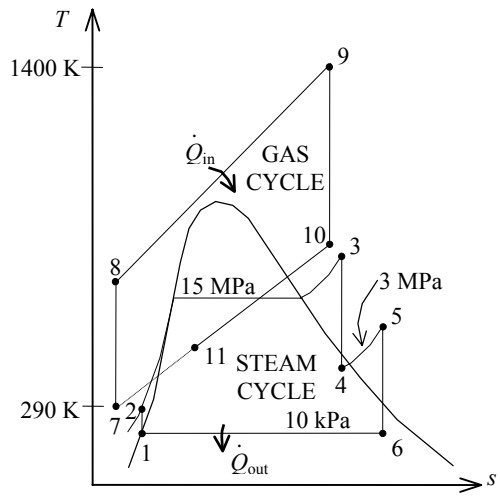
10-99 A combined gas-steam power plant is considered. The topping cycle is an ideal gas-turbine cycle and the bottoming cycle is an ideal reheat Rankine cycle. The mass flow rate of air in the gas-turbine cycle, the rate of total heat input, and the thermal efficiency of the combined cycle are to be 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



$$T_7 = 290 \text{ K} \longrightarrow h_7 = 290.16 \text{ kJ/kg}$$
$$P_{r_7} = 1.2311$$

$$P_{r_8} = \frac{P_8}{P_7} P_{r_7} = (8)(1.2311) = 9.849 \longrightarrow h_8 = 526.12 \text{ kJ/kg}$$

$$T_9 = 1400 \text{ K} \longrightarrow h_9 = 1515.42 \text{ kJ/kg}$$
$$P_{r_9} = 450.5$$

$$P_{r_{10}} = \frac{P_{10}}{P_9} P_{r_9} = \left(\frac{1}{8}\right)(450.5) = 56.3 \longrightarrow h_{10} = 860.35 \text{ kJ/kg}$$

$$T_{11} = 520 \text{ K} \longrightarrow h_{11} = 523.63 \text{ kJ/kg}$$

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

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

$$w_{\text{pI,in}} = v_1(P_2 - P_1) = (0.00101 \text{ m}^3\text{/kg})(15{,}000 - 10 \text{ kPa})\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right) = 15.14 \text{ kJ/kg}$$

$$h_2 = h_1 + w_{\text{pI,in}} = 191.81 + 15.14 = 206.95 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_3 = 15 \text{ MPa} \\ T_3 = 450°\text{C} \end{array}\right\} \begin{array}{l} h_3 = 3157.9 \text{ kJ/kg} \\ s_3 = 6.1434 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_4 = 3 \text{ MPa} \\ s_4 = s_3 \end{array}\right\} \begin{array}{l} x_4 = \dfrac{s_4 - s_f}{s_{fg}} = \dfrac{6.1434 - 2.6454}{3.5402} = 0.9880 \\ h_4 = h_f + x_4 h_{fg} = 1008.3 + (0.9880)(1794.9) = 2781.7 \text{ kJ/kg} \end{array}$$

$$\left.\begin{array}{l} P_5 = 3 \text{ MPa} \\ T_5 = 500°\text{C} \end{array}\right\} \begin{array}{l} h_5 = 3457.2 \text{ kJ/kg} \\ s_5 = 7.2359 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_6 = 10 \text{ kPa} \\ s_6 = s_5 \end{array}\right\} \begin{array}{l} x_6 = \dfrac{s_6 - s_f}{s_{fg}} = \dfrac{7.2355 - 0.6492}{7.4996} = 0.8783 \\ h_6 = h_f + x_6 h_{fg} = 191.81 + (0.8783)(2392.1) = 2292.8 \text{ kJ/kg} \end{array}$$

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

$$\dot{E}_{\text{in}} = \dot{E}_{\text{out}} \longrightarrow \sum \dot{m}_i h_i = \sum \dot{m}_e h_e \longrightarrow \dot{m}_s(h_3 - h_2) = \dot{m}_{\text{air}}(h_{10} - h_{11})$$

$$\dot{m}_{\text{air}} = \frac{h_3 - h_2}{h_{10} - h_{11}} \dot{m}_s = \frac{3157.9 - 206.95}{860.35 - 523.63}(30 \text{ kg/s}) = \mathbf{262.9\ kg/s}$$

(*b*)
$$\dot{Q}_{\text{in}} = \dot{Q}_{\text{air}} + \dot{Q}_{\text{reheat}} = \dot{m}_{\text{air}}(h_9 - h_8) + \dot{m}_{\text{reheat}}(h_5 - h_4)$$
$$= (262.9 \text{ kg/s})(1515.42 - 526.12) \text{ kJ/kg} + (30 \text{ kg/s})(3457.2 - 2781.7) \text{kJ/kg} = 280{,}352 \text{ kW}$$
$$\cong \mathbf{2.80 \times 10^5\ kW}$$

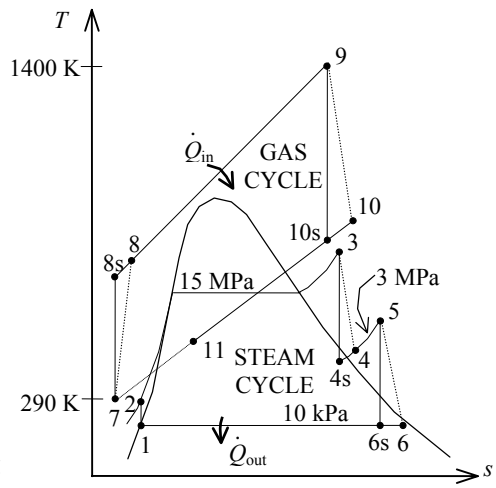
(*c*)
$$\dot{Q}_{\text{out}} = \dot{Q}_{\text{out,air}} + \dot{Q}_{\text{out,steam}} = \dot{m}_{\text{air}}(h_{11} - h_7) + \dot{m}_s(h_6 - h_1)$$
$$= (262.9 \text{ kg/s})(523.63 - 290.16) \text{ kJ/kg} + (30 \text{ kg/s})(2292.8 - 191.81) \text{ kJ/kg} = 124{,}409 \text{ kW}$$

$$\eta_{\text{th}} = 1 - \frac{\dot{Q}_{\text{out}}}{\dot{Q}_{\text{in}}} = 1 - \frac{124{,}409 \text{ kW}}{280{,}352 \text{ kW}} = \mathbf{55.6\%}$$

