}} = \dot{E}_{\text{out}}$$

$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e \longrightarrow \dot{m}_s(h_3 - h_2) = \dot{m}_{\text{air}}(h_8 - h_9)$$

$$\dot{m}_s = \frac{h_8 - h_9}{h_3 - h_2}\dot{m}_{\text{air}} = \frac{c_p(T_8 - T_9)}{h_3 - h_2}\dot{m}_{\text{air}} = \frac{(1.005\text{ kJ/kg}\cdot\text{K})(679.3 - 420)\text{ K}}{(3097.0 - 236.06)\text{ kJ/kg}}(14\text{ kg/s}) = \mathbf{1.275\ kg/s}$$

(*b*)
$$\dot{W}_{\text{T,steam}} = \dot{m}_s(h_3 - h_4) = (1.275\text{ kg/s})(3097.0 - 2011.5)\text{ kJ/kg} = 1384\text{ kW}$$

$$\dot{W}_{\text{p,steam}} = \dot{m}_s w_p = (1.275\text{ kg/s})(10.12\text{ kJ/kg}) = 12.9\text{ kW}$$

$$\dot{W}_{\text{net,steam}} = \dot{W}_{\text{T,steam}} - \dot{W}_{\text{p,steam}} = 1384 - 12.9 = 1371\text{ kW}$$

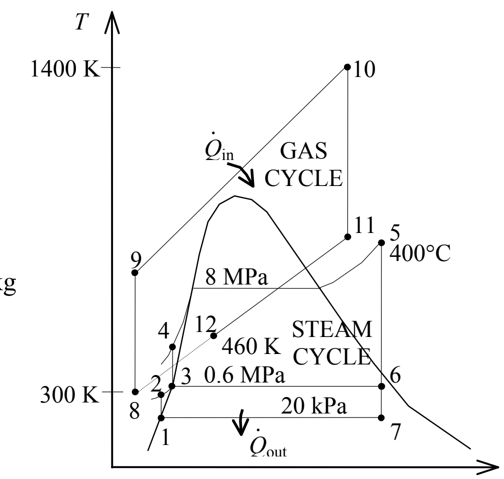
and
$$\dot{W}_{\text{net}} = \dot{W}_{\text{net,steam}} + \dot{W}_{\text{net,gas}} = 1371 + 6448 = \mathbf{7819\ kW}$$

(*c*)
$$\eta_{\text{th}} = \frac{\dot{W}_{\text{net}}}{\dot{Q}_{\text{in}}} = \frac{7819\text{ kW}}{11{,}784\text{ kW}} = \mathbf{66.4\%}$$

10-77 [*Also solved by EES on enclosed CD*] A 450-MW combined gas-steam power plant is considered. The topping cycle is a gas-turbine cycle and the bottoming cycle is an ideal Rankine cycle with an open feedwater heater. The mass flow rate of air to steam, the required rate of heat input in the combustion chamber, and the thermal efficiency of the combined cycle are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible. **3** Air is an ideal gas with variable specific heats.

Analysis (*a*) The analysis of gas cycle yields (Table A-17)



$$T_8 = 300 \text{ K} \longrightarrow h_8 = 300.19 \text{ kJ/kg}$$
$$P_{r_8} = 1.386$$

$$P_{r_9} = \frac{P_9}{P_8} P_{r_8} = (14)(1.386) = 19.40 \longrightarrow h_9 = 635.5 \text{ kJ/kg}$$

$$T_{10} = 1400 \text{ K} \longrightarrow h_{10} = 1515.42 \text{ kJ/kg}$$
$$P_{r_{10}} = 450.5$$

$$P_{r_{11}} = \frac{P_{11}}{P_{10}} P_{r_{10}} = \left(\frac{1}{14}\right)(450.5) = 32.18 \longrightarrow h_{11} = 735.8 \text{ kJ/kg}$$

$$T_{12} = 460 \text{ K} \longrightarrow h_{12} = 462.02 \text{ kJ/kg}$$

From the steam tables (Tables A-4, A-5, A-6),

$$h_1 = h_{f\,@\,20\text{ kPa}} = 251.42 \text{ kJ/kg}$$
$$v_1 = v_{f\,@\,20\text{ kPa}} = 0.001017 \text{ m}^3\text{/kg}$$

$$w_{pI,in} = v_1(P_2 - P_1) = \left(0.001017 \text{ m}^3\text{/kg}\right)\left(600 - 20 \text{ kPa}\right)\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right) = 0.59 \text{ kJ/kg}$$

$$h_2 = h_1 + w_{pI,in} = 251.42 + 0.59 = 252.01 \text{ kJ/kg}$$

$$h_3 = h_{f\,@\,0.6\text{ MPa}} = 670.38 \text{ kJ/kg}$$
$$v_3 = v_{f\,@\,0.6\text{ MPa}} = 0.001101 \text{ m}^3\text{/kg}$$

$$w_{pII,in} = v_3(P_4 - P_3) = \left(0.001101 \text{ m}^3\text{/kg}\right)\left(8{,}000 - 600 \text{ kPa}\right)\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right) = 8.15 \text{ kJ/kg}$$

$$h_4 = h_3 + w_{pI,in} = 670.38 + 8.15 = 678.53 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_5 = 8 \text{ MPa} \\ T_5 = 400°\text{C} \end{array}\right\} \begin{array}{l} h_5 = 3139.4 \text{ kJ/kg} \\ s_5 = 6.3658 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_6 = 0.6 \text{ MPa} \\ s_6 = s_5 \end{array}\right\} \begin{array}{l} x_6 = \dfrac{s_6 - s_f}{s_{fg}} = \dfrac{6.3658 - 1.9308}{4.8285} = 0.9185 \\ h_6 = h_f + x_6 h_{fg} = 670.38 + (0.9185)(2085.8) = 2586.1 \text{ kJ/kg} \end{array}$$

$$\left.\begin{array}{l} P_7 = 20 \text{ kPa} \\ s_7 = s_5 \end{array}\right\} \begin{array}{l} x_7 = \dfrac{s_7 - s_f}{s_{fg}} = \dfrac{6.3658 - 0.8320}{7.0752} = 0.7821 \\ h_7 = h_f + x_7 h_{fg} = 251.42 + (0.7821)(2357.5) = 2095.2 \text{ kJ/kg} \end{array}$$

Noting that $\dot{Q} \cong \dot{W} \cong \Delta\text{ke} \cong \Delta\text{pe} \cong 0$ for the heat exchanger, the steady-flow energy balance equation yields

$$\dot{E}_{in} - \dot{E}_{out} = \Delta\dot{E}_{system}^{\nearrow 0\,(steady)} = 0$$

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e \longrightarrow \dot{m}_s (h_5 - h_4) = \dot{m}_{air}(h_{11} - h_{12})$$

$$\frac{\dot{m}_{air}}{\dot{m}_s} = \frac{h_5 - h_4}{h_{11} - h_{12}} = \frac{3139.4 - 678.53}{735.80 - 462.02} = \mathbf{8.99\ kg\ air\ /\ kg\ steam}$$

(*b*) Noting that $\dot{Q} \cong \dot{W} \cong \Delta ke \cong \Delta pe \cong 0$ for the open FWH, the steady-flow energy balance equation yields

$$\dot{E}_{in} - \dot{E}_{out} = \Delta\dot{E}_{system}^{\nearrow 0\,(steady)} = 0$$

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e \longrightarrow \dot{m}_2 h_2 + \dot{m}_6 h_6 = \dot{m}_3 h_3 \longrightarrow y h_6 + (1 - y) h_2 = (1) h_3$$

