A combined gas-steam power plant is considered. The topping cycle is an ideal gas-turbine cycle and the bottoming cycle is an ideal reheat Rankine cycle. The mass flow rate of air in the gas-turbine cycle, the rate of total heat input, 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

\[
\begin{align*}
T_7 &= 290 \text{ K} \rightarrow h_7 = 290.16 \text{ kJ/kg} \\
P_{r_7} &= 1.2311 \\
T_9 &= 1400 \text{ K} \rightarrow h_9 = 1515.42 \text{ kJ/kg} \\
P_{r_9} &= 450.5 \\
P_{r_{10}} &= \frac{P_{r_{10}}}{P_9} = \frac{1}{8} \left( \frac{450.5}{8} \right) = 56.3 \rightarrow h_{10} = 860.35 \text{ kJ/kg} \\
T_{11} &= 520 \text{ K} \rightarrow h_{11} = 523.63 \text{ kJ/kg} \\
\end{align*}
\]

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

\[
\begin{align*}
\nu_f &= 0.00101 \text{ m}^3/\text{kg} \\
w_{pl, in} &= \nu_f \left( P_2 - P_1 \right) = 0.00101 \text{ m}^3/\text{kg} \times 15,000 - 10 \text{ kPa} = 15.14 \text{ kJ/kg} \\
h_2 &= h_1 + w_{pl, in} = 191.81 + 15.14 = 206.95 \text{ kJ/kg} \\
P_3 &= 15 \text {MPa} \\
h_5 &= 3157.9 \text {kJ/kg} \\
T_3 &= 450^\circ \text{C} \\
s_3 &= 6.1434 \text{kJ/kg K} \\
P_4 &= 3 \text{MPa} \\
x_4 &= \frac{s_4 - s_f}{s_{fg}} = \frac{6.1434 - 2.6454}{3.5402} = 0.9880 \\
\eta_{reheat} &= \frac{	ext{in}}{0} = 1008.3 + (0.9880) (1.7949) = 2781.7 \text{ kJ/kg} \\
P_5 &= 3 \text{MPa} \\
h_7 &= 3457.2 \text{kJ/kg} \\
T_5 &= 500^\circ \text{C} \\
s_5 &= 7.2359 \text{kJ/kg K} \\
P_6 &= 10 \text{ kPa} \\
x_6 &= \frac{s_6 - s_f}{s_{fg}} = \frac{7.2355 - 0.6492}{7.4996} = 0.8783 \\
\eta_{air, out} &= 1 - \frac{\dot{Q}_{out}}{\dot{Q}_{in}} = 1 - \frac{124,409 \text{ kJ}}{280,352 \text{ kJ}} = 55.6\% \\
\end{align*}
\]

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

\[
\begin{align*}
\dot{E}_{in} &= \dot{E}_{out} \rightarrow \sum m_i h_i = \sum m_e h_e \rightarrow m_i \left( h_3 - h_2 \right) = m_{air} \left( h_{10} - h_1 \right) \\
m_{air} &= \frac{h_3 - h_2}{h_{10} - h_1} = \frac{3157.9 - 206.95}{860.35 - 523.63} (30 \text{ kg/s}) = 262.9 \text{ kg/s} \\
(\text{b}) \dot{Q}_{in} &= \dot{Q}_{in, out} + \dot{Q}_{in, reheat} = m_{air} \left( h_3 - h_2 \right) + m_{reheat} \left( h_5 - h_4 \right) = (262.9 \text{ kg/s}) (1515.42 - 526.12) \text{kJ/kg} + (30 \text{ kg/s}) (3457.2 - 2781.7) \text{kJ/kg} = 280,352 \text{ kJ} \\
&\cong 2.80 \times 10^5 \text{ kW} \\
(\text{c}) \dot{Q}_{out} &= \dot{Q}_{out, air} + \dot{Q}_{out, steam} = m_{air} \left( h_{11} - h_7 \right) + m_1 \left( h_{6} - h_1 \right) = (262.9 \text{ kg/s}) (523.63 - 290.16) \text{kJ/kg} + (30 \text{ kg/s}) (2292.8 - 191.81) \text{kJ/kg} = 124,409 \text{ kW} \\
\eta_{th} &= 1 - \frac{\dot{Q}_{out}}{\dot{Q}_{in}} = 1 - \frac{124,409 \text{ kW}}{280,352 \text{ kW}} = 55.6\% \\
\end{align*}
\]
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 mass flow rate of air in the gas-turbine cycle, the rate of total heat input, 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)

\[ T_2 = 290 \text{ K} \rightarrow h_2 = 290.16 \text{ kJ/kg} \]

\[ P_{r_2} = \frac{P_{r_2}}{P_{r_1}} = (8)(1.2311) = 9.849 \rightarrow h_{r_2} = 526.12 \text{ kJ/kg} \]

\[ \eta_C = \frac{h_{r_2} - h_2}{h_2 - h_2} \rightarrow h_9 = h_2 + (h_{r_2} - h_2)/\eta_C \]

\[ = 290.16 + (526.12 - 290.16)/(0.80) \]

\[ = 585.1 \text{ kJ/kg} \]

\[ T_0 = 1400 \text{ K} \rightarrow h_9 = 1515.42 \text{ kJ/kg} \]

\[ P_{r_9} = 450.5 \]

\[ P_{r_{10s}} = \frac{P_{r_{10s}}}{P_{r_9}} = \left(\frac{1}{8}\right)(450.5) = 56.3 \rightarrow h_{10s} = 860.35 \text{ kJ/kg} \]

\[ \eta_T = \frac{h_9 - h_0}{h_9 - h_{10s}} \rightarrow h_{10} = h_9 - \eta_T(h_9 - h_{10s}) \]

\[ = 1515.42 - (0.85)(1515.42 - 860.35) \]

\[ = 958.4 \text{ kJ/kg} \]

\[ T_{11} = 520 \text{ K} \rightarrow h_1 = 523.63 \text{ kJ/kg} \]

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

\[ h_1 = h_f @ 10 \text{ kPa} = 191.81 \text{ kJ/kg} \]

\[ v_1 = v_f @ 10 \text{ kPa} = 0.00101 \text{ m}^3/\text{kg} \]

\[ w_{pl.in} = v_1(P_2 - P_1) \]

\[ = (0.00101 \text{ m}^3/\text{kg})(15,000 - 10 \text{ kPa})\left(\frac{1 \text{ kJ}}{1 \text{ kPa} \cdot \text{m}^3}\right) \]

\[ = 15.14 \text{ kJ/kg} \]

\[ h_2 = h_1 + w_{pl.in} = 191.81 + 15.14 = 206.95 \text{ kJ/kg} \]

\[ P_3 = 15 \text{ MPa} \]

\[ T_3 = 450^\circ\text{C} \]

\[ s_3 = 6.1428 \text{ kJ/kg} \cdot \text{K} \]

\[ P_4 = 3 \text{ MPa} \]

\[ x_{4s} = \frac{s_{4s} - s_f}{s_{fg}} = \frac{6.1434 - 2.6454}{3.5402} = 0.9880 \]

\[ s_{4s} = s_3 \]

\[ h_{4s} = h_f + x_{4s}h_{fg} = 1008.3 + (0.9879)(1794.9) = 2781.7 \text{ kJ/kg} \]

\[ \eta_T = \frac{h_3 - h_4}{h_3 - h_{4s}} \rightarrow h_4 = h_3 - \eta_T(h_3 - h_{4s}) \]

\[ = 3157.9 - (0.85)(3157.9 - 2781.7) \]

\[ = 2838.1 \text{ kJ/kg} \]
\[ P_5 = 3 \text{ MPa} \] \[ h_5 = 3457.2 \text{ kJ/kg} \]
\[ T_5 = 500^\circ \text{C} \] \[ s_5 = 7.2359 \text{ kJ/kg} \cdot \text{K} \]
\[ P_6 = 10 \text{ kPa} \] \[ x_{6s} = \frac{s_{6s} - s_f}{s_f} = \frac{7.2359 - 0.6492}{7.4996} = 0.8783 \]
\[ s_{6s} = s_5 \] \[ h_{6s} = h_f + x_{6s} h_{fs} = 191.81 + (0.8782)(2392.1) = 2292.8 \text{ kJ/kg} \]
\[ \eta_T = \frac{h_s - h_6}{h_5 - h_{6s}} \rightarrow h_b = h_5 - \eta_T (h_5 - h_{6s}) \]
\[ = 3457.2 - (0.85)(3457.2 - 2292.8) = 2467.5 \text{ kJ/kg} \]