10-100 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)



$$T_7 = 290 \text{ K} \longrightarrow h_7 = 290.16 \text{ kJ/kg}, \quad P_{r_7} = 1.2311$$

$$P_{r_{8s}} = \frac{P_{8s}}{P_7} P_{r_7} = (8)(1.2311) = 9.849 \longrightarrow h_{8s} = 526.12 \text{ kJ/kg}$$

$$\eta_C = \frac{h_{8s} - h_7}{h_8 - h_7} \longrightarrow h_8 = h_7 + (h_{8s} - h_7)/\eta_C = 290.16 + (526.12 - 290.16)/(0.80) = 585.1 \text{ kJ/kg}$$

$$T_9 = 1400 \text{ K} \longrightarrow h_9 = 1515.42 \text{ kJ/kg}, \quad P_{r_9} = 450.5$$

$$P_{r_{10s}} = \frac{P_{10s}}{P_9} P_{r_9} = \left(\frac{1}{8}\right)(450.5) = 56.3 \longrightarrow h_{10s} = 860.35 \text{ kJ/kg}$$

$$\eta_T = \frac{h_9 - h_{10}}{h_9 - h_{10s}} \longrightarrow h_{10} = h_9 - \eta_T (h_9 - h_{10s}) = 1515.42 - (0.85)(1515.42 - 860.35) = 958.4 \text{ kJ/kg}$$

$$T_{11} = 520 \text{ K} \longrightarrow h_{11} = 523.63 \text{ kJ/kg}$$

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

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

$$w_{\text{pI,in}} = v_1 (P_2 - P_1) = (0.00101 \text{ m}^3/\text{kg})(15{,}000 - 10 \text{ kPa})\left(\frac{1 \text{ kJ}}{1 \text{ kPa} \cdot \text{m}^3}\right) = 15.14 \text{ kJ/kg}$$

$$h_2 = h_1 + w_{\text{pI,in}} = 191.81 + 15.14 = 206.95 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_3 = 15 \text{ MPa} \\ T_3 = 450°\text{C} \end{array}\right\} \begin{array}{l} h_3 = 3157.9 \text{ kJ/kg} \\ s_3 = 6.1428 \text{ kJ/kg} \cdot \text{K} \end{array}$$

$$\left.\begin{array}{l} P_4 = 3 \text{ MPa} \\ s_{4s} = s_3 \end{array}\right\} \begin{array}{l} x_{4s} = \dfrac{s_{4s} - s_f}{s_{fg}} = \dfrac{6.1434 - 2.6454}{3.5402} = 0.9880 \\ h_{4s} = h_f + x_{4s} h_{fg} = 1008.3 + (0.9879)(1794.9) = 2781.7 \text{ kJ/kg} \end{array}$$

$$\eta_T = \frac{h_3 - h_4}{h_3 - h_{4s}} \longrightarrow h_4 = h_3 - \eta_T (h_3 - h_{4s}) = 3157.9 - (0.85)(3157.9 - 2781.7) = 2838.1 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_5 = 3 \text{ MPa} \\ T_5 = 500°\text{C} \end{array}\right\} \begin{array}{l} h_5 = 3457.2 \text{ kJ/kg} \\ s_5 = 7.2359 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_6 = 10 \text{ kPa} \\ s_{6s} = s_5 \end{array}\right\} \begin{array}{l} x_{6s} = \dfrac{s_{6s} - s_f}{s_{fg}} = \dfrac{7.2359 - 0.6492}{7.4996} = 0.8783 \\ h_{6s} = h_f + x_{6s} h_{fg} = 191.81 + (0.8782)(2392.1) = 2292.8 \text{ kJ/kg} \end{array}$$

$$\eta_T = \frac{h_5 - h_6}{h_5 - h_{6s}} \longrightarrow \begin{array}{l} h_6 = h_5 - \eta_T (h_5 - h_{6s}) \\ \quad = 3457.2 - (0.85)(3457.2 - 2292.8) \\ \quad = 2467.5 \text{ kJ/kg} \end{array}$$

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

$$\begin{aligned} \dot{E}_{\text{in}} - \dot{E}_{\text{out}} &= \Delta\dot{E}_{\text{system}}^{\nearrow 0 \text{ (steady)}} = 0 \\ \dot{E}_{\text{in}} &= \dot{E}_{\text{out}} \\ \sum \dot{m}_i h_i &= \sum \dot{m}_e h_e \longrightarrow \dot{m}_s (h_3 - h_2) = \dot{m}_{\text{air}} (h_{10} - h_{11}) \\ \dot{m}_{\text{air}} &= \frac{h_3 - h_2}{h_{10} - h_{11}} \dot{m}_s = \frac{3157.9 - 206.95}{958.4 - 523.63}(30 \text{ kg/s}) = \mathbf{203.6\ kg/s} \end{aligned}$$

(*b*) $$\begin{aligned} \dot{Q}_{\text{in}} &= \dot{Q}_{\text{air}} + \dot{Q}_{\text{reheat}} = \dot{m}_{\text{air}} (h_9 - h_8) + \dot{m}_{\text{reheat}} (h_5 - h_4) \\ &= (203.6 \text{ kg/s})(1515.42 - 585.1) \text{ kJ/kg} + (30 \text{ kg/s})(3457.2 - 2838.1) \text{ kJ/kg} = \mathbf{207{,}986\ kW} \end{aligned}$$