Thus,

$$y = \frac{h_3 - h_2}{h_6 - h_2} = \frac{670.38 - 252.01}{2586.1 - 252.01} = 0.1792 \quad (\text{the fraction of steam extracted})$$

$$w_T = h_5 - h_6 + (1 - y)(h_6 - h_7)$$
$$= 3139.4 - 2586.1 + (1 - 0.1792)(2586.1 - 2095.2) = 956.23\ \text{kJ/kg}$$

$$w_{net,steam} = w_T - w_{p,in} = w_T - (1 - y) w_{p,I} - w_{p,II}$$
$$= 956.23 - (1 - 0.1792)(0.59) - 8.15 = 948.56\ \text{kJ/kg}$$

$$w_{net,gas} = w_T - w_{C,in} = (h_{10} - h_{11}) - (h_9 - h_8)$$
$$= 1515.42 - 735.8 - (635.5 - 300.19) = 444.3\ \text{kJ/kg}$$

The net work output per unit mass of gas is

$$w_{net} = w_{net,gas} + \tfrac{1}{8.99} w_{net,steam} = 444.3 + \tfrac{1}{8.99}(948.56) = 549.8\ \text{kJ/kg}$$

$$\dot{m}_{air} = \frac{\dot{W}_{net}}{w_{net}} = \frac{450{,}000\ \text{kJ/s}}{549.7\ \text{kJ/kg}} = 818.7\ \text{kg/s}$$

and

$$\dot{Q}_{in} = \dot{m}_{air}(h_{10} - h_9) = (818.5\ \text{kg/s})(1515.42 - 635.5)\ \text{kJ/kg} = \mathbf{720{,}215\ \ kW}$$

(*c*) $$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{450{,}000\ \text{kW}}{720{,}215\ \text{kW}} = \mathbf{62.5\%}$$

10-78 EES Problem 10-77 is reconsidered. The effect of the gas cycle pressure ratio on the ratio of gas flow rate to steam flow rate and cycle thermal efficiency is to be investigated.

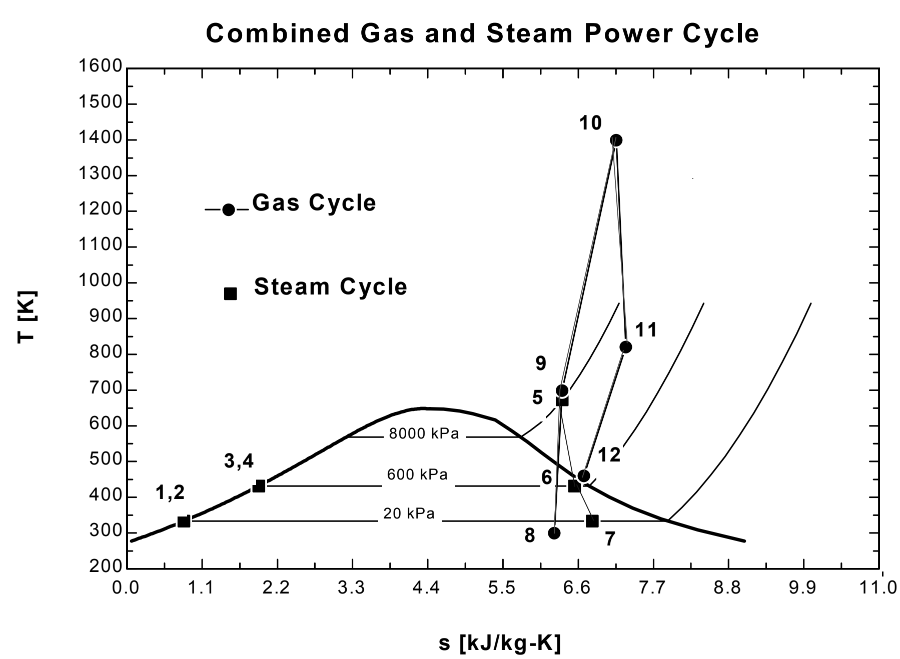
Analysis The problem is solved using EES, and the solution is given below.

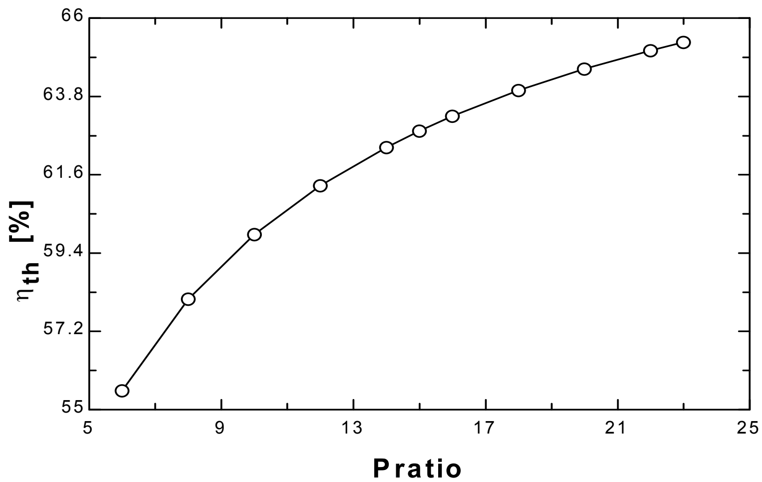
```
"Input data"
T[8] = 300 [K]              "Gas compressor inlet"
P[8] = 14.7 [kPa]           "Assumed air inlet pressure"
"Pratio = 14"               "Pressure ratio for gas compressor"
T[10] = 1400 [K]            "Gas turbine inlet"
T[12] = 460 [K]             "Gas exit temperature from Gas-to-steam heat exchanger "
P[12] = P[8]                "Assumed air exit pressure"
W_dot_net=450 [MW]
Eta_comp = 1.0
Eta_gas_turb = 1.0
Eta_pump = 1.0
Eta_steam_turb = 1.0
P[5] = 8000 [kPa]           "Steam turbine inlet"
T[5] =(400+273) "[K]"       "Steam turbine inlet"
P[6] = 600 [kPa]            "Extraction pressure for steam open feedwater heater"
P[7] = 20 [kPa]             "Steam condenser pressure"

"GAS POWER CYCLE ANALYSIS"

"Gas Compressor anaysis"
s[8]=ENTROPY(Air,T=T[8],P=P[8])
ss9=s[8] "For the ideal case the entropies are constant across the compressor"
P[9] = Pratio*P[8]
Ts9=temperature(Air,s=ss9,P=P[9])"Ts9 is the isentropic value of T[9] at compressor exit"
Eta_comp = w_gas_comp_isen/w_gas_comp "compressor adiabatic efficiency, w_comp >
w_comp_isen"
h[8] + w_gas_comp_isen =hs9"SSSF conservation of energy for the isentropic compressor,
assuming: adiabatic, ke=pe=0 per unit gas mass flow rate in kg/s"
h[8]=ENTHALPY(Air,T=T[8])
hs9=ENTHALPY(Air,T=Ts9)
h[8] + w_gas_comp = h[9]"SSSF conservation of energy for the actual compressor, assuming:
adiabatic, ke=pe=0"
T[9]=temperature(Air,h=h[9])
s[9]=ENTROPY(Air,T=T[9],P=P[9])

"Gas Cycle External heat exchanger analysis"
h[9] + q_in = h[10]"SSSF conservation of energy for the external heat exchanger, assuming W=0,
ke=pe=0"
h[10]=ENTHALPY(Air,T=T[10])
P[10]=P[9]                          "Assume process 9-10 is SSSF constant pressure"
Q_dot_in"MW"*1000"kW/MW"=m_dot_gas*q_in

"Gas Turbine analysis"
s[10]=ENTROPY(Air,T=T[10],P=P[10])
ss11=s[10] "For the ideal case the entropies are constant across the turbine"
P[11] = P[10] /Pratio
Ts11=temperature(Air,s=ss11,P=P[11])"Ts11 is the isentropic value of T[11] at gas turbine exit"
Eta_gas_turb = w_gas_turb /w_gas_turb_isen "gas turbine adiabatic efficiency, w_gas_turb_isen
> w_gas_turb"
h[10] = w_gas_turb_isen + hs11"SSSF conservation of energy for the isentropic gas turbine,
assuming: adiabatic, ke=pe=0"
```