Noting that \( \dot{Q} \equiv \dot{W} \equiv \Delta k e \equiv \Delta p e \equiv 0 \) for the heat exchanger, the steady-flow energy balance equation yields
\[
\dot{E}_{in} - \dot{E}_{out} = \Delta \dot{E}_{system}^{0(\text{steady})} = 0
\]

\[
\dot{E}_{in} = \dot{E}_{out}
\]
\[
\sum m_i h_i = \sum m_i h_2 \rightarrow m_s (h_1 - h_2) = m_{air}(h_{10} - h_1)
\]
\[
m_{air} = \frac{m_3 - m_2}{m_3 - m_1} = \frac{3157.9 - 206.95}{958.4 - 523.63} (30 \text{ kg/s}) = 203.6 \text{ kg/s}
\]

\[(b) \quad \dot{Q}_{in} = \dot{Q}_{air} + \dot{Q}_{reheat} = \dot{m}_{air}(h_9 - h_8) + \dot{m}_{reheat}(h_5 - h_4)
\]
\[= (203.6 \text{ kg/s})(1515.42 - 585.1) \text{ kJ/kg} + (30 \text{ kg/s})(3457.2 - 2838.1) \text{ kJ/kg} = 207,986 \text{ kW}
\]
\[(c) \quad \dot{Q}_{out} = \dot{Q}_{out,air} + \dot{Q}_{out,steam} = \dot{m}_{air}(h_11 - h_7) + \dot{m}_{s}(h_6 - h_1)
\]
\[= (203.6 \text{ kg/s})(523.63 - 290.16) \text{ kJ/kg} + (30 \text{ kg/s})(2467.5 - 191.81) \text{ kJ/kg} = 115,805 \text{ kW}
\]
\[\eta_{th} = 1 - \frac{\dot{Q}_{out}}{\dot{Q}_{in}} = 1 - \frac{115,805 \text{ kW}}{207,986 \text{ kW}} = 44.3\%
\]

10-101 It is to be shown that the exergy destruction associated with a simple ideal Rankine cycle can be expressed as
\[ x_{\text{destroyed}} = q_{in}(\eta_{th,Carnot} - \eta_{th}) \]
where \( \eta_{th} \) is efficiency of the Rankine cycle and \( \eta_{th,Carnot} \) is the efficiency of the Carnot cycle operating between the same temperature limits.

**Analysis** The exergy destruction associated with a cycle is given on a unit mass basis as
\[ x_{\text{destroyed}} = T_0 \sum \frac{q_R}{T_R} \]
where the direction of \( q_{in} \) is determined with respect to the reservoir (positive if to the reservoir and negative if from the reservoir). For a cycle that involves heat transfer only with a source at \( T_H \) and a sink at \( T_0 \), the irreversibility becomes
\[ x_{\text{destroyed}} = T_0 \left( \frac{q_{out}}{T_0} - \frac{q_{in}}{T_H} \right) = q_{out} - T_0 \frac{T_0}{T_H} q_{in} = q_{in} \left( \frac{T_0}{T_H} \right) \]
\[ = q_{in} \left( 1 - \eta_{th} \right) \left( 1 - \eta_{th,C} \right) = q_{in} \left( \eta_{th,C} - \eta_{th} \right) \]

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A cogeneration plant is to produce power and process heat. There are two turbines in the cycle: a high-pressure turbine and a low-pressure turbine. The temperature, pressure, and mass flow rate of steam at the inlet of high-pressure turbine 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),

\[
\begin{align*}
P_4 &= 1.4 \text{ MPa} \quad h_4 = h_g @ 1.4 \text{ MPa} = 2788.9 \text{ kJ/kg} \\
\text{sat. vapor} &\quad s_4 = s_g @ 1.4 \text{ MPa} = 6.4675 \text{ kJ/kg} \cdot \text{K} \\
x_{5s} &= s_{4s} - s_f = 6.4675 - 0.6492 = 7.4996 \\
P_5 &= 10 \text{ kPa} \\
s_{5s} &= s_4 \\
h_{5s} &= h_f + x_{5s}h_{fg} = 191.81 + (0.7758)(2392.1) = 2047.6 \text{ kJ/kg} \\
\eta_T &= \frac{h_4 - h_5}{h_4 - h_{5s}} \quad h_5 = h_4 - \eta_T (h_4 - h_{5s}) \\
&= 2788.9 - (0.60)(2788.9 - 2047.6) \\
&= 2344.1 \text{ kJ/kg} \\
\end{align*}
\]

and

\[
\begin{align*}
w_{\text{turb,low}} &= h_4 - h_5 = 2788.9 - 2344.1 = 444.8 \text{ kJ/kg} \\
\dot{m}_{\text{low turb}} &= \frac{\dot{W}_{\text{turb,II}}}{h_{\text{turb,low}}} = \frac{800 \text{ kJ/s}}{444.8 \text{ kJ/kg}} = 1.799 \text{ kg/s} = 107.9 \text{ kg/min} \\
\end{align*}
\]

Therefore,

\[
\dot{m}_{\text{total}} = 1000 + 108 = 1108 \text{ kg/min} = \mathbf{18.47 \text{ kg/s}}
\]

\[
\begin{align*}
w_{\text{turb,high}} &= \frac{\dot{W}_{\text{turb,II}}}{\dot{m}_{\text{high turb}}} = \frac{1000 \text{ kJ/s}}{18.47 \text{ kg/s}} = 54.15 \text{ kJ/kg} = h_3 - h_4 \\
h_3 &= w_{\text{turb,high}} + h_4 = 54.15 + 2788.9 = 2843.0 \text{ kJ/kg} \\
\eta_T &= \frac{h_3 - h_4}{h_3 - h_{4s}} \quad h_{4s} = h_3 - (h_3 - h_4) / \eta_T \\
&= 2843.0 - (2843.0 - 2788.9) / (0.75) \\
&= 2770.8 \text{ kJ/kg} \\
P_{4s} &= 1.4 \text{ MPa} \quad x_{4s} = \frac{h_{4s} - h_f}{h_{fg}} = \frac{2770.8 - 829.96}{1958.9} = 0.9908 \\
s_{4s} &= s_f + x_{4s}s_{fg} = 2.2835 + (0.9908)(4.1840) = 6.4289 \text{ kJ/kg} \cdot \text{K} \\
\end{align*}
\]

Then from the tables or the software, the turbine inlet temperature and pressure becomes

\[
\begin{align*}
h_3 &= 2843.0 \text{ kJ/kg} \quad P_3 = \mathbf{2 \text{ MPa}} \\
s_3 &= 6.4289 \text{ kJ/kg} \cdot \text{K} \quad T_3 = \mathbf{227.5^\circ C}
\end{align*}
\]
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 rate of process heat, 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),

\[ h_1 = h_{f @ 20 \text{ kPa}} = 251.42 \text{ kJ/kg} \]
\[ \nu_1 = \nu_{f @ 20 \text{ kPa}} = 0.001017 \text{ m}^3/\text{kg} \]

\[ w_{\text{pl,in}} = \nu_1 (P_2 - P_1) / \eta_p \]
\[ = (0.001017 \text{ m}^3/\text{kg}) (2000 - 20 \text{ kPa}) (1 \text{ kJ} / 1 \text{ kPa} \cdot \text{m}^3) / 0.88 \]
\[ = 2.29 \text{ kJ/kg} \]

\[ h_2 = h_1 + w_{\text{pl,in}} = 251.42 + 2.29 = 253.71 \text{ kJ/kg} \]

\[ h_3 = h_{f @ 2 \text{ MPa}} = 908.47 \text{ kJ/kg} \]

Mixing chamber:

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

\((4 \text{ kg/s})(908.47 \text{ kJ/kg}) + (11 - 4 \text{ kg/s})(253.71 \text{ kJ/kg})\) = \((11 \text{ kg/s})h_4 \rightarrow h_4 = 491.81 \text{ kJ/kg} \]

\[ \nu_4 = \nu_{f @ h_4 = 491.81 \text{ kJ/kg}} = 0.001058 \text{ m}^3/\text{kg} \]

\[ w_{\text{pl,in}} = \nu_4 (P_5 - P_3) / \eta_p \]
\[ = (0.001058 \text{ m}^3/\text{kg}) (8000 - 2000 \text{ kPa}) (1 \text{ kJ} / 1 \text{ kPa} \cdot \text{m}^3) / 0.88 \]
\[ = 7.21 \text{ kJ/kg} \]

\[ h_5 = h_4 + w_{\text{pl,in}} = 491.81 + 7.21 = 499.02 \text{ kJ/kg} \]

\[ P_6 = 8 \text{ MPa} \]
\[ h_6 = 3399.5 \text{ kJ/kg} \]

\[ T_6 = 500^\circ \text{C} \]
\[ s_6 = 6.7266 \text{ kJ/kg} \cdot \text{K} \]

\[ P_7 = 2 \text{ MPa} \]
\[ s_7 = s_6 \]

\[ h_{\text{7s}} = 3000.4 \text{ kJ/kg} \]

\[ \eta_T = \frac{h_6 - h_7}{h_6 - h_{\text{7s}}} \rightarrow h_7 = h_6 - \eta_T (h_6 - h_{\text{7s}}) = 3399.5 - (0.88)(3399.5 - 3000.4) = 3048.3 \text{ kJ/kg} \]

\[ P_8 = 20 \text{ kPa} \]
\[ s_8 = s_6 \]
\[ h_{\text{8s}} = 2215.5 \text{ kJ/kg} \]

\[ \eta_T = \frac{h_6 - h_8}{h_6 - h_{\text{8s}}} \rightarrow h_8 = h_6 - \eta_T (h_6 - h_{\text{8s}}) = 3399.5 - (0.88)(3399.5 - 2215.5) = 2357.6 \text{ kJ/kg} \]

Then,

\[ Q_{\text{process}} = \dot{m}_7 (h_7 - h_1) = (4 \text{ kg/s})(3048.3 - 908.47) \text{ kJ/kg} = 8559 \text{ kW} \]

(b) Cycle analysis:

\[ W_{\text{T,out}} = \dot{m}_7 (h_6 - h_7) + \dot{m}_4 (h_6 - h_8) \]
\[ = (4 \text{ kg/s})(3399.5 - 3048.3)\text{kJ/kg} + (7 \text{ kg/s})(3399.5 - 2357.6)\text{kJ/kg} = 8698 \text{ kW} \]

\[ W_{\text{p,in}} = \dot{m}_1 w_{\text{pl,in}} + \dot{m}_4 w_{\text{pl,in}} = (7 \text{ kg/s})(2.29 \text{ kJ/kg}) + (11 \text{ kg/s})(7.21 \text{ kJ/kg}) = 95 \text{ kW} \]

\[ W_{\text{net}} = W_{\text{T,out}} - W_{\text{p,in}} = 8698 - 95 = 8603 \text{ kW} \]

(c) Then,

\[ Q_{\text{in}} = \dot{m}_5 (h_6 - h_5) = (11 \text{ kg/s})(3399.5 - 499.02) = 31,905 \text{ kW} \]

and

\[ \eta_u = \frac{W_{\text{net}} + Q_{\text{process}}}{Q_{\text{in}}} = \frac{8603 + 8559}{31,905} = 0.538 = 53.8\% \]
10-104 EES The effect of the condenser pressure on the performance a simple ideal Rankine cycle is to be investigated.

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

```plaintext
function x4$(x4) "this function returns a string to indicate the state of steam at point 4"
    x4$=""
    if (x4>1) then x4$='(superheated)'
    if (x4<0) then x4$='(compressed)'
end

P[3] = 5000 [kPa]
T[3] = 500 [°C]
"P[4] = 5 [kPa]"
Eta_t = 1.0 "Turbine isentropic efficiency"
Eta_p = 1.0 "Pump isentropic efficiency"

"Pump analysis"
Fluid$='Steam_IAPWS'
x[1]=0 "Sat'd liquid"
h[1]=enthalpy(Fluid$,P=P[1],x=x[1])
v[1]=volume(Fluid$,P=P[1],x=x[1])
s[1]=entropy(Fluid$,P=P[1],x=x[1])
T[1]=temperature(Fluid$,P=P[1],x=x[1])
W_p_s=v[1]*(P[2]-P[1]) "SSSF isentropic pump work assuming constant specific volume"
W_p=W_p_s/Eta_p
s[2]=entropy(Fluid$,P=P[2],h=h[2])
T[2]=temperature(Fluid$,P=P[2],h=h[2])

"Turbine analysis"
h[3]=enthalpy(Fluid$,T=T[3],P=P[3])
s[3]=entropy(Fluid$,T=T[3],P=P[3])
s_s[4]=s[3]
hs[4]=enthalpy(Fluid$,s=s_s[4],P=P[4])
Ts[4]=temperature(Fluid$,s=s_s[4],P=P[4])
Eta_t=(h[3]-h[4])/(h[3]-hs[4]) "Definition of turbine efficiency"
T[4]=temperature(Fluid$,P=P[4],h=h[4])
s[4]=entropy(Fluid$,h=h[4],P=P[4])
x[4]=quality(Fluid$,h=h[4],P=P[4])
x4s$=x4$(x[4])

"Boiler analysis"

"Condenser analysis"

"Cycle Statistics"
W_net=W_t-W_p
Eta_th=W_net/Q_in
```

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**Steam**

![Diagram of steam properties](image)

![Graph of net work vs. pressure](image)

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educators for course preparation. If you are a student using this Manual, you are using it without permission.**
The effect of the boiler pressure on the performance a simple ideal Rankine cycle is to be investigated.

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

function \( x_4(x_4) \) "this function returns a string to indicate the state of steam at point 4"

\[
x_4'' =
\]

if \( (x_4 > 1) \) then \( x_4'' = \text{'(superheated)'} \)
if \( (x_4 < 0) \) then \( x_4'' = \text{'(compressed)'} \)
end

\[
\{ P[3] = 20000 \text{ [kPa]} \} \\
T[3] = 500 \text{ [C]} \\
P[4] = 10 \text{ [kPa]} \\
\text{Eta}_t = 1.0 \text{ "Turbine isentropic efficiency"} \\
\text{Eta}_p = 1.0 \text{ "Pump isentropic efficiency"}
\]

"Pump analysis"
Fluid$='\text{Steam\_IAPWS}'
x[1]=0 "\text{Sat'd liquid}"
\h[1]=\text{enthalpy(Fluid$},P=P[1],x=x[1]) \\
\v[1]=\text{volume(Fluid$},P=P[1],x=x[1]) \\
\s[1]=\text{entropy(Fluid$},P=P[1],x=x[1]) \\
T[1]=\text{temperature(Fluid$},P=P[1],x=x[1]) \\
W\_p\_s=\v[1]*(P[2]-P[1])"\text{SSF isentropic pump work assuming constant specific volume}" \\
W\_p=W\_p\_s/\text{Eta}_p \\
\h[2]=\h[1]+W\_p "\text{SSF First Law for the pump}" \\
\s[2]=\text{entropy(Fluid$},P=P[2],h=\h[2]) \\
T[2]=\text{temperature(Fluid$},P=P[2],h=\h[2])

"Turbine analysis"
\h[3]=\text{enthalpy(Fluid$},T=T[3],P=P[3]) \\
\s[3]=\text{entropy(Fluid$},T=T[3],P=P[3]) \\
\s\_s[4]=\s[3] \\
\hs[4]=\text{enthalpy(Fluid$},s=\s\_s[4],P=P[4]) \\
\Ts[4]=\text{temperature(Fluid$},s=\s\_s[4],P=P[4]) \\
\text{Eta}_t=(\h[3]-\h[4])/(\h[3]-\hs[4])"\text{Definition of turbine efficiency}" \\
T[4]=\text{temperature(Fluid$},P=P[4],h=\h[4]) \\
\s[4]=\text{entropy(Fluid$},h=\h[4],P=P[4]) \\
x[4]=\text{quality(Fluid$},h=\h[4],P=P[4]) \\
x_4s''=x_4'(x[4])

"Boiler analysis" \\

"Condenser analysis" \\
\h[4]=Q\_out+\h[1] "\text{SSF First Law for the Condenser}"

"Cycle Statistics" \\
W\_net=W\_t-W\_p \\
\text{Eta}_th=W\_net/Q\_in
The table and graph in the image show the properties of steam at different pressures and enthalpies. The table lists values for $\eta_{In}$, $W_{net}$, $X_4$, $P_3$, $Q_{in}$, $Q_{out}$, $W_p$, and $W_t$ in [kJ/kg] and [kPa]. The graph illustrates the relationship between $s$ [kJ/kg-K] and $P$ [kPa] for steam, with points 1 to 4 marking specific conditions. The graph also shows the variation of $W_{net}$ [kJ/kg] with $P_3$ [kPa].
The effect of superheating the steam on the performance a simple ideal Rankine cycle is to be investigated.