(*c*) $$\begin{aligned} \dot{Q}_{\text{out}} &= \dot{Q}_{\text{out,air}} + \dot{Q}_{\text{out,steam}} = \dot{m}_{\text{air}} (h_{11} - h_7) + \dot{m}_s (h_6 - h_1) \\ &= (203.6 \text{ kg/s})(523.63 - 290.16) \text{ kJ/kg} + (30 \text{ kg/s})(2467.5 - 191.81) \text{ kJ/kg} = 115{,}805 \text{ kW} \end{aligned}$$

$$\eta_{\text{th}} = 1 - \frac{\dot{Q}_{\text{out}}}{\dot{Q}_{\text{in}}} = 1 - \frac{115{,}805 \text{ kW}}{207{,}986 \text{ kW}} = \mathbf{44.3\%}$$

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

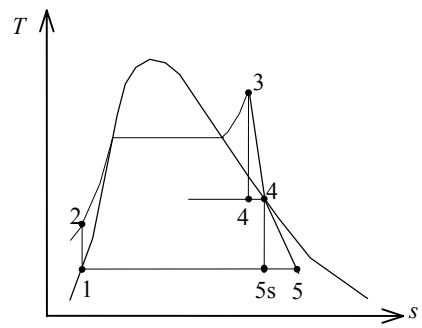
$$\begin{aligned} x_{\text{destroyed}} &= T_0 \left(\frac{q_{\text{out}}}{T_0} - \frac{q_{\text{in}}}{T_H} \right) = q_{\text{out}} - \frac{T_0}{T_H} q_{\text{in}} = q_{\text{in}} \left(\frac{q_{\text{out}}}{q_{\text{in}}} - \frac{T_0}{T_H} \right) \\ &= q_{\text{in}} \left[(1 - \eta_{th}) - (1 - \eta_{th,C}) \right] = q_{\text{in}} (\eta_{th,C} - \eta_{th}) \end{aligned}$$

10-102 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),

$$\left.\begin{array}{l} P_4 = 1.4 \text{ MPa} \\ \text{sat. vapor} \end{array}\right\} \begin{array}{l} h_4 = h_{g\,@\,1.4\text{ MPa}} = 2788.9 \text{ kJ/kg} \\ s_4 = s_{g\,@\,1.4\text{ MPa}} = 6.4675 \text{ kJ/kg}\cdot\text{K} \end{array}$$



$$\left.\begin{array}{l} P_5 = 10 \text{ kPa} \\ s_{5s} = s_4 \end{array}\right\} \begin{array}{l} x_{5s} = \dfrac{s_{4s} - s_f}{s_{fg}} = \dfrac{6.4675 - 0.6492}{7.4996} = 0.7758 \\ h_{5s} = h_f + x_{5s} h_{fg} \\ = 191.81 + (0.7758)(2392.1) = 2047.6 \text{ kJ/kg} \end{array}$$

$$\eta_T = \frac{h_4 - h_5}{h_4 - h_{5s}} \longrightarrow \begin{array}{l} h_5 = h_4 - \eta_T (h_4 - h_{5s}) \\ = 2788.9 - (0.60)(2788.9 - 2047.6) \\ = 2344.1 \text{ kJ/kg} \end{array}$$

and

$$w_{\text{turb,low}} = h_4 - h_5 = 2788.9 - 2344.1 = 444.8 \text{ kJ/kg}$$

$$\dot{m}_{\text{low turb}} = \frac{\dot{W}_{\text{turb,II}}}{w_{\text{turb,low}}} = \frac{800 \text{ kJ/s}}{444.8 \text{ kJ/kg}} = 1.799 \text{ kg/s} = 107.9 \text{ kg/min}$$

Therefore ,

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

$$w_{\text{turb,high}} = \frac{\dot{W}_{\text{turb},I}}{\dot{m}_{\text{high,turb}}} = \frac{1000 \text{ kJ/s}}{18.47 \text{ kg/s}} = 54.15 \text{ kJ/kg} = h_3 - h_4$$

$$h_3 = w_{\text{turb,high}} + h_4 = 54.15 + 2788.9 = 2843.0 \text{ kJ/kg}$$

$$\eta_T = \frac{h_3 - h_4}{h_3 - h_{4s}} \longrightarrow \begin{array}{l} h_{4s} = h_3 - (h_3 - h_4)/\eta_T \\ = 2843.0 - (2843.0 - 2788.9)/(0.75) \\ = 2770.8 \text{ kJ/kg} \end{array}$$

$$\left.\begin{array}{l} P_{4s} = 1.4 \text{ MPa} \\ s_{4s} = s_3 \end{array}\right\} \begin{array}{l} x_{4s} = \dfrac{h_{4s} - h_f}{h_{fg}} = \dfrac{2770.8 - 829.96}{1958.9} = 0.9908 \\ s_{4s} = s_f + x_{4s} s_{fg} = 2.2835 + (0.9908)(4.1840) = 6.4289 \text{ kJ/kg}\cdot\text{K} \end{array}$$

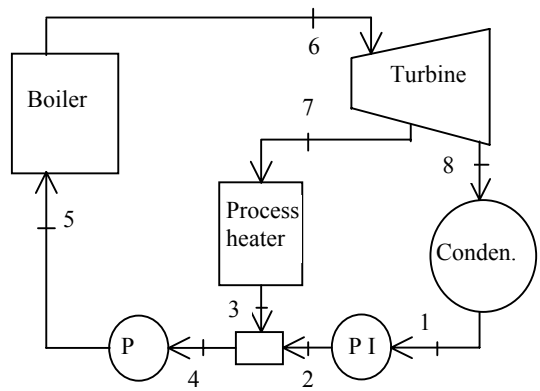
Then from the tables or the software, the turbine inlet temperature and pressure becomes

$$\left.\begin{array}{l} h_3 = 2843.0 \text{ kJ/kg} \\ s_3 = 6.4289 \text{ kJ/kg}\cdot\text{K} \end{array}\right\} \begin{array}{l} P_3 = \mathbf{2\ MPa} \\ T_3 = \mathbf{227.5°C} \end{array}$$