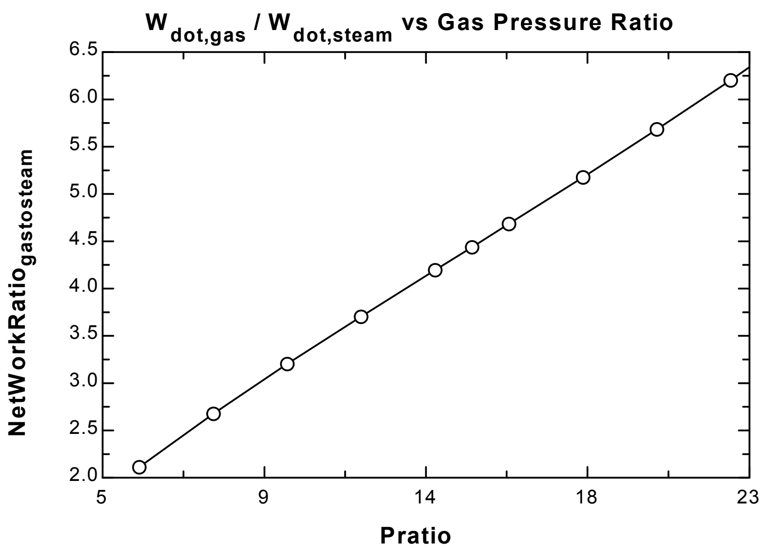
```
hs11=ENTHALPY(Air,T=Ts11)
h[10] = w_gas_turb + h[11]"SSSF conservation of energy for the actual gas turbine, assuming:
adiabatic, ke=pe=0"
T[11]=temperature(Air,h=h[11])
s[11]=ENTROPY(Air,T=T[11],P=P[11])

"Gas-to-Steam Heat Exchanger"
"SSSF conservation of energy for the gas-to-steam heat exchanger, assuming: adiabatic,
W=0, ke=pe=0"
m_dot_gas*h[11] + m_dot_steam*h[4] = m_dot_gas*h[12] + m_dot_steam*h[5]
h[12]=ENTHALPY(Air, T=T[12])
s[12]=ENTROPY(Air,T=T[12],P=P[12])

"STEAM CYCLE ANALYSIS"
"Steam Condenser exit pump  or Pump 1 analysis"
Fluid$='Steam_IAPWS'
P[1] = P[7]
P[2]=P[6]
h[1]=enthalpy(Fluid$,P=P[1],x=0)      {Saturated liquid}
v1=volume(Fluid$,P=P[1],x=0)
s[1]=entropy(Fluid$,P=P[1],x=0)
T[1]=temperature(Fluid$,P=P[1],x=0)
w_pump1_s=v1*(P[2]-P[1])"SSSF isentropic pump work assuming constant specific volume"
w_pump1=w_pump1_s/Eta_pump "Definition of pump efficiency"
h[1]+w_pump1= h[2]  "Steady-flow conservation of energy"
s[2]=entropy(Fluid$,P=P[2],h=h[2])
T[2]=temperature(Fluid$,P=P[2],h=h[2])
"Open Feedwater Heater analysis"
y*h[6] + (1-y)*h[2] = 1*h[3] "Steady-flow conservation of energy"
P[3]=P[6]
h[3]=enthalpy(Fluid$,P=P[3],x=0)      "Condensate leaves heater as sat. liquid at P[3]"
T[3]=temperature(Fluid$,P=P[3],x=0)
s[3]=entropy(Fluid$,P=P[3],x=0)
"Boiler condensate pump  or Pump 2 analysis"
P[4] = P[5]
v3=volume(Fluid$,P=P[3],x=0)
w_pump2_s=v3*(P[4]-P[3])"SSSF isentropic pump work assuming constant specific volume"
w_pump2=w_pump2_s/Eta_pump "Definition of pump efficiency"
h[3]+w_pump2= h[4]  "Steady-flow conservation of energy"
s[4]=entropy(Fluid$,P=P[4],h=h[4])
T[4]=temperature(Fluid$,P=P[4],h=h[4])
w_steam_pumps = (1-y)*w_pump1+ w_pump2 "Total steam pump work input/ mass steam"
"Steam Turbine analysis"
h[5]=enthalpy(Fluid$,T=T[5],P=P[5])
s[5]=entropy(Fluid$,P=P[5],T=T[5])
ss6=s[5]
hs6=enthalpy(Fluid$,s=ss6,P=P[6])
Ts6=temperature(Fluid$,s=ss6,P=P[6])
h[6]=h[5]-Eta_steam_turb*(h[5]-hs6)"Definition of steam turbine efficiency"
T[6]=temperature(Fluid$,P=P[6],h=h[6])
s[6]=entropy(Fluid$,P=P[6],h=h[6])
ss7=s[5]
hs7=enthalpy(Fluid$,s=ss7,P=P[7])
Ts7=temperature(Fluid$,s=ss7,P=P[7])
h[7]=h[5]-Eta_steam_turb*(h[5]-hs7)"Definition of steam turbine efficiency"
T[7]=temperature(Fluid$,P=P[7],h=h[7])
```

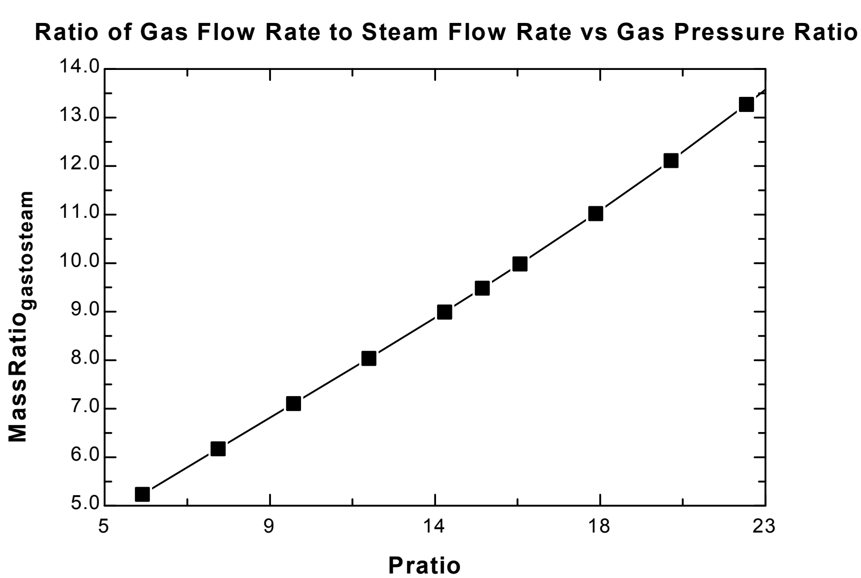
```
s[7]=entropy(Fluid$,P=P[7],h=h[7])
"SSSF conservation of energy for the steam turbine: adiabatic, neglect ke and pe"
h[5] = w_steam_turb + y*h[6] +(1-y)*h[7]
"Steam Condenser analysis"
(1-y)*h[7]=q_out+(1-y)*h[1]"SSSF conservation of energy for the Condenser per unit mass"
Q_dot_out*Convert(MW, kW)=m_dot_steam*q_out
"Cycle Statistics"
MassRatio_gastosteam =m_dot_gas/m_dot_steam
W_dot_net*Convert(MW, kW)=m_dot_gas*(w_gas_turb-w_gas_comp)+
m_dot_steam*(w_steam_turb - w_steam_pumps)"definition of the net cycle work"
Eta_th=W_dot_net/Q_dot_in*Convert(, %) "Cycle thermal efficiency, in percent"
Bwr=(m_dot_gas*w_gas_comp + m_dot_steam*w_steam_pumps)/(m_dot_gas*w_gas_turb +
m_dot_steam*w_steam_turb) "Back work ratio"
W_dot_net_steam = m_dot_steam*(w_steam_turb - w_steam_pumps)
W_dot_net_gas = m_dot_gas*(w_gas_turb - w_gas_comp)
NetWorkRatio_gastosteam = W_dot_net_gas/W_dot_net_steam
```