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

```plaintext
function x4$(x4) "this function returns a string to indicate the state of steam at point 4"
    x4$=""
    if (x4>1) then x4$="(superheated)"
    if (x4<0) then x4$="(compressed)"
end

P[3] = 3000 [kPa]
{T[3] = 600 [C]}
P[4] = 10 [kPa]
Eta_t = 1.0 "Turbine isentropic efficiency"
Eta_p = 1.0 "Pump isentropic efficiency"

"Pump analysis"
Fluid$='Steam_IAPWS'
x[1]=0 "Sat'd liquid"
h[1]=enthalpy(Fluid$,P=P[1],x=x[1])
v[1]=volume(Fluid$,P=P[1],x=x[1])
s[1]=entropy(Fluid$,P=P[1],x=x[1])
T[1]=temperature(Fluid$,P=P[1],x=x[1])
W_p_s=v[1]*(P[2]-P[1]) "SSSF isentropic pump work assuming constant specific volume"
W_p=W_p_s/Eta_p
s[2]=entropy(Fluid$,P=P[2],h=h[2])
T[2]=temperature(Fluid$,P=P[2],h=h[2])

"Turbine analysis"
h[3]=enthalpy(Fluid$,T=T[3],P=P[3])
s[3]=entropy(Fluid$,T=T[3],P=P[3])
s_s[4]=s[3]
h_s[4]=enthalpy(Fluid$,s=s_s[4],P=P[4])
T_s[4]=temperature(Fluid$,s=s_s[4],P=P[4])
Eta_t=(h[3]-h[4])/(h[3]-h_s[4]) "Definition of turbine efficiency"
T[4]=temperature(Fluid$,h=h[4],P=P[4])
s[4]=entropy(Fluid$,h=h[4],P=P[4])
x[4]=quality(Fluid$,h=h[4],P=P[4])
x4s$=x4$(x[4])

"Boiler analysis"

"Condenser analysis"

"Cycle Statistics"
W_net=W_t-W_p
Eta_th=W_net/Q_in
```
<table>
<thead>
<tr>
<th>$T_3$ [°C]</th>
<th>$\eta_{th}$</th>
<th>$W_{net}$ [kJ/kg]</th>
<th>$x_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>0.324</td>
<td>862.8</td>
<td>0.752</td>
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<tr>
<td>344.4</td>
<td>0.333</td>
<td>970.6</td>
<td>0.81</td>
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<tr>
<td>438.9</td>
<td>0.346</td>
<td>1083</td>
<td>0.8536</td>
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<td>533.3</td>
<td>0.361</td>
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<td>0.8909</td>
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<tr>
<td>627.8</td>
<td>0.377</td>
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<td>0.9244</td>
</tr>
<tr>
<td>722.2</td>
<td>0.393</td>
<td>1485</td>
<td>0.955</td>
</tr>
<tr>
<td>816.7</td>
<td>0.410</td>
<td>1639</td>
<td>0.9835</td>
</tr>
<tr>
<td>911.1</td>
<td>0.427</td>
<td>1803</td>
<td>100</td>
</tr>
<tr>
<td>1006</td>
<td>0.442</td>
<td>1970</td>
<td>100</td>
</tr>
<tr>
<td>1100</td>
<td>0.456</td>
<td>2139</td>
<td>100</td>
</tr>
</tbody>
</table>
The effect of reheat pressure on the performance of an ideal Rankine cycle is to be investigated.

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

```
function x6$(x6) "this function returns a string to indicate the state of steam at point 6"
  x6$=""
  if (x6>1) then x6$='(superheated)'
  if (x6<0) then x6$='(subcooled)'
end

P[6] = 10 [kPa]
P[3] = 15000 [kPa]
T[3] = 500 [°C]
"P[4] = 3000 [kPa]"
T[5] = 500 [°C]
Eta_t = 100/100 "Turbine isentropic efficiency"
Eta_p = 100/100 "Pump isentropic efficiency"

"Pump analysis"
Fluid$='Steam_IAPWS'
x[1]=0 "Sat'd liquid"
h[1]=enthalpy(Fluid$,P=P[1],x=x[1])
v[1]=volume(Fluid$,P=P[1],x=x[1])
s[1]=entropy(Fluid$,P=P[1],x=x[1])
T[1]=temperature(Fluid$,P=P[1],x=x[1])
W_p_s=v[1]*(P[2]-P[1]) "SSSF isentropic pump work assuming constant specific volume"
W_p=W_p_s/Eta_p
v[2]=volume(Fluid$,P=P[2],h=h[2])
s[2]=entropy(Fluid$,P=P[2],h=h[2])
T[2]=temperature(Fluid$,P=P[2],h=h[2])

"High Pressure Turbine analysis"
h[3]=enthalpy(Fluid$,T=T[3],P=P[3])
s[3]=entropy(Fluid$,T=T[3],P=P[3])
v[3]=volume(Fluid$,T=T[3],P=P[3])
s_s[4]=s[3]
h_s[4]=enthalpy(Fluid$,s=s_s[4],P=P[4])
T_s[4]=temperature(Fluid$,s=s_s[4],P=P[4])
Eta_t=(h[3]-h_s[4])/(h[3]-h[4]) "Definition of turbine efficiency"
T[4]=temperature(Fluid$,P=P[4],h=h[4])
s[4]=entropy(Fluid$,h=h[4],P=P[4])
v[4]=volume(Fluid$,s=s[4],P=P[4])

"Low Pressure Turbine analysis"
s[5]=entropy(Fluid$,T=T[5],P=P[5])
h[5]=enthalpy(Fluid$,T=T[5],P=P[5])
h_s[6]=enthalpy(Fluid$,s=s_s[6],P=P[6])
T_s[6]=temperature(Fluid$,s=s_s[6],P=P[6])
vs[6]=volume(Fluid$,s=s_s[6],P=P[6])
Eta_t=(h[5]-h_s[6])/(h[5]-h[6]) "Definition of turbine efficiency"
```
h[5]=W_t_lp+h[6]"SSSF First Law for the low pressure turbine"

x[6]=quality(Fluid$,h=h[6],P=P[6])

"Boiler analysis"

"Condenser analysis"

h[6]=Q_out+h[1]"SSSF First Law for the Condenser"

T[6]=temperature(Fluid$,h=h[6],P=P[6])
s[6]=entropy(Fluid$,h=h[6],P=P[6])
x6s$=x6$(x[6])

"Cycle Statistics"

W_net=W_t_hp+W_t_lp-W_p

Eta_th=W_net/Q_in

<table>
<thead>
<tr>
<th>P_4</th>
<th>η_th</th>
<th>W_net</th>
<th>X_6</th>
</tr>
</thead>
<tbody>
<tr>
<td>[kPa]</td>
<td></td>
<td>[kJ/kg]</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>0.4128</td>
<td>1668</td>
<td>0.9921</td>
</tr>
<tr>
<td>1833</td>
<td>0.4253</td>
<td>1611</td>
<td>0.9102</td>
</tr>
<tr>
<td>3167</td>
<td>0.4283</td>
<td>1567</td>
<td>0.8747</td>
</tr>
<tr>
<td>4500</td>
<td>0.4287</td>
<td>1528</td>
<td>0.8511</td>
</tr>
<tr>
<td>5833</td>
<td>0.428</td>
<td>1492</td>
<td>0.8332</td>
</tr>
<tr>
<td>7167</td>
<td>0.4268</td>
<td>1458</td>
<td>0.8184</td>
</tr>
<tr>
<td>8500</td>
<td>0.4252</td>
<td>1426</td>
<td>0.8058</td>
</tr>
<tr>
<td>9833</td>
<td>0.4233</td>
<td>1395</td>
<td>0.7947</td>
</tr>
<tr>
<td>11167</td>
<td>0.4212</td>
<td>1366</td>
<td>0.7847</td>
</tr>
<tr>
<td>12500</td>
<td>0.4189</td>
<td>1337</td>
<td>0.7755</td>
</tr>
</tbody>
</table>

Ideal Rankine cycle with reheat
The effect of number of reheat stages on the performance an ideal Rankine cycle is to be investigated.