10-103 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),



$$h_1 = h_{f\,@\,20\text{ kPa}} = 251.42 \text{ kJ/kg}$$

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

$$w_{\text{pI,in}} = v_1(P_2 - P_1)/\eta_p = (0.001017 \text{ m}^3\text{/kg})(2000 - 20 \text{ kPa})\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right)/0.88 = 2.29 \text{ kJ/kg}$$

$$h_2 = h_1 + w_{\text{pI,in}} = 251.42 + 2.29 = 253.71 \text{ kJ/kg}$$

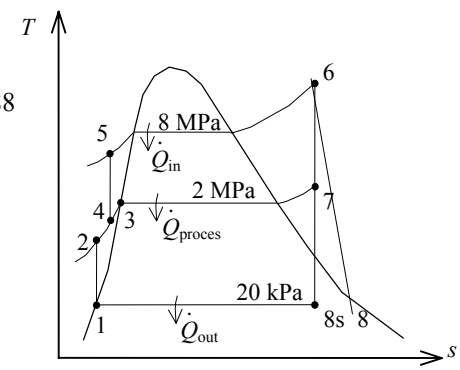
$$h_3 = h_{f\,@\,2\text{ MPa}} = 908.47 \text{ kJ/kg}$$

Mixing chamber:

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

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

$$v_4 \cong v_{f\,@\,h_f = 491.81\text{ kJ/kg}} = 0.001058 \text{ m}^3\text{/kg}$$



$$w_{p\text{II,in}} = v_4(P_5 - P_4)/\eta_p = (0.001058 \text{ m}^3\text{/kg})(8000 - 2000 \text{ kPa})\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right)/0.88 = 7.21 \text{ kJ/kg}$$

$$h_5 = h_4 + w_{p\text{II,in}} = 491.81 + 7.21 = 499.02 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_6 = 8 \text{ MPa} \\ T_6 = 500°\text{C} \end{array}\right\} \begin{array}{l} h_6 = 3399.5 \text{ kJ/kg} \\ s_6 = 6.7266 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_7 = 2 \text{ MPa} \\ s_7 = s_6 \end{array}\right\} h_{7s} = 3000.4 \text{ kJ/kg}$$

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

$$\left.\begin{array}{l} P_8 = 20 \text{ kPa} \\ s_8 = s_6 \end{array}\right\} h_{8s} = 2215.5 \text{ kJ/kg}$$

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

Then, $\dot{Q}_{\text{process}} = \dot{m}_7(h_7 - h_3) = (4 \text{ kg/s})(3048.3 - 908.47) \text{ kJ/kg} = \mathbf{8559\ kW}$

(*b*) Cycle analysis:

$$\dot{W}_{\text{T,out}} = \dot{m}_7(h_6 - h_7) + \dot{m}_8(h_6 - h_8) = (4 \text{ kg/s})(3399.5 - 3048.3)\text{kJ/kg} + (7 \text{ kg/s})(3399.5 - 2357.6)\text{kJ/kg} = 8698 \text{ kW}$$

$$\dot{W}_{\text{p,in}} = \dot{m}_1 w_{\text{pI,in}} + \dot{m}_4 w_{\text{pII,in}} = (7 \text{ kg/s})(2.29 \text{ kJ/kg}) + (11 \text{ kg/s})(7.21 \text{ kJ/kg}) = 95 \text{ kW}$$

$$\dot{W}_{\text{net}} = \dot{W}_{\text{T,out}} - \dot{W}_{\text{p,in}} = 8698 - 95 = \mathbf{8603\ kW}$$

(*c*) Then,

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

and

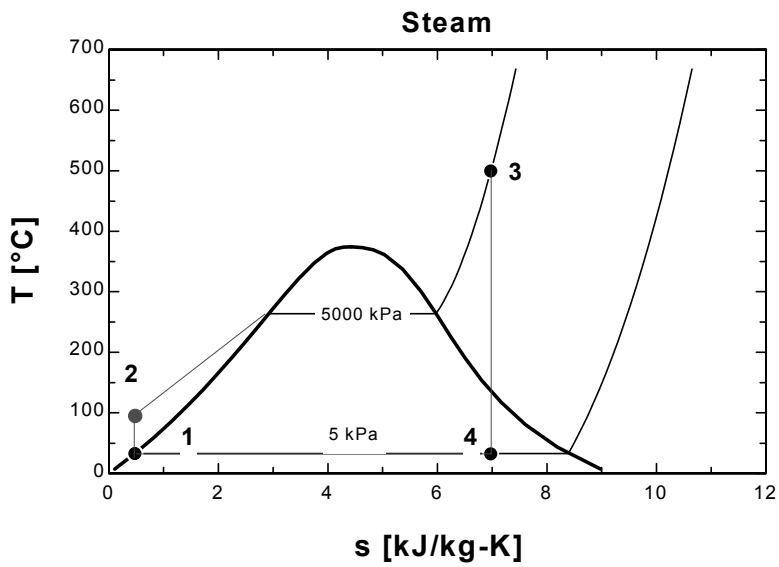
$$\varepsilon_u = \frac{\dot{W}_{\text{net}} + \dot{Q}_{\text{process}}}{\dot{Q}_{\text{in}}} = \frac{8603 + 8559}{31{,}905} = 0.538 = \mathbf{53.8\%}$$

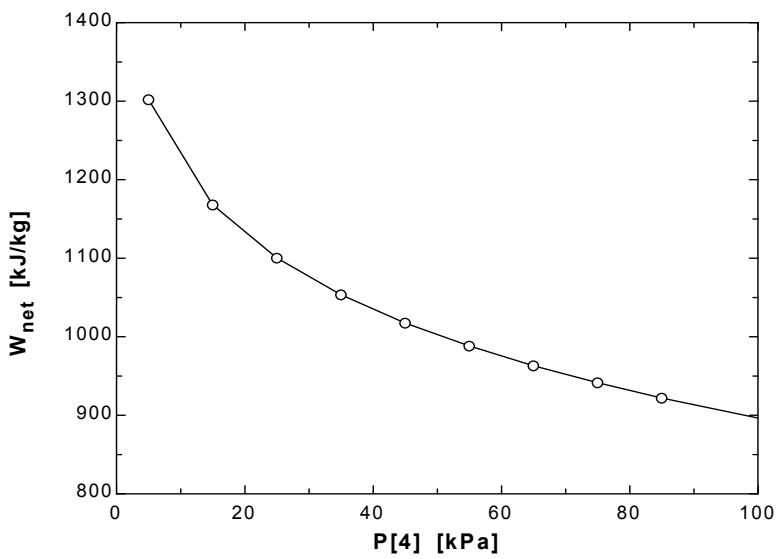
10-104 EES The effect of the condenser pressure on the performance a simple ideal Rankine cycle is to be investigated.