Pratio	$MassRatio_{gastosteam}$	W_{netgas} [kW]	$W_{netsteam}$ [kW]	η_{th} [%]	$NetWorkRatio_{gastosteam}$
10	7.108	342944	107056	59.92	3.203
11	7.574	349014	100986	60.65	3.456
12	8.043	354353	95647	61.29	3.705
13	8.519	359110	90890	61.86	3.951
14	9.001	363394	86606	62.37	4.196
15	9.492	367285	82715	62.83	4.44
16	9.993	370849	79151	63.24	4.685
17	10.51	374135	75865	63.62	4.932
18	11.03	377182	72818	63.97	5.18
19	11.57	380024	69976	64.28	5.431
20	12.12	382687	67313	64.57	5.685




66
63.8
61.6
59.4
57.2
55
5
9
13
17
21
25
η_{th} [%]
Pratio


W dot,gas / W dot,steam vs Gas Pressure Ratio
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
5
9
14
18
23
NetWorkRatio gastosteam
Pratio


Ratio of Gas Flow Rate to Steam Flow Rate vs Gas Pressure Ratio
14.0
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
5
9
14
18
23
MassRatio gastosteam
Pratio

10-79 A 450-MW combined gas-steam power plant is considered. The topping cycle is a gas-turbine cycle and the bottoming cycle is a nonideal Rankine cycle with an open feedwater heater. The mass flow rate of air to steam, the required rate of heat input in the combustion chamber, and the thermal efficiency of the combined cycle are to be determined.

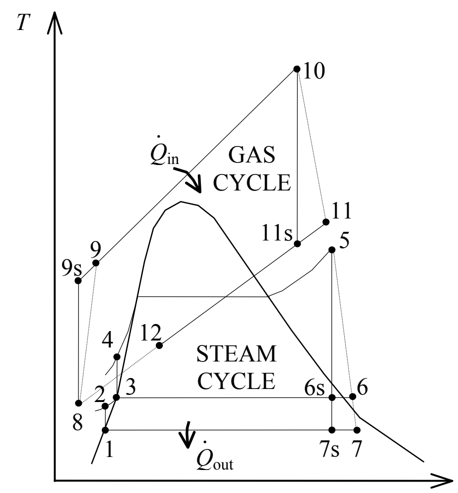
Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible. **3** Air is an ideal gas with variable specific heats.

Analysis (*a*) Using the properties of air from Table A-17, the analysis of gas cycle yields

$$T_8 = 300 \text{ K} \longrightarrow h_8 = 300.19 \text{ kJ/kg}, \quad P_{r_8} = 1.386$$

$$P_{r_9} = \frac{P_9}{P_8} P_{r_8} = (14)(1.386) = 19.40 \longrightarrow h_{9s} = 635.5 \text{ kJ/kg}$$

$$\eta_C = \frac{h_{9s} - h_8}{h_9 - h_8} \longrightarrow h_9 = h_8 + (h_{9s} - h_8)/\eta_C = 300.19 + (635.5 - 300.19)/(0.82) = 709.1 \text{ kJ/kg}$$



$$T_{10} = 1400 \text{ K} \longrightarrow h_{10} = 1515.42 \text{ kJ/kg}, \quad P_{r_{10}} = 450.5$$

$$P_{r_{11}} = \frac{P_{11}}{P_{10}} P_{r_{10}} = \left(\frac{1}{14}\right)(450.5) = 32.18 \longrightarrow h_{11s} = 735.8 \text{ kJ/kg}$$

$$\eta_T = \frac{h_{10} - h_{11}}{h_{10} - h_{11s}} \longrightarrow h_{11} = h_{10} - \eta_T (h_{10} - h_{11s}) = 1515.42 - (0.86)(1515.42 - 735.8) = 844.95 \text{ kJ/kg}$$

$$T_{12} = 460 \text{ K} \longrightarrow h_{12} = 462.02 \text{ kJ/kg}$$

From the steam tables (Tables A-4, A-5, and A-6),

$$h_1 = h_{f \text{ @ 20 kPa}} = 251.42 \text{ kJ/kg}$$
$$\boldsymbol{v}_1 = \boldsymbol{v}_{f \text{ @ 20 kPa}} = 0.001017 \text{ m}^3\text{/kg}$$

$$w_{\text{pI,in}} = \boldsymbol{v}_1 (P_2 - P_1) = (0.001017 \text{ m}^3\text{/kg})(600 - 20 \text{ kPa})\left(\frac{1 \text{ kJ}}{1 \text{ kPa} \cdot \text{m}^3}\right) = 0.59 \text{ kJ/kg}$$

$$h_2 = h_1 + w_{\text{pI,in}} = 251.42 + 0.59 = 252.01 \text{ kJ/kg}$$

$$h_3 = h_{f \text{ @ 0.6 MPa}} = 670.38 \text{ kJ/kg}$$
$$\boldsymbol{v}_3 = \boldsymbol{v}_{f \text{ @ 0.6 MPa}} = 0.001101 \text{ m}^3\text{/kg}$$

$$w_{\text{pII,in}} = \boldsymbol{v}_3 (P_4 - P_3) = (0.001101 \text{ m}^3\text{/kg})(8{,}000 - 600 \text{ kPa})\left(\frac{1 \text{ kJ}}{1 \text{ kPa} \cdot \text{m}^3}\right) = 8.15 \text{ kJ/kg}$$

$$h_4 = h_3 + w_{\text{pI,in}} = 670.38 + 8.15 = 678.52 \text{ kJ/kg}$$

$$\left.\begin{aligned} P_5 &= 8 \text{ MPa} \\ T_5 &= 400°\text{C} \end{aligned}\right\} \begin{aligned} h_5 &= 3139.4 \text{ kJ/kg} \\ s_5 &= 6.3658 \text{ kJ/kg} \cdot \text{K} \end{aligned}$$

$$\left.\begin{array}{l} P_6 = 0.6\text{ MPa} \\ s_{6s} = s_5 \end{array}\right\} \begin{array}{l} x_{6s} = \dfrac{s_{6s} - s_f}{s_{fg}} = \dfrac{6.3658 - 1.9308}{4.8285} = 0.9184 \\ h_{6s} = h_f + x_{6s} h_{fg} = 670.38 + (0.9184)(2085.8) = 2585.9\text{ kJ/kg} \end{array}$$