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

```plaintext
function x6$(x6) "this function returns a string to indicate the state of steam at point 6"
    x6$=""
    if (x6>1) then x6$='(superheated)'
    if (x6<0) then x6$='(subcooled)'
end

Procedure Reheat(P[3],T[3],T[5],h[4],NoRHStages,Pratio,Eta_t,Q_in_reheat,W_t_lp,h6)
    P3=P[3]
    T5=T[5]
    h4=h[4]
    Q_in_reheat =0
    W_t_lp = 0
    R_P=(1/Pratio)^(1/(NoRHStages+1))

    imax:=NoRHStages - 1
    i:=0

    REPEAT
        i:=i+1
        P4 = P3*R_P
        P5=P4
        P6=P5*R_P
        Fluid$='Steam_IAPWS'
        s5=entropy(Fluid$,T=T5,P=P5)
        h5=enthalpy(Fluid$,T=T5,P=P5)
        s_s6=s5
        h6=enthalpy(Fluid$,s=s_s6,P=P6)
        T6=temperature(Fluid$,s=s_s6,P=P6)
        v6=volume(Fluid$,s=s_s6,P=P6)
        "Eta_t=(h5-h6)/(h5-hs6)""Definition of turbine efficiency"
        h6=h5-Eta_t*(h5-hs6)
        W_t_lp=W_t_lp+h5-h6"SSSF First Law for the low pressure turbine"
        x6=QUALITY(Fluid$,h=h6,P=P6)
        Q_in_reheat =Q_in_reheat + (h5 - h4)
        P3=P4

    UNTIL (i>imax)
END

"NoRHStages = 2"
P[6] = 10"kPa"
P[3] = 15000"kPa"
P_extract = P[6] "Select a lower limit on the reheat pressure"
T[3] = 500"C"
T[5] = 500"C"
Eta_t = 1.0 "Turbine isentropic efficiency"
Eta_p = 1.0 "Pump isentropic efficiency"
Pratio = P[3]/P_extract
```

**PROPRIETARY MATERIAL.** © 2006 The McGraw-Hill Companies, Inc. Limited distribution permitted only to teachers and educators for course preparation. If you are a student using this Manual, you are using it without permission.
P[4] = P[3]^((1/Pratio)^((1/(NoRHStages+1)))"kPa"

Fluid$='Steam_IAPWS'

"Pump analysis"
x[1]=0 "Sat'd liquid"
h[1]=enthalpy(Fluid$,P=P[1],x=x[1])
v[1]=volume(Fluid$,P=P[1],x=x[1])
s[1]=entropy(Fluid$,P=P[1],x=x[1])
T[1]=temperature(Fluid$,P=P[1],x=x[1])
W_p_s=v[1]*(P[2]-P[1])"SSSF isentropic pump work assuming constant specific volume"  
W_p=W_p_s/Eta_p
v[2]=volume(Fluid$,P=P[2],h=h[2])
s[2]=entropy(Fluid$,P=P[2],h=h[2])
T[2]=temperature(Fluid$,P=P[2],h=h[2])

"High Pressure Turbine analysis"
h[3]=enthalpy(Fluid$,T=T[3],P=P[3])
s[3]=entropy(Fluid$,T=T[3],P=P[3])
v[3]=volume(Fluid$,T=T[3],P=P[3])
s_s[4]=s[3]
hs[4]=enthalpy(Fluid$,s=s_s[4],P=P[4])
Ts[4]=temperature(Fluid$,s=s_s[4],P=P[4])
Eta_t=(h[3]-hs[4])/(h[3]-h[4])"Definition of turbine efficiency"
T[4]=temperature(Fluid$,P=P[4],h=h[4])
s[4]=entropy(Fluid$,h=h[4],P=P[4])
v[4]=volume(Fluid$,s=s[4],P=P[4])

"Low Pressure Turbine analysis"
Call Reheat(P[3],T[3],T[5],h[4],NoRHStages,Pratio,Eta_t:Q_in_reheat,W_t_lp,h6)
h[6]=h6

s[5]=entropy(Fluid$,T=T[5],P=P[5])
h[5]=enthalpy(Fluid$,T=T[5],P=P[5])
hs[6]=enthalpy(Fluid$,s=s_s[6],P=P[6])
Ts[6]=temperature(Fluid$,s=s_s[6],P=P[6])
v[6]=volume(Fluid$,s=s_s[6],P=P[6])
Eta_t=(h[5]-hs[6])/(h[5]-h[6])"Definition of turbine efficiency"
x[6]=QUALITY(Fluid$,h=h[6],P=P[6])
W_t_lp_total = NoRHStages*W_t_lp
Q_in_reheat = NoRHStages*(h[5] - h[4])

"Boiler analysis"
Q_in_boiler + h[2]=h[3]"SSSF First Law for the Boiler"
Q_in = Q_in_boiler+Q_in_reheat

"Condenser analysis"
h[6]=Q_out+h[1]"SSSF First Law for the Condenser"
T[6]=temperature(Fluid$,h=h[6],P=P[6])
s[6]=entropy(Fluid$,h=h[6],P=P[6])
x[6]=QUALITY(Fluid$,h=h[6],P=P[6])
x6s$x=x6$(x[6])

"Cycle Statistics"
W_net=W_t_hp+W_t_lp - W_p
Eta_th=W_net/Q_in

<table>
<thead>
<tr>
<th>η_th</th>
<th>NoRH</th>
<th>Q_in [kJ/kg]</th>
<th>W_net [kJ/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.409</td>
<td>7</td>
<td>4085</td>
<td>1674</td>
</tr>
<tr>
<td>0.412</td>
<td>2</td>
<td>4628</td>
<td>1908</td>
</tr>
<tr>
<td>0.408</td>
<td>5</td>
<td>5020</td>
<td>2051</td>
</tr>
<tr>
<td>0.401</td>
<td>8</td>
<td>5333</td>
<td>2143</td>
</tr>
<tr>
<td>0.394</td>
<td>1</td>
<td>5600</td>
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<tr>
<td>0.386</td>
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<td>2253</td>
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<td>0.354</td>
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<td>6651</td>
<td>2358</td>
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</tbody>
</table>
**10-109 EES** The effect of extraction pressure on the performance an ideal regenerative Rankine cycle with one open feedwater heater is to be investigated.

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

"**Input Data**"

- \( P[5] = 15000 \text{ [kPa]} \)
- \( T[5] = 600 \text{ [C]} \)
- \( P_{\text{extract}}=1400 \text{ [kPa]} \)
- \( P[6] = P_{\text{extract}} \)
- \( P_{\text{cond}}=10 \text{ [kPa]} \)
- \( P[7] = P_{\text{cond}} \)
- \( \text{Eta}_turb= 1.0 \ "\text{Turbine isentropic efficiency}" \)
- \( \text{Eta}_pump = 1.0 \ "\text{Pump isentropic efficiency}" \)

"**Condenser exit pump or Pump 1 analysis**"

Fluid$='Steam_IAPWS' \n\( h[1]=\text{enthalpy(Fluid$},P=P[1],x=0) \) \{Sat'd liquid\}
\( v1=\text{volume(Fluid$},P=P[1],x=0) \)
\( s[1]=\text{entropy(Fluid$},P=P[1],x=0) \)
\( T[1]=\text{temperature(Fluid$},P=P[1],x=0) \)
\( w_{\text{pump1}}=v1*(P[2]-P[1])\ "\text{SSSF isentropic pump work assuming constant specific volume}"
\( w_{\text{pump1}}=w_{\text{pump1}}/\text{Eta}_pump \ "\text{Definition of pump efficiency}"
\( h[1]+w_{\text{pump1}}= h[2] \ "\text{Steady-flow conservation of energy}"
\( s[2]=\text{entropy(Fluid$},P=P[2],h=h[2]) \)
\( T[2]=\text{temperature(Fluid$},P=P[2],h=h[2]) \)

"**Open Feedwater Heater analysis:**"

\( h[3]=\text{enthalpy(Fluid$},P=P[3],x=0) \)
\( T[3]=\text{temperature(Fluid$},P=P[3],x=0) \ "\text{Condensate leaves heater as sat. liquid at P[3]}"
\( s[3]=\text{entropy(Fluid$},P=P[3],x=0) \)

"**Boiler condensate pump or Pump 2 analysis**"