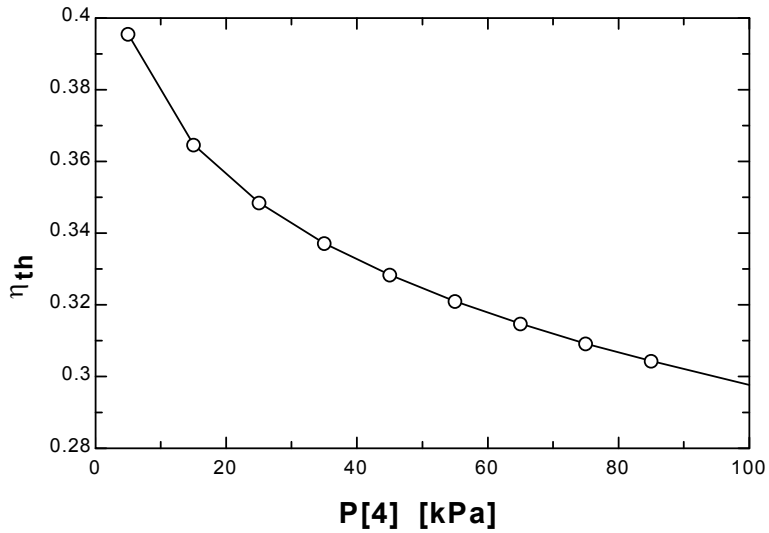
Analysis The problem is solved using EES, and the solution is given below.