$$\eta_T = \frac{h_5 - h_6}{h_5 - h_{6s}} \longrightarrow h_6 = h_5 - \eta_T (h_5 - h_{6s}) = 3139.4 - (0.86)(3139.4 - 2585.9) = 2663.3\text{ kJ/kg}$$

$$\left.\begin{array}{l} P_7 = 20\text{ kPa} \\ s_7 = s_5 \end{array}\right\} \begin{array}{l} x_{7s} = \dfrac{s_7 - s_f}{s_{fg}} = \dfrac{6.3658 - 0.8320}{7.0752} = 0.7820 \\ h_{7s} = h_f + x_7 h_{fg} = 251.42 + (0.7820)(2357.5) = 2095.1\text{ kJ/kg} \end{array}$$

$$\eta_T = \frac{h_5 - h_7}{h_5 - h_{7s}} \longrightarrow h_7 = h_5 - \eta_T (h_5 - h_{7s}) = 3139.4 - (0.86)(3139.4 - 2095.1) = 2241.3\text{ kJ/kg}$$

Noting that $\dot{Q} \cong \dot{W} \cong \Delta\text{ke} \cong \Delta\text{pe} \cong 0$ for the heat exchanger, the steady-flow energy balance equation yields

$$\dot{E}_{\text{in}} - \dot{E}_{\text{out}} = \Delta\dot{E}_{\text{system}}^{\nearrow 0\text{ (steady)}} = 0$$

$$\dot{E}_{\text{in}} = \dot{E}_{\text{out}}$$

$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e \longrightarrow \dot{m}_s (h_5 - h_4) = \dot{m}_{\text{air}} (h_{11} - h_{12})$$

$$\frac{\dot{m}_{\text{air}}}{\dot{m}_s} = \frac{h_5 - h_4}{h_{11} - h_{12}} = \frac{3139.4 - 678.52}{844.95 - 462.02} = \mathbf{6.425\ \ kg\ air / kg\ steam}$$

(*b*) Noting that $\dot{Q} \cong \dot{W} \cong \Delta\text{ke} \cong \Delta\text{pe} \cong 0$ for the open FWH, the steady-flow energy balance equation yields

$$\dot{E}_{\text{in}} - \dot{E}_{\text{out}} = \Delta\dot{E}_{\text{system}}^{\nearrow 0\text{ (steady)}} = 0 \rightarrow \dot{E}_{\text{in}} = \dot{E}_{\text{out}}$$

$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e \longrightarrow \dot{m}_2 h_2 + \dot{m}_6 h_6 = \dot{m}_3 h_3 \longrightarrow y h_6 + (1 - y) h_2 = (1) h_3$$

Thus,

$$y = \frac{h_3 - h_2}{h_6 - h_2} = \frac{670.38 - 252.01}{2663.3 - 252.01} = 0.1735 \quad \text{(the fraction of steam extracted)}$$

$$w_T = \eta_T [h_5 - h_6 + (1 - y)(h_6 - h_7)]$$
$$= (0.86)[3139.4 - 2663.3 + (1 - 0.1735)(2663.3 - 2241.3)] = 824.5\text{ kJ/kg}$$

$$w_{\text{net,steam}} = w_T - w_{\text{p,in}} = w_T - (1 - y) w_{\text{p,I}} - w_{\text{p,II}}$$
$$= 824.5 - (1 - 0.1735)(0.59) - 8.15 = 815.9\text{ kJ/kg}$$

$$w_{\text{net,gas}} = w_T - w_{C,\text{in}} = (h_{10} - h_{11}) - (h_9 - h_8)$$
$$= 1515.42 - 844.95 - (709.1 - 300.19) = 261.56\text{ kJ/kg}$$

The net work output per unit mass of gas is

$$w_{\text{net}} = w_{\text{net,gas}} + \tfrac{1}{6.423} w_{\text{net,steam}} = 261.56 + \tfrac{1}{6.425}(815.9) = 388.55\text{ kJ/kg}$$

$$\dot{m}_{\text{air}} = \frac{\dot{W}_{\text{net}}}{w_{\text{net}}} = \frac{450{,}000\text{ kJ/s}}{388.55\text{ kJ/kg}} = 1158.2\text{ kg/s}$$

and $\quad \dot{Q}_{\text{in}} = \dot{m}_{\text{air}} (h_{10} - h_9) = (1158.2\text{ kg/s})(1515.42 - 709.1)\text{ kJ/kg} = \mathbf{933{,}850\ kW}$

(*c*) $\quad \eta_{th} = \dfrac{\dot{W}_{\text{net}}}{\dot{Q}_{\text{in}}} = \dfrac{450{,}000\text{ kW}}{933{,}850\text{ kW}} = \mathbf{48.2\%}$

10-80 EES Problem 10-79 is reconsidered. The effect of the gas cycle pressure ratio on the ratio of gas flow rate to steam flow rate and cycle thermal efficiency is to be investigated.

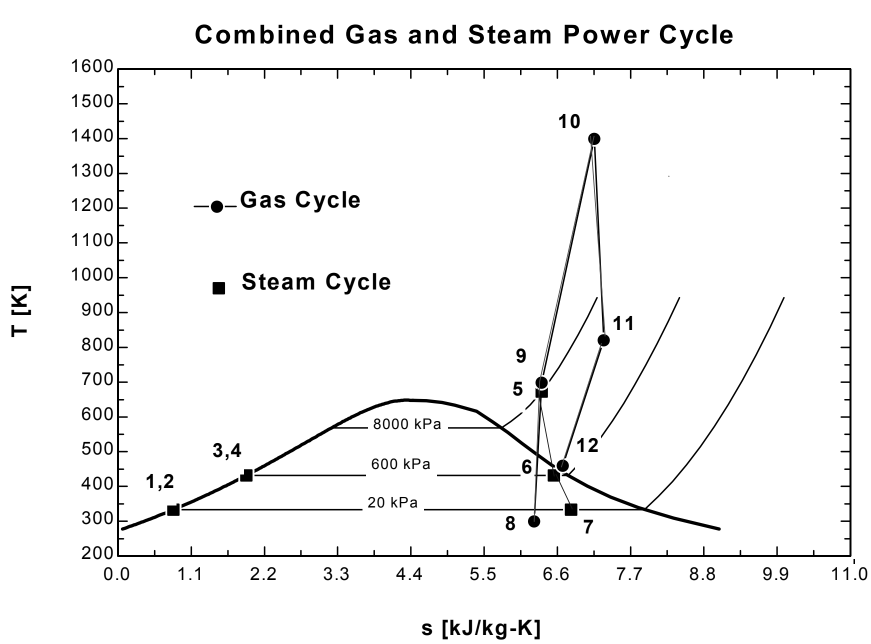
Analysis The problem is solved using EES, and the solution is given below.