\( v3=\text{volume(Fluid$},P=P[3],x=0) \)
\( w_{\text{pump2}}=v3*(P[4]-P[3])\ "\text{SSSF isentropic pump work assuming constant specific volume}"
\( w_{\text{pump2}}=w_{\text{pump2}}/\text{Eta}_pump \ "\text{Definition of pump efficiency}"
\( h[3]+w_{\text{pump2}}= h[4] \ "\text{Steady-flow conservation of energy}"
\( s[4]=\text{entropy(Fluid$},P=P[4],h=h[4]) \)
\( T[4]=\text{temperature(Fluid$},P=P[4],h=h[4]) \)

"**Boiler analysis**"

\( q_{in} + h[4]=h[5] \ "\text{SSSF conservation of energy for the Boiler}"
\( h[5]=\text{enthalpy(Fluid$}, T=T[5], P=P[5]) \)
\( s[5]=\text{entropy(Fluid$}, T=T[5], P=P[5]) \)

"**Turbine analysis**"

\( hs[6]=\text{enthalpy(Fluid$},s=ss[6],P=P[6]) \)
\( Ts[6]=\text{temperature(Fluid$},s=ss[6],P=P[6]) \)
\( h[6]=h[5]-\text{Eta}_turb*(h[5]-h[6]) \ "\text{Definition of turbine efficiency for high pressure stages}"
\( T[6]=\text{temperature(Fluid$},P=P[6],h=h[6]) \)
\( s[6]=\text{entropy(Fluid$},P=P[6],h=h[6]) \)
hs[7]=enthalpy(Fluid$,s=ss[7],P=P[7])
Ts[7]=temperature(Fluid$,s=ss[7],P=P[7])
hi[7]=h[6]-Eta_turb*(h[6]-hs[7])"Definition of turbine efficiency for low pressure stages"
T[7]=temperature(Fluid$,P=P[7],h=h[7])
s[7]=entropy(Fluid$,P=P[7],h=h[7])

"Condenser analysis"
(1- y)*h[7]=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

<table>
<thead>
<tr>
<th>ηth</th>
<th>P_extract [kPa]</th>
<th>W_net [kJ/kg]</th>
<th>q_in [kJ/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4456</td>
<td>50</td>
<td>1438</td>
<td>3227</td>
</tr>
<tr>
<td>0.4512</td>
<td>100</td>
<td>1421</td>
<td>3150</td>
</tr>
<tr>
<td>0.4608</td>
<td>500</td>
<td>1349</td>
<td>2927</td>
</tr>
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</table>
The effect of number of regeneration stages on the performance an ideal regenerative Rankine cycle with one open feedwater heater is to be investigated.

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

```
Procedure Reheat(NoFwh,T[5],P[5],P_cond,Eta_turb,Eta_pump:q_in,w_net)

Fluid$='Steam_IAPWS'
Tcond = temperature(Fluid$,P=P_cond,x=0)
Tboiler = temperature(Fluid$,P=P[5],x=0)
P[7] = P_cond
s[5]=entropy(Fluid$, T=T[5], P=P[5])
h[5]=enthalpy(Fluid$, T=T[5], P=P[5])
h[1]=enthalpy(Fluid$, P=P[7],x=0)


DELTAT_cond_boiler = Tboiler - Tcond

If NoFWH = 0 Then

"the following are h7, h2, w_net, and q_in for zero feedwater heaters, NoFWH = 0"

h7=enthalpy(Fluid$, s=s[5],P=P[7])
h2=h[1]+volume(Fluid$, P=P[7],x=0)*(P[5] - P[7])/Eta_pump
w_net = Eta_turb*(h[5]-h7)-(h2-h[1])
q_in = h[5] - h2

else

i=0
REPEAT
i=i+1
"The following maintains the same temperature difference between any two regeneration stages."
T_FWH[i] = (NoFWH +1 - i)*DELTAT_cond_boiler/(NoFWH + 1)+Tcond"[C]"
P_extract[i] = pressure(Fluid$,T=T_FWH[i],x=0)"[kPa]"
P3[i]=P_extract[i]
P6[i]=P_extract[i]
If i > 1 then P4[i] = P6[i - 1]
UNTIL i=NoFWH

P4[NoFWH+1]=P6[NoFWH]
h4[NoFWH+1]=h[1]+volume(Fluid$, P=P[7],x=0)*(P4[NoFWH+1] - P[7])/Eta_pump

i=0
REPEAT
i=i+1
"Boiler condensate pump or the Pumps 2 between feedwater heaters analysis"

h3[i]=enthalpy(Fluid$,P=P3[i],x=0)
v3[i]=volume(Fluid$,P=P3[i],x=0)
w_pump2_s =v3[i]*(P4[i]-P3[i])"SSSF isentropic pump work assuming constant specific volume"
w_pump2[i]=w_pump2_s/Eta_pump "Definition of pump efficiency"
h4[i]= w_pump2[i] +h3[i] "Steady-flow conservation of energy"
s4[i]=entropy(Fluid$,P=P4[i],h=h4[i])
T4[i]=temperature(Fluid$,P=P4[i],h=h4[i])
```

Until i = NoFWH

**PROPRIETARY MATERIAL. © 2006 The McGraw-Hill Companies, Inc. Limited distribution permitted only to teachers and educators for course preparation. If you are a student using this Manual, you are using it without permission.**
i=0
REPEAT
i=i+1
"Open Feedwater Heater analysis:"
\(h_2[i] = h_6[i]\)
s5[i] = s[5]
ss6[i]=s5[i]
hs6[i]=enthalpy(Fluid$,s=ss6[i],P=P6[i])
Ts6[i]=temperature(Fluid$,s=ss6[i],P=P6[i])
\(h_6[i]=h_5-[Eta_turb \cdot (h_5 - hs6[i])]\) "Definition of turbine efficiency for high pressure stages"
If i=1 then \(y[1]=(h_3[1] - h_4[2])/(h_6[1] - h_4[2])\) "Steady-flow conservation of energy for the FWH"
If i > 1 then
  js = i - 1
  j = 0
  sumyj = 0
  REPEAT
    j = j+1
    sumyj = sumyj + y[j]
  UNTIL j = js
  \(y[i]=(1- sumyj) \cdot (h_3[i] - h_4[i+1])/(h_6[i] - h_4[i+1])\)
ENDIF
T3[i]=temperature(Fluid$,P=P3[i],x=0) "Condensate leaves heater as sat. liquid at P[3]"
s3[i]=entropy(Fluid$,P=P3[i],x=0)

"Turbine analysis"
T6[i]=temperature(Fluid$,P=P6[i],h=h6[i])
s6[i]=entropy(Fluid$,P=P6[i],h=h6[i])
yh6[i] = y[i]*h6[i]
UNTIL i=NoFWH
ss[7]=s6[i]
hs[7]=enthalpy(Fluid$,s=ss[7],P=P[7])
Ts[7]=temperature(Fluid$,s=ss[7],P=P[7])
\(h[7]=h_6[i]-[Eta_turb \cdot (h_6[i]-hs[7])]\) "Definition of turbine efficiency for low pressure stages"
T[7]=temperature(Fluid$,P=P[7],h=h[7])
s[7]=entropy(Fluid$,P=P[7],h=h[7])
sumyi = 0
sumyh6i = 0
wp2i = W_pump2[1]
i=0
REPEAT
i=i+1
sumyi = sumyi + y[i]
sumyh6i = sumyh6i + yh6[i]
If NoFWH > 1 then wp2i = wp2i + (1- sumyi)*W_pump2[i]
UNTIL i = NoFWH

"Condenser Pump--Pump_1 Analysis:"
P[2] = P6 [ NoFWH]
P[1] = P_cond
\(h[1]=enthalpy(Fluid$,P=P[1],x=0)\) {Sat'd liquid}
v1=volume(Fluid$,P=P[1],x=0)
s[1]=entropy(Fluid$,P=P[1],x=0)
T[1]=temperature(Fluid$,P=P[1],x=0)
w_pump1_s=v1*(P[2]-P[1])"SSSF isentropic pump work assuming constant specific volume"
w_pump1=w_pump1_s/Eta_pump "Definition of pump efficiency"
s[2]=entropy(Fluid$,P=P[2],h=h[2])
T[2]=temperature(Fluid$,P=P[2],h=h[2])

"Boiler analysis"
q_in = h[5] - h4[1]"SSSF conservation of energy for the Boiler"
w_turb = h[5] - sumyh6i - (1- sumyi)*h[7]  "SSSF conservation of energy for turbine"