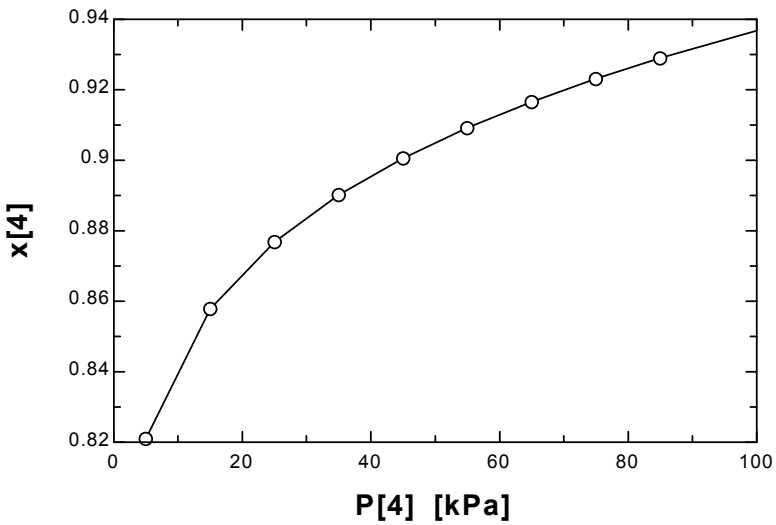
```
function x4$(x4) "this function returns a string to indicate the state of steam at point 4"
        x4$=''
        if (x4>1) then x4$='(superheated)'
        if (x4<0) then x4$='(compressed)'
end

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$='Steam_IAPWS'
P[1] = P[4]
P[2]=P[3]
x[1]=0  "Sat'd liquid"
h[1]=enthalpy(Fluid$,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$,P=P[1],x=x[1])
W_p_s=v[1]*(P[2]-P[1])"SSSF isentropic pump work assuming constant specific volume"
W_p=W_p_s/Eta_p
h[2]=h[1]+W_p   "SSSF First Law for the pump"
s[2]=entropy(Fluid$,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$,h=h[4],P=P[4])
h[3] =W_t+h[4]"SSSF First Law for the turbine"
x4s$=x4$(x[4])

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

"Condenser analysis"
h[4]=Q_out+h[1]"SSSF First Law for the Condenser"

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

η_{th}	P_4 [kPa]	W_{net} [kJ/kg]	x_4	Q_{in} [kJ/kg]	Q_{out} [kJ/kg]
0.3956	5	1302	0.8212	3292	1990
0.3646	15	1168	0.8581	3204	2036
0.3484	25	1100	0.8772	3158	2057
0.3371	35	1054	0.8905	3125	2072
0.3283	45	1018	0.9009	3100	2082
0.321	55	988.3	0.9096	3079	2091
0.3147	65	963.2	0.917	3061	2098
0.3092	75	941.5	0.9235	3045	2104
0.3042	85	922.1	0.9293	3031	2109
0.2976	100	896.5	0.9371	3012	2116






0.4
0.38
0.36
0.34
0.32
0.3
0.28
ηth
0
20
40
60
80
100
P[4] [kPa]

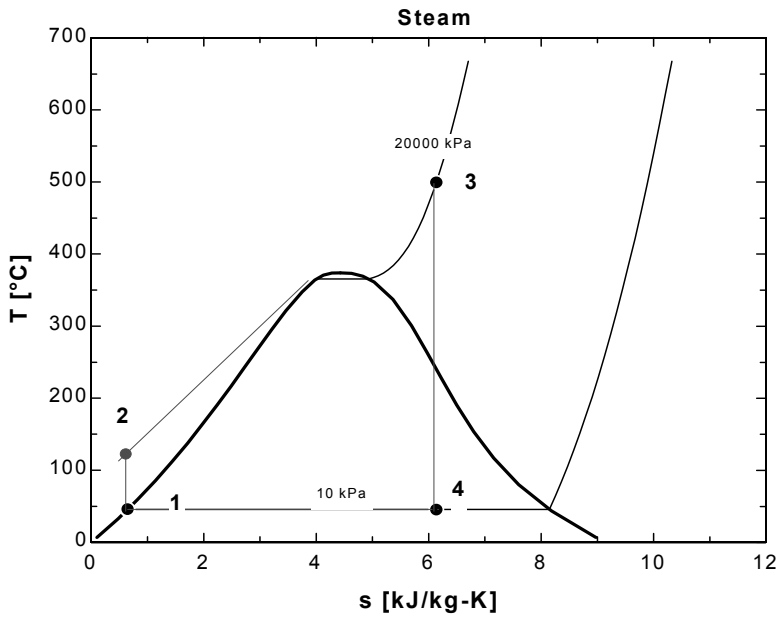

0.94
0.92
0.9
0.88
0.86
0.84
0.82
x[4]
0
20
40
60
80
100
P[4] [kPa]

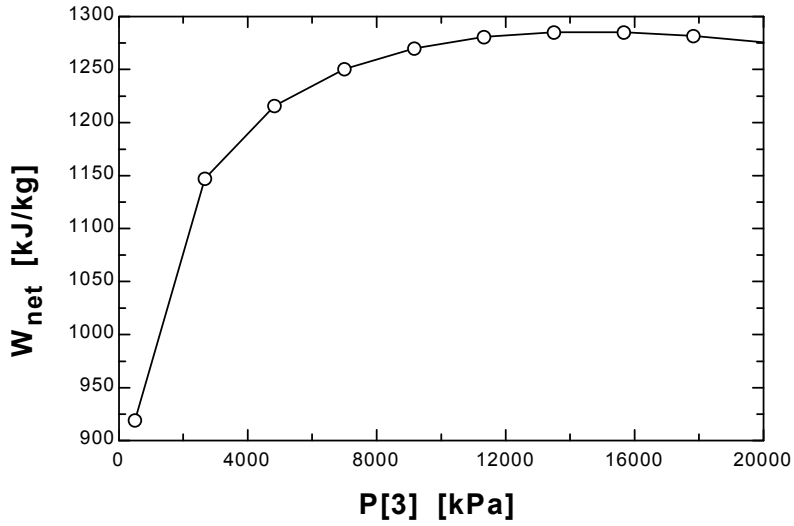
10-105 EES The effect of the boiler pressure on the performance a simple ideal Rankine cycle is to be investigated.

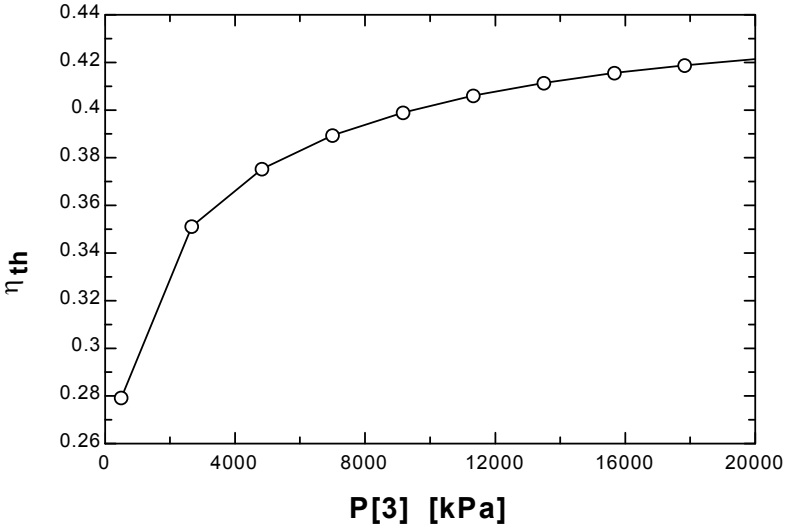
Analysis The problem is solved using EES, and the solution is given below.

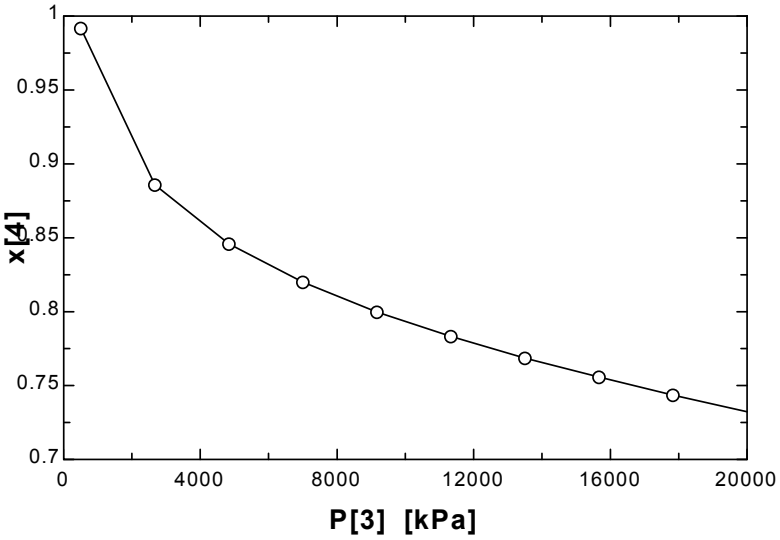
```
function x4$(x4) "this function returns a string to indicate the state of steam at point 4"
        x4$=''
        if (x4>1) then x4$='(superheated)'
        if (x4<0) then x4$='(compressed)'
end

{P[3] = 20000 [kPa]}
T[3] = 500 [C]
P[4] = 10 [kPa]
Eta_t = 1.0 "Turbine isentropic efficiency"
Eta_p = 1.0 "Pump isentropic efficiency"