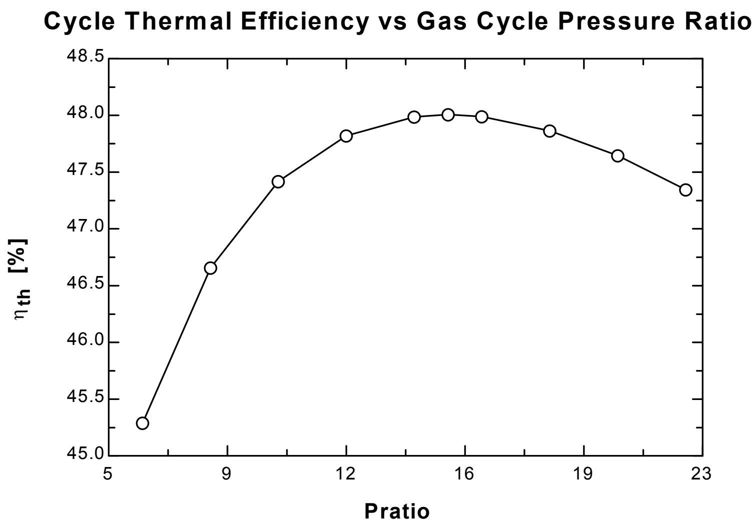
```
"Input data"
T[8] = 300 [K]            "Gas compressor inlet"
P[8] = 14.7 [kPa]         "Assumed air inlet pressure"
"Pratio = 14"             "Pressure ratio for gas compressor"
T[10] = 1400 [K]          "Gas turbine inlet"
T[12] = 460 [K]           "Gas exit temperature from Gas-to-steam heat exchanger "
P[12] = P[8]              "Assumed air exit pressure"
W_dot_net=450 [MW]
Eta_comp = 0.82
Eta_gas_turb = 0.86
Eta_pump = 1.0
Eta_steam_turb = 0.86
P[5] = 8000 [kPa]          "Steam turbine inlet"
T[5] =(400+273) "K"        "Steam turbine inlet"
P[6] = 600 [kPa]          "Extraction pressure for steam open feedwater heater"
P[7] = 20 [kPa]           "Steam condenser pressure"

"GAS POWER CYCLE ANALYSIS"

"Gas Compressor anaysis"
s[8]=ENTROPY(Air,T=T[8],P=P[8])
ss9=s[8] "For the ideal case the entropies are constant across the compressor"
P[9] = Pratio*P[8]
Ts9=temperature(Air,s=ss9,P=P[9])"Ts9 is the isentropic value of T[9] at compressor exit"
Eta_comp = w_gas_comp_isen/w_gas_comp "compressor adiabatic efficiency, w_comp >
w_comp_isen"
h[8] + w_gas_comp_isen =hs9"SSSF conservation of energy for the isentropic compressor,
assuming: adiabatic, ke=pe=0 per unit gas mass flow rate in kg/s"
h[8]=ENTHALPY(Air,T=T[8])
hs9=ENTHALPY(Air,T=Ts9)
h[8] + w_gas_comp = h[9]"SSSF conservation of energy for the actual compressor, assuming:
adiabatic, ke=pe=0"
T[9]=temperature(Air,h=h[9])
s[9]=ENTROPY(Air,T=T[9],P=P[9])

"Gas Cycle External heat exchanger analysis"
h[9] + q_in = h[10]"SSSF conservation of energy for the external heat exchanger, assuming W=0,
ke=pe=0"
h[10]=ENTHALPY(Air,T=T[10])
P[10]=P[9]                        "Assume process 9-10 is SSSF constant pressure"
Q_dot_in"MW"*1000"kW/MW"=m_dot_gas*q_in

"Gas Turbine analysis"
s[10]=ENTROPY(Air,T=T[10],P=P[10])
ss11=s[10] "For the ideal case the entropies are constant across the turbine"
P[11] = P[10] /Pratio
Ts11=temperature(Air,s=ss11,P=P[11])"Ts11 is the isentropic value of T[11] at gas turbine exit"
Eta_gas_turb = w_gas_turb /w_gas_turb_isen "gas turbine adiabatic efficiency, w_gas_turb_isen
> w_gas_turb"
h[10] = w_gas_turb_isen + hs11"SSSF conservation of energy for the isentropic gas turbine,
assuming: adiabatic, ke=pe=0"
```

```
hs11=ENTHALPY(Air,T=Ts11)
h[10] = w_gas_turb + h[11]"SSSF conservation of energy for the actual gas turbine, assuming: adiabatic, ke=pe=0"
T[11]=temperature(Air,h=h[11])
s[11]=ENTROPY(Air,T=T[11],P=P[11])

"Gas-to-Steam Heat Exchanger"
"SSSF conservation of energy for the gas-to-steam heat exchanger, assuming: adiabatic, W=0, ke=pe=0"
m_dot_gas*h[11] + m_dot_steam*h[4] = m_dot_gas*h[12] + m_dot_steam*h[5]
h[12]=ENTHALPY(Air, T=T[12])
s[12]=ENTROPY(Air,T=T[12],P=P[12])

"STEAM CYCLE ANALYSIS"
"Steam Condenser exit pump  or Pump 1 analysis"
Fluid$='Steam_IAPWS'
P[1] = P[7]
P[2]=P[6]
h[1]=enthalpy(Fluid$,P=P[1],x=0)      {Saturated liquid}
v1=volume(Fluid$,P=P[1],x=0)
s[1]=entropy(Fluid$,P=P[1],x=0)
T[1]=temperature(Fluid$,P=P[1],x=0)
w_pump1_s=v1*(P[2]-P[1])"SSSF isentropic pump work assuming constant specific volume"
w_pump1=w_pump1_s/Eta_pump "Definition of pump efficiency"
h[1]+w_pump1= h[2]  "Steady-flow conservation of energy"
s[2]=entropy(Fluid$,P=P[2],h=h[2])
T[2]=temperature(Fluid$,P=P[2],h=h[2])
"Open Feedwater Heater analysis"
y*h[6] + (1-y)*h[2] = 1*h[3] "Steady-flow conservation of energy"
P[3]=P[6]
h[3]=enthalpy(Fluid$,P=P[3],x=0)      "Condensate leaves heater as sat. liquid at P[3]"
T[3]=temperature(Fluid$,P=P[3],x=0)
s[3]=entropy(Fluid$,P=P[3],x=0)
"Boiler condensate pump  or Pump 2 analysis"
P[4] = P[5]
v3=volume(Fluid$,P=P[3],x=0)
w_pump2_s=v3*(P[4]-P[3])"SSSF isentropic pump work assuming constant specific volume"
w_pump2=w_pump2_s/Eta_pump "Definition of pump efficiency"
h[3]+w_pump2= h[4]  "Steady-flow conservation of energy"
s[4]=entropy(Fluid$,P=P[4],h=h[4])
T[4]=temperature(Fluid$,P=P[4],h=h[4])
w_steam_pumps = (1-y)*w_pump1+ w_pump2 "Total steam pump work input/ mass steam"
"Steam Turbine analysis"
h[5]=enthalpy(Fluid$,T=T[5],P=P[5])
s[5]=entropy(Fluid$,P=P[5],T=T[5])
ss6=s[5]
hs6=enthalpy(Fluid$,s=ss6,P=P[6])
Ts6=temperature(Fluid$,s=ss6,P=P[6])
h[6]=h[5]-Eta_steam_turb*(h[5]-hs6)"Definition of steam turbine efficiency"
T[6]=temperature(Fluid$,P=P[6],h=h[6])
s[6]=entropy(Fluid$,P=P[6],h=h[6])
ss7=s[5]
hs7=enthalpy(Fluid$,s=ss7,P=P[7])
Ts7=temperature(Fluid$,s=ss7,P=P[7])
h[7]=h[5]-Eta_steam_turb*(h[5]-hs7)"Definition of steam turbine efficiency"
T[7]=temperature(Fluid$,P=P[7],h=h[7])
```