"Condenser analysis"
q_out=(1- sumyi)*(h[7] - h[1])"SSSF First Law for the Condenser"

"Cycle Statistics"
w_net=w_turb - ((1- sumyi)*w_pump1+ wp2i)
endif
END

"Input Data"
NoFWH = 2
P[5] = 15000 [kPa]
T[5] = 600 [°C]
P_cond=5 [kPa]
Eta_turb= 1.0  "Turbine isentropic efficiency"
Eta_pump = 1.0 "Pump isentropic efficiency"
P[1] = P_cond

"Condenser exit pump or Pump 1 analysis"
Call Reheat(NoFwh,T[5],P[5],P_cond,Eta_turb,Eta_pump,q_in,w_net)
Eta_th=w_net/q_in

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Fundamentals of Engineering (FE) Exam Problems

10-111 Consider a steady-flow Carnot cycle with water as the working fluid executed under the saturation dome between the pressure limits of 8 MPa and 20 kPa. Water changes from saturated liquid to saturated vapor during the heat addition process. The net work output of this cycle is (a) 494 kJ/kg  (b) 975 kJ/kg  (c) 596 kJ/kg  (d) 845 kJ/kg  (e) 1148 kJ/kg

Answer  (c) 596 kJ/kg

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

P1=8000 "kPa"
P2=20 "kPa"
h_fg=ENTHALPY(Steam_IAPWS,x=1,P=P1)-ENTHALPY(Steam_IAPWS,x=0,P=P1)
T1=TEMPERATURE(Steam_IAPWS,x=0,P=P1)+273
T2=TEMPERATURE(Steam_IAPWS,x=0,P=P2)+273
q_in=h_fg
Eta_Carnot=1-T2/T1
w_net=Eta_Carnot*q_in

"Some Wrong Solutions with Common Mistakes:
W1_work = Eta1*q_in; Eta1=T2/T1 "Taking Carnot efficiency to be T2/T1"
W2_work = Eta2*q_in; Eta2=1-(T2-273)/(T1-273)  "Using C instead of K"
W3_work = Eta_Carnot*ENTHALPY(Steam_IAPWS,x=1,P=P1)  "Using h_g instead of h_fg"
W4_work = Eta_Carnot*q2; q2=ENTHALPY(Steam_IAPWS,x=1,P=P2)-ENTHALPY(Steam_IAPWS,x=0,P=P2)  "Using h_fg at P2"

10-112 A simple ideal Rankine cycle operates between the pressure limits of 10 kPa and 3 MPa, with a turbine inlet temperature of 600°C. Disregarding the pump work, the cycle efficiency is (a) 24%  (b) 37%  (c) 52%  (d) 63%  (e) 71%

Answer  (b) 37%

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

P1=10 "kPa"
P2=3000 "kPa"
P3=P2
P4=P1
T3=600 "C"
s4=s3
h1=ENTHALPY(Steam_IAPWS,x=0,P=P1)
v1=VOLUME(Steam_IAPWS,x=0,P=P1)
w_pump=v1*(P2-P1) "kJ/kg"
h2=h1+w_pump
h3=ENTHALPY(Steam_IAPWS,T=T3,P=P3)
s3=ENTROPY(Steam_IAPWS,T=T3,P=P3)
h4=ENTHALPY(Steam_IAPWS,s=s4,P=P4)
q_in=h3-h2
q_out=h4-h1
Eta_th=1-q_out/q_in

"Some Wrong Solutions with Common Mistakes:"
W1_Eff = q_out/q_in "Using wrong relation"
W2_Eff = 1-(h44-h1)/(h3-h2); h44 = ENTHALPY(Steam_IAPWS,x=1,P=P4) "Using h_g for h4"
W3_Eff = 1-(T1+273)/(T3+273); T1=TEMPERATURE(Steam_IAPWS,x=0,P=P1) "Using Carnot efficiency"
W4_Eff = (h3-h4)/q_in "Disregarding pump work"

10-113 A simple ideal Rankine cycle operates between the pressure limits of 10 kPa and 5 MPa, with a
 turbine inlet temperature of 600°C. The mass fraction of steam that condenses at the turbine exit is
(a) 6%  (b) 9%  (c) 12%  (d) 15%  (e) 18%
Answer  (c) 12%

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on
a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical
values).
P1=10 "kPa"
P2=5000 "kPa"
P3=P2
P4=P1
T3=600 "C"
s4=s3
h3=ENTHALPY(Steam_IAPWS,T=T3,P=P3)
s3=ENTROPY(Steam_IAPWS,T=T3,P=P3)
h4=ENTHALPY(Steam_IAPWS,s=s4,P=P4)
x4=QUALITY(Steam_IAPWS,s=s4,P=P4)
m=1-x4

"Some Wrong Solutions with Common Mistakes:"
W1_moisture = x4 "Taking quality as moisture"
W2_moisture = 0 "Assuming superheated vapor"

10-114 A steam power plant operates on the simple ideal Rankine cycle between the pressure limits of 10
kPa and 10 MPa, with a turbine inlet temperature of 600°C. The rate of heat transfer in the boiler is 800
kJ/s. Disregarding the pump work, the power output of this plant is
(a) 243 kW  (b) 284 kW  (c) 508 kW  (d) 335 kW  (e) 800 kW
Answer  (d) 335 kW

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on
a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical
values).
P1=10 "kPa"
P2=10000 "kPa"
Consider a combined gas-steam power plant. Water for the steam cycle is heated in a well-insulated heat exchanger by the exhaust gases that enter at 800 K at a rate of 60 kg/s and leave at 400 K. Water enters the heat exchanger at 200 °C and 8 MPa and leaves at 350 °C and 8 MPa. If the exhaust gases are treated as air with constant specific heats at room temperature, the mass flow rate of water through the heat exchanger becomes

(a) 11 kg/s  
(b) 24 kg/s  
(c) 46 kg/s  
(d) 53 kg/s  
(e) 60 kg/s

**Answer**  (a) 11 kg/s

**Solution** Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
m_gas=60 "kg/s"
Cp=1.005 "kJ/kg.K"
T3=800 "K"
T4=400 "K"
Q_gas=m_gas*Cp*(T3-T4)
P1=8000 "kPa"
T1=200 "C"
P2=8000 "kPa"
T2=350 "C"
h1=ENTHALPY(Steam_IAPWS,T=T1,P=P1)
h2=ENTHALPY(Steam_IAPWS,T=T2,P=P2)
Q_steam=m_steam*(h2-h1)
Q_gas=Q_steam
```

"Some Wrong Solutions with Common Mistakes:"

W1_power = Q_rate "Assuming all heat is converted to power"
W3_power = Q_rate*Carnot; Carnot = 1-(T1+273)/(T3+273); T1=TEMPERATURE(Steam_IAPWS,x=0,P=P1) "Using Carnot efficiency"
W4_power = m*(h3-h44); h44 = ENTHALPY(Steam_IAPWS,x=1,P=P4) "Taking h4=h_g"
An ideal reheat Rankine cycle operates between the pressure limits of 10 kPa and 8 MPa, with reheat occurring at 4 MPa. The temperature of steam at the inlets of both turbines is 500°C, and the enthalpy of steam is 3185 kJ/kg at the exit of the high-pressure turbine, and 2247 kJ/kg at the exit of the low-pressure turbine. Disregarding the pump work, the cycle efficiency is

(a) 29%  (b) 32%  (c) 36%  (d) 41%  (e) 49%

Answer  (d) 41%

Solution  Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
P1=10 "kPa"
P2=8000 "kPa"
P3=P2
P4=4000 "kPa"
P5=P4
P6=P1
T3=500 "C"
T5=500 "C"
s4=s3
s6=s5
h1=ENTHALPY(Steam_IAPWS,x=0,P=P1)
h2=h1
h44=3185 "kJ/kg - for checking given data"
h66=2247 "kJ/kg - for checking given data"
h3=ENTHALPY(Steam_IAPWS,T=T3,P=P3)
s3=ENTROPY(Steam_IAPWS,T=T3,P=P3)
h4=ENTHALPY(Steam_IAPWS,s=s4,P=P4)
h5=ENTHALPY(Steam_IAPWS,T=T5,P=P5)
s5=ENTROPY(Steam_IAPWS,T=T5,P=P5)
h6=ENTHALPY(Steam_IAPWS,s=s6,P=P6)
q_in=(h3-h2)+(h5-h4)
q_out=h6-h1
Eta_th=1-q_out/q_in
```

"Some Wrong Solutions with Common Mistakes:"