"Pump analysis"
Fluid$='Steam_IAPWS'
P[1] = P[4]
P[2]=P[3]
x[1]=0  "Sat'd liquid"
h[1]=enthalpy(Fluid$,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$,P=P[1],x=x[1])
W_p_s=v[1]*(P[2]-P[1])"SSSF isentropic pump work assuming constant specific volume"
W_p=W_p_s/Eta_p
h[2]=h[1]+W_p   "SSSF First Law for the pump"
s[2]=entropy(Fluid$,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$,h=h[4],P=P[4])
h[3] =W_t+h[4] "SSSF First Law for the turbine"
x4s$=x4$(x[4])

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

"Condenser analysis"
h[4]=Q_out+h[1] "SSSF First Law for the Condenser"

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

η_{th}	W_{net} [kJ/kg]	x_4	P_3 [kPa]	Q_{in} [kJ/kg]	Q_{out} [kJ/kg]	W_p [kJ/kg]	W_t [kJ/kg]
0.2792	919.1	0.9921	500	3292	2373	0.495	919.6
0.3512	1147	0.886	2667	3266	2119	2.684	1150
0.3752	1216	0.8462	4833	3240	2024	4.873	1221
0.3893	1251	0.8201	7000	3213	1962	7.062	1258
0.399	1270	0.8001	9167	3184	1914	9.251	1280
0.406	1281	0.7835	11333	3155	1874	11.44	1292
0.4114	1286	0.769	13500	3125	1840	13.63	1299
0.4156	1286	0.756	15667	3094	1808	15.82	1302
0.4188	1283	0.744	17833	3062	1780	18.01	1301
0.4214	1276	0.7328	20000	3029	1753	20.2	1297






0.44
0.42
0.4
0.38
0.36
0.34
0.32
0.3
0.28
0.26
η th
0
4000
8000
12000
16000
20000
P[3] [kPa]

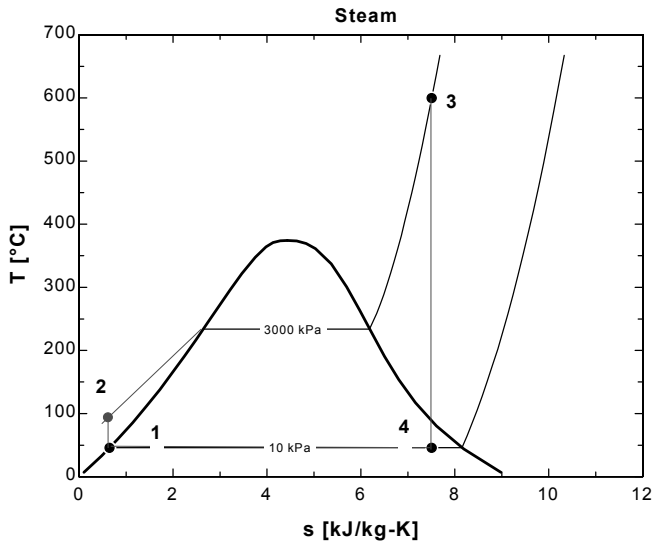

1
0.95
0.9
0.85
0.8
0.75
0.7
x[4]
0
4000
8000
12000
16000
20000
P[3] [kPa]

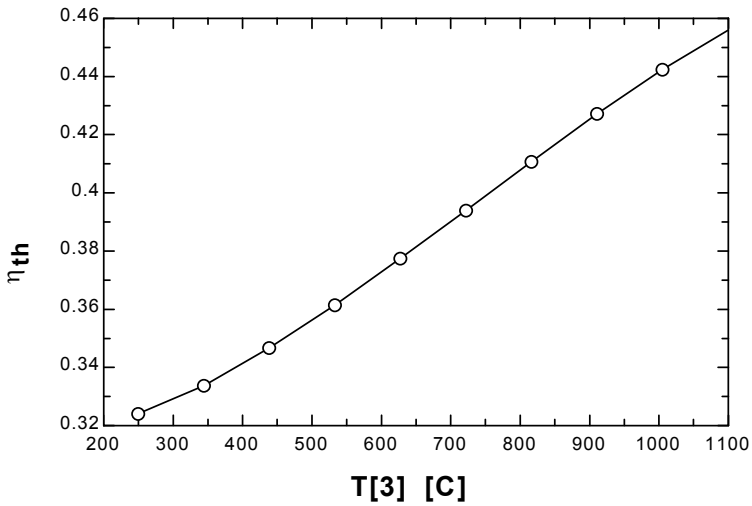
10-106 EES The effect of superheating the steam on the performance a simple ideal Rankine cycle is to be investigated.