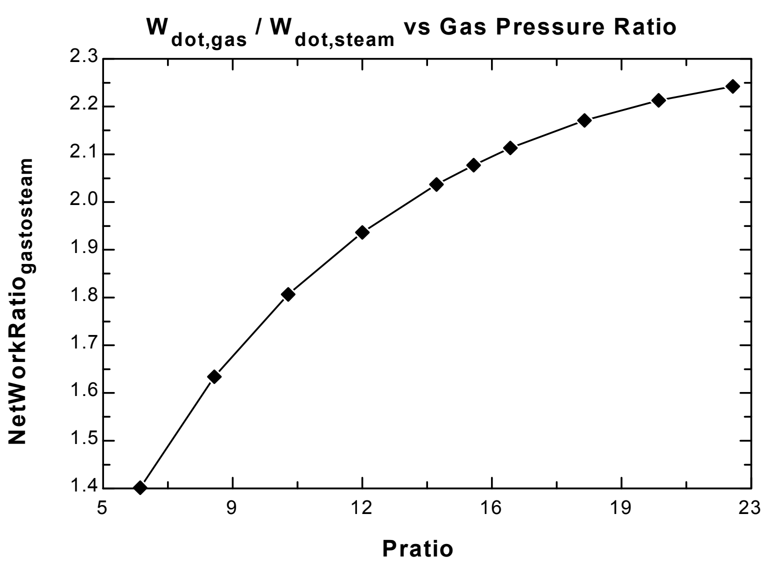
```
s[7]=entropy(Fluid$,P=P[7],h=h[7])
"SSSF conservation of energy for the steam turbine: adiabatic, neglect ke and pe"
h[5] = w_steam_turb + y*h[6] +(1-y)*h[7]
"Steam Condenser analysis"
(1-y)*h[7]=q_out+(1-y)*h[1]"SSSF conservation of energy for the Condenser per unit mass"
Q_dot_out*Convert(MW, kW)=m_dot_steam*q_out
"Cycle Statistics"
MassRatio_gastosteam =m_dot_gas/m_dot_steam
W_dot_net*Convert(MW, kW)=m_dot_gas*(w_gas_turb-w_gas_comp)+
m_dot_steam*(w_steam_turb - w_steam_pumps)"definition of the net cycle work"
Eta_th=W_dot_net/Q_dot_in*Convert(, %) "Cycle thermal efficiency, in percent"
Bwr=(m_dot_gas*w_gas_comp + m_dot_steam*w_steam_pumps)/(m_dot_gas*w_gas_turb +
m_dot_steam*w_steam_turb)  "Back work ratio"
W_dot_net_steam = m_dot_steam*(w_steam_turb - w_steam_pumps)
W_dot_net_gas = m_dot_gas*(w_gas_turb - w_gas_comp)
NetWorkRatio_gastosteam = W_dot_net_gas/W_dot_net_steam
```

Pratio	MassRatio gastosteam	W_{netgas} [kW]	$W_{netsteam}$ [kW]	η_{th} [%]	NetWorkRatio gastosteam
6	4.463	262595	187405	45.29	1.401
8	5.024	279178	170822	46.66	1.634
10	5.528	289639	160361	47.42	1.806
12	5.994	296760	153240	47.82	1.937
14	6.433	301809	148191	47.99	2.037
15	6.644	303780	146220	48.01	2.078
16	6.851	305457	144543	47.99	2.113
18	7.253	308093	141907	47.87	2.171
20	7.642	309960	140040	47.64	2.213
22	8.021	311216	138784	47.34	2.242

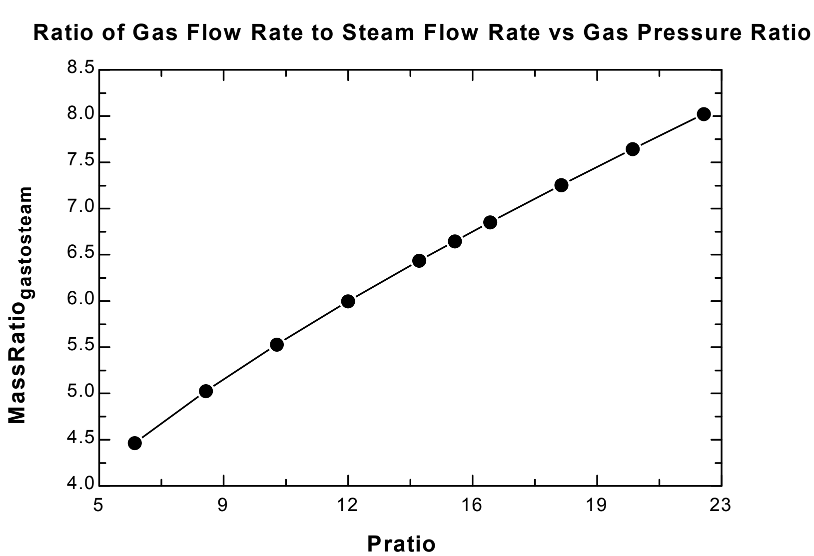




Cycle Thermal Efficiency vs Gas Cycle Pressure Ratio
η_th [%]
48.5
48.0
47.5
47.0
46.5
46.0
45.5
45.0
5
9
12
16
19
23
Pratio



W_dot,gas / W_dot,steam vs Gas Pressure Ratio
NetWorkRatio_gastosteam
2.3
2.2
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
5
9
12
16
19
23
Pratio

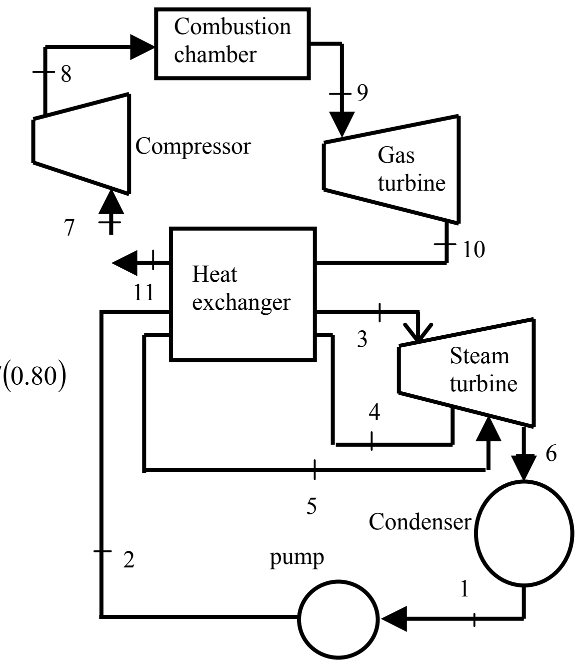


Ratio of Gas Flow Rate to Steam Flow Rate vs Gas Pressure Ratio
MassRatio_gastosteam
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
5
9
12
16
19
23
Pratio

10-81 A combined gas-steam power plant is considered. The topping cycle is a gas-turbine cycle and the bottoming cycle is a nonideal reheat Rankine cycle. The moisture percentage at the exit of the low-pressure turbine, the steam temperature at the inlet of the high-pressure turbine, and the thermal efficiency of the combined cycle are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible. **3** Air is an ideal gas with variable specific heats.