W1_Eff = q_out/q_in "Using wrong relation"
W2_Eff = 1-q_out/(h3-h2) "Disregarding heat input during reheat"
W3_Eff = 1-(T1+273)/(T3+273); T1=TEMPERATURE(Steam_IAPWS,x=0,P=P1) "Using Carnot efficiency"
W4_Eff = 1-q_out/(h5-h4) "Using wrong relation for q_in"
Pressurized feedwater in a steam power plant is to be heated in an ideal open feedwater heater that operates at a pressure of 0.5 MPa with steam extracted from the turbine. If the enthalpy of feedwater is 252 kJ/kg and the enthalpy of extracted steam is 2665 kJ/kg, the mass fraction of steam extracted from the turbine is

(a) 4%  (b) 10%  (c) 16%  (d) 27%  (e) 12%

Answer  (c) 16%

Solution   Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
h_feed=252 "kJ/kg"
h_extracted=2665 "kJ/kg"
P3=500 "kPa"
h3=ENTHALPY(Steam_IAPWS,x=0,P=P3)
"Energy balance on the FWH"
h3=x_ext*h_extracted+(1-x_ext)*h_feed

"Some Wrong Solutions with Common Mistakes:
W1_ext = h_feed/h_extracted "Using wrong relation"
W2_ext = h3/(h_extracted-h_feed) "Using wrong relation"
W3_ext = h_feed/(h_extracted-h_feed) "Using wrong relation"
```

Consider a steam power plant that operates on the regenerative Rankine cycle with one open feedwater heater. The enthalpy of the steam is 3374 kJ/kg at the turbine inlet, 2797 kJ/kg at the location of bleeding, and 2346 kJ/kg at the turbine exit. The net power output of the plant is 120 MW, and the fraction of steam bled off the turbine for regeneration is 0.172. If the pump work is negligible, the mass flow rate of steam at the turbine inlet is

(a) 117 kg/s  (b) 126 kg/s  (c) 219 kg/s  (d) 288 kg/s  (e) 679 kg/s

Answer  (b) 126 kg/s

Solution   Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
h_in=3374 "kJ/kg"
h_out=2346 "kJ/kg"
h_extracted=2797 "kJ/kg"
Wnet_out=120000 "kW"
x_bleed=0.172
w_turb=(h_in-h_extracted)+(1-x_bleed)*(h_extracted-h_out)
m=Wnet_out/w_turb

"Some Wrong Solutions with Common Mistakes:
W1_mass = Wnet_out/(h_in-h_out) "Disregarding extraction of steam"
W2_mass = Wnet_out/(x_bleed*(h_in-h_out)) "Assuming steam is extracted at turbine inlet"
W3_mass = Wnet_out/(h_in-h_out-x_bleed*h_extracted) "Using wrong relation"
```
10-119 Consider a simple ideal Rankine cycle. If the condenser pressure is lowered while keeping turbine inlet state the same, (select the correct statement)

(a) the turbine work output will decrease.
(b) the amount of heat rejected will decrease.
(c) the cycle efficiency will decrease.
(d) the moisture content at turbine exit will decrease.
(e) the pump work input will decrease.

*Answer* (b) the amount of heat rejected will decrease.

10-120 Consider a simple ideal Rankine cycle with fixed boiler and condenser pressures. If the steam is superheated to a higher temperature, (select the correct statement)

(a) the turbine work output will decrease.
(b) the amount of heat rejected will decrease.
(c) the cycle efficiency will decrease.
(d) the moisture content at turbine exit will decrease.
(e) the amount of heat input will decrease.

*Answer* (d) the moisture content at turbine exit will decrease.

10-121 Consider a simple ideal Rankine cycle with fixed boiler and condenser pressures. If the cycle is modified with reheating, (select the correct statement)

(a) the turbine work output will decrease.
(b) the amount of heat rejected will decrease.
(c) the pump work input will decrease.
(d) the moisture content at turbine exit will decrease.
(e) the amount of heat input will decrease.

*Answer* (d) the moisture content at turbine exit will decrease.

10-122 Consider a simple ideal Rankine cycle with fixed boiler and condenser pressures. If the cycle is modified with regeneration that involves one open feed water heater, (select the correct statement per unit mass of steam flowing through the boiler)

(a) the turbine work output will decrease.
(b) the amount of heat rejected will increase.
(c) the cycle thermal efficiency will decrease.
(d) the quality of steam at turbine exit will decrease.
(e) the amount of heat input will increase.

*Answer* (a) the turbine work output will decrease.
Consider a cogeneration power plant modified with regeneration. Steam enters the turbine at 6 MPa and 450°C at a rate of 20 kg/s and expands to a pressure of 0.4 MPa. At this pressure, 60% of the steam is extracted from the turbine, and the remainder expands to a pressure of 10 kPa. Part of the extracted steam is used to heat feedwater in an open feedwater heater. The rest of the extracted steam is used for process heating and leaves the process heater as a saturated liquid at 0.4 MPa. It is subsequently mixed with the feedwater leaving the feedwater heater, and the mixture is pumped to the boiler pressure. The steam in the condenser is cooled and condensed by the cooling water from a nearby river, which enters the adiabatic condenser at a rate of 463 kg/s.

\[
\begin{align*}
h_1 &= 191.81 \\
h_2 &= 192.20 \\
h_3 &= h_4 = h_9 = 604.66 \\
h_5 &= 610.73 \\
h_6 &= 3302.9 \\
h_7 &= h_8 = h_{10} = 2665.6 \\
h_{11} &= 2128.8
\end{align*}
\]

1. The total power output of the turbine is
   (a) 17.0 MW  (b) 8.4 MW  (c) 12.2 MW  (d) 20.0 MW  (e) 3.4 MW

   **Answer**  (a) 17.0 MW

2. The temperature rise of the cooling water from the river in the condenser is
   (a) 8.0°C  (b) 5.2°C  (c) 9.6°C  (d) 12.9°C  (e) 16.2°C

   **Answer**  (a) 8.0°C

3. The mass flow rate of steam through the process heater is
   (a) 1.6 kg/s  (b) 3.8 kg/s  (c) 5.2 kg/s  (d) 7.6 kg/s  (e) 10.4 kg/s

   **Answer**  (e) 10.4 kg/s

4. The rate of heat supply from the process heater per unit mass of steam passing through it is
   (a) 246 kJ/kg  (b) 893 kJ/kg  (c) 1344 kJ/kg  (d) 1891 kJ/kg  (e) 2060 kJ/kg

   **Answer**  (e) 2060 kJ/kg
5. The rate of heat transfer to the steam in the boiler is
(a) 26.0 MJ/s  (b) 53.8 MJ/s  (c) 39.5 MJ/s  (d) 62.8 MJ/s  (e) 125.4 MJ/s

Answer  (b) 53.8 MJ/s

Solution  Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

Note: The solution given below also evaluates all enthalpies given on the figure.

P1=10 "kPa"
P11=P1
P2=400 "kPa"
P3=P2; P4=P2; P7=P2; P8=P2; P9=P2; P10=P2
P5=6000 "kPa"
P6=P5
T6=450 "C"
m_total=20 "kg/s"
m7=0.6*m_total
m_cond=0.4*m_total
C=4.18 "kJ/kg.K"
m_cooling=463 "kg/s"
s7=s6
s11=s6
h1=ENTHALPY(Steam_IAPWS,x=0,P=P1)
v1=VOLUME(Steam_IAPWS,x=0,P=P1)
w_pump=v1*(P2-P1)
h2=h1+w_pump
h3=ENTHALPY(Steam_IAPWS,x=0,P=P3)
h4=h3; h9=h3
v4=VOLUME(Steam_IAPWS,x=0,P=P4)
w_pump2=v4*(P5-P4)
h5=h4+w_pump2
h6=ENTHALPY(Steam_IAPWS,T=T6,P=P6)
s6=ENTROPY(Steam_IAPWS,T=T6,P=P6)
h7=ENTHALPY(Steam_IAPWS,s=s7,P=P7)
h8=h7; h10=h7
h11=ENTHALPY(Steam_IAPWS,s=s11,P=P11)
W_turb=m_process*(h6-h7)+m_cond*(h7-h11)
m_cooling*C*T_rise=m_cond*(h11-h1)
m_cond*h2+m_feed*h10=(m_cond+m_feed)*h3
m_process=m7-m_feed
q_process=h8-h9
Q_in=m_total*(h6-h5)