Analysis (*a*) We obtain the air properties from EES. The analysis of gas cycle is as follows



$$T_7 = 15°\text{C} \longrightarrow h_7 = 288.50 \text{ kJ/kg}$$

$$\left.\begin{array}{l} T_7 = 15°\text{C} \\ P_7 = 100 \text{ kPa} \end{array}\right\} s_7 = 5.6648 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_8 = 700 \text{ kPa} \\ s_8 = s_7 \end{array}\right\} h_{8s} = 503.47 \text{ kJ/kg}$$

$$\eta_C = \frac{h_{8s} - h_7}{h_8 - h_7} \longrightarrow h_8 = h_7 + (h_{8s} - h_7)/\eta_C$$
$$= 290.16 + (503.47 - 290.16)/(0.80)$$
$$= 557.21 \text{ kJ/kg}$$

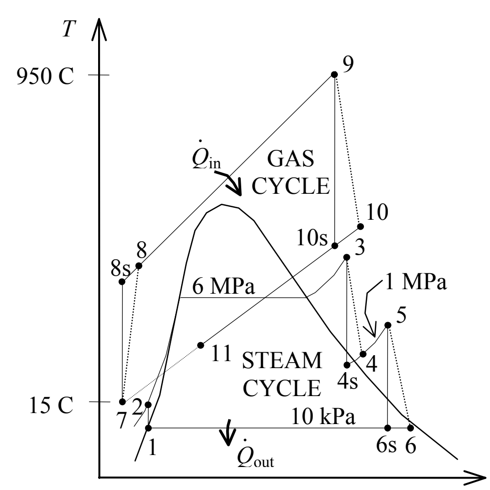
$$T_9 = 950°\text{C} \longrightarrow h_9 = 1304.8 \text{ kJ/kg}$$

$$\left.\begin{array}{l} T_9 = 950°\text{C} \\ P_9 = 700 \text{ kPa} \end{array}\right\} s_9 = 6.6456 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_{10} = 100 \text{ kPa} \\ s_{10} = s_9 \end{array}\right\} h_{10s} = 763.79 \text{ kJ/kg}$$

$$\eta_T = \frac{h_9 - h_{10}}{h_9 - h_{10s}} \longrightarrow h_{10} = h_9 - \eta_T(h_9 - h_{10s})$$
$$= 1304.8 - (0.80)(1304.8 - 763.79)$$
$$= 871.98 \text{ kJ/kg}$$

$$T_{11} = 200°\text{C} \longrightarrow h_{11} = 475.62 \text{ kJ/kg}$$



From the steam tables (Tables A-4, A-5, and A-6 or from EES),

$$h_1 = h_{f\,@\,10\text{ kPa}} = 191.81 \text{ kJ/kg}$$
$$v_1 = v_{f\,@\,10\text{ kPa}} = 0.00101 \text{ m}^3/\text{kg}$$

$$w_{\text{pI,in}} = v_1(P_2 - P_1)/\eta_p$$
$$= (0.00101 \text{ m}^3/\text{kg})(6000 - 10 \text{ kPa})\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right)/0.80$$
$$= 7.56 \text{ kJ/kg}$$

$$h_2 = h_1 + w_{\text{pI,in}} = 191.81 + 7.65 = 199.37 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_5 = 1 \text{ MPa} \\ T_5 = 400°\text{C} \end{array}\right\} \begin{array}{l} h_5 = 3264.5 \text{ kJ/kg} \\ s_5 = 7.4670 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_6 = 10 \text{ kPa} \\ s_{6s} = s_5 \end{array}\right\} \begin{array}{l} x_{6s} = \dfrac{s_{6s} - s_f}{s_{fg}} = \dfrac{7.4670 - 0.6492}{7.4996} = 0.9091 \\ h_{6s} = h_f + x_{6s}h_{fg} = 191.81 + (0.9091)(2392.1) = 2366.4 \text{ kJ/kg} \end{array}$$

$$\eta_T = \frac{h_5 - h_6}{h_5 - h_{6s}} \longrightarrow h_6 = h_5 - \eta_T(h_5 - h_{6s}) = 3264.5 - (0.80)(3264.5 - 2366.4) = 2546.0 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_6 = 10 \text{ kPa} \\ h_6 = 2546.5 \text{ kJ/kg} \end{array}\right\} x_6 = 0.9842$$

Moisture Percentage $= 1 - x_6 = 1 - 0.9842 = 0.0158 =$ **1.6%**

(*b*) Noting that $\dot{Q} \cong \dot{W} \cong \Delta\text{ke} \cong \Delta\text{pe} \cong 0$ for the heat exchanger, the steady-flow energy balance equation yields

$$\dot{E}_{\text{in}} = \dot{E}_{\text{out}}$$

$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e$$

$$\dot{m}_s(h_3 - h_2) + \dot{m}_s(h_5 - h_4) = \dot{m}_{\text{air}}(h_{10} - h_{11})$$

$$(1.15)[(3346.5 - 199.37) + (3264.5 - h_4)] = (10)(871.98 - 475.62) \longrightarrow h_4 = 2965.0 \text{ kJ/kg}$$

Also,

$$\left.\begin{array}{l} P_3 = 6 \text{ MPa} \\ T_3 = ? \end{array}\right\} \begin{array}{l} h_3 = \\ s_3 = \end{array} \qquad \left.\begin{array}{l} P_4 = 1 \text{ MPa} \\ s_{4s} = s_3 \end{array}\right\} h_{4s} =$$

$$\eta_T = \frac{h_3 - h_4}{h_3 - h_{4s}} \longrightarrow h_4 = h_3 - \eta_T(h_3 - h_{4s})$$

The temperature at the inlet of the high-pressure turbine may be obtained by a trial-error approach or using EES from the above relations. The answer is T_3 = **468.0ºC**. Then, the enthalpy at state 3 becomes: h_3 = 3346.5 kJ/kg

(*c*)

$$\dot{W}_{\text{T,gas}} = \dot{m}_{\text{air}}(h_9 - h_{10}) = (10 \text{ kg/s})(1304.8 - 871.98) \text{ kJ/kg} = 4328 \text{ kW}$$

$$\dot{W}_{\text{C,gas}} = \dot{m}_{\text{air}}(h_8 - h_7) = (10 \text{ kg/s})(557.21 - 288.50) \text{ kJ/kg} = 2687 \text{ kW}$$

$$\dot{W}_{\text{net,gas}} = \dot{W}_{\text{T,gas}} - \dot{W}_{\text{C,gas}} = 4328 - 2687 = 1641 \text{ kW}$$

$$\dot{W}_{\text{T,steam}} = \dot{m}_s(h_3 - h_4 + h_5 - h_6) = (1.15 \text{ kg/s})(3346.5 - 2965.0 + 3264.5 - 2546.0) \text{ kJ/kg} = 1265 \text{ kW}$$

$$\dot{W}_{\text{P,steam}} = \dot{m}_s w_{pump} = (1.15 \text{ kg/s})(7.564) \text{ kJ/kg} = 8.7 \text{ kW}$$

$$\dot{W}_{\text{net,steam}} = \dot{W}_{\text{T,steam}} - \dot{W}_{\text{P,steam}} = 1265 - 8.7 = 1256 \text{ kW}$$

$$\dot{W}_{\text{net,plant}} = \dot{W}_{\text{net,gas}} + \dot{W}_{\text{net,steam}} = 1641 + 1256 = \mathbf{2897 \text{ kW}}$$

(*d*)

$$\dot{Q}_{\text{in}} = \dot{m}_{\text{air}}(h_9 - h_8) = (10 \text{ kg/s})(1304.8 - 557.21) \text{ kJ/kg} = 7476 \text{ kW}$$

$$\eta_{\text{th}} = \frac{\dot{W}_{\text{net,plant}}}{\dot{Q}_{\text{in}}} = \frac{2897 \text{ kW}}{7476 \text{ kW}} = 0.388 = \mathbf{38.8\%}$$