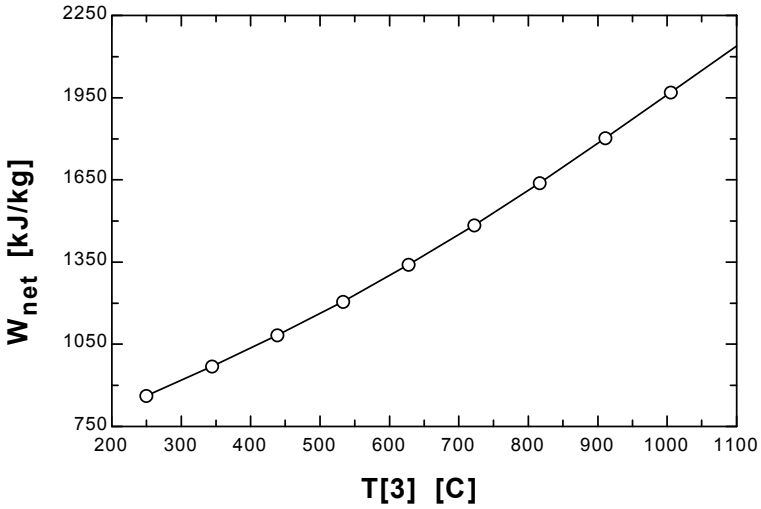
Analysis The problem is solved using EES, and the solution is given below.

```
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$='Steam_IAPWS'
P[1] = P[4]
P[2]=P[3]
x[1]=0 "Sat'd liquid"
h[1]=enthalpy(Fluid$,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$,P=P[1],x=x[1])
W_p_s=v[1]*(P[2]-P[1])"SSSF isentropic pump work assuming constant specific volume"
W_p=W_p_s/Eta_p
h[2]=h[1]+W_p   "SSSF First Law for the pump"
s[2]=entropy(Fluid$,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$,h=h[4],P=P[4])
h[3] =W_t+h[4]"SSSF First Law for the turbine"
x4s$=x4$(x[4])

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

"Condenser analysis"
h[4]=Q_out+h[1]"SSSF First Law for the Condenser"

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

T_3 [C]	η_{th}	W_{net} [kJ/kg]	x_4
250	0.3241	862.8	0.752
344.4	0.3338	970.6	0.81
438.9	0.3466	1083	0.8536
533.3	0.3614	1206	0.8909
627.8	0.3774	1340	0.9244
722.2	0.3939	1485	0.955
816.7	0.4106	1639	0.9835
911.1	0.4272	1803	100
1006	0.4424	1970	100
1100	0.456	2139	100






2250
1950
1650
1350
1050
750
200
300
400
500
600
700
800
900
1000
1100
W net [kJ/kg]
T[3] [C]

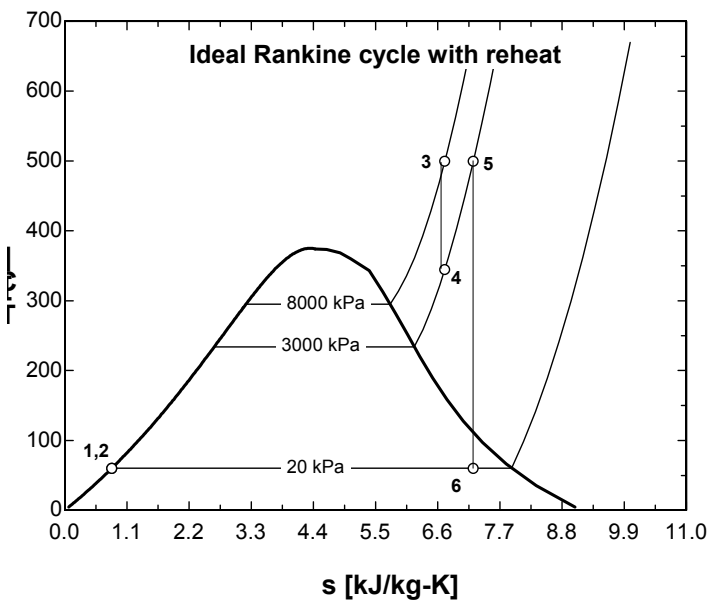
10-107 EES The effect of reheat pressure on the performance an ideal Rankine cycle is to be investigated.

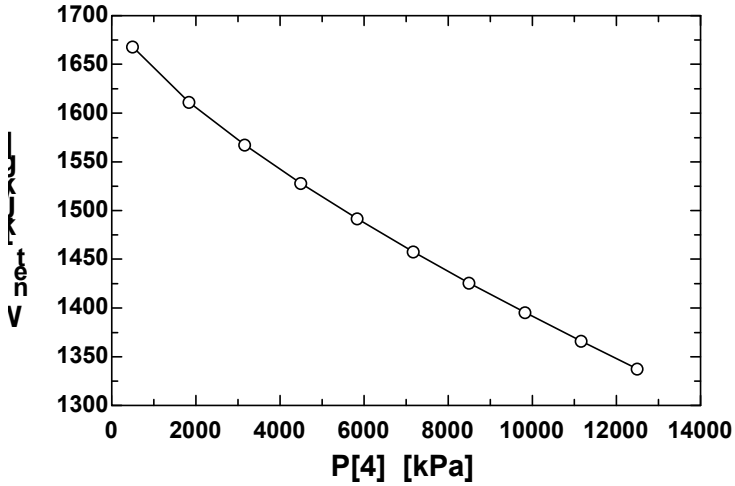
Analysis The problem is solved using EES, and the solution is given below.

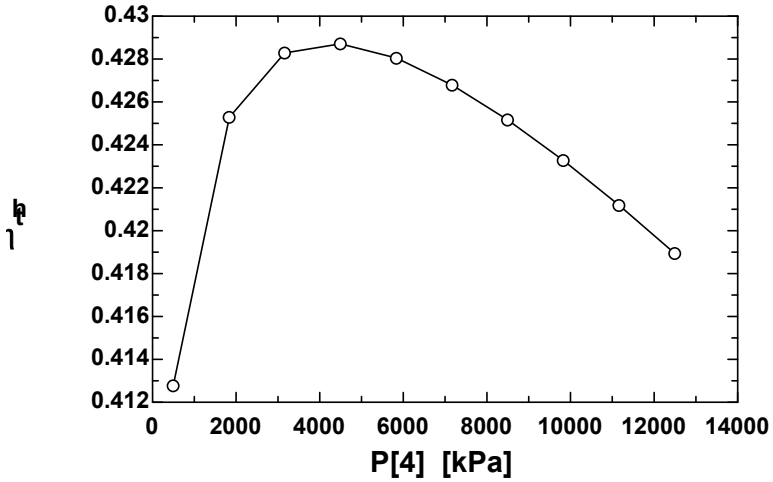
```
function x6$(x6) "this function returns a string to indicate the state of steam at point 6"
        x6$=''
        if (x6>1) then x6$='(superheated)'
        if (x6<0) then x6$='(subcooled)'
end

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$='Steam_IAPWS'
P[1] = P[6]
P[2]=P[3]
x[1]=0 "Sat'd liquid"
h[1]=enthalpy(Fluid$,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$,P=P[1],x=x[1])
W_p_s=v[1]*(P[2]-P[1])"SSSF isentropic pump work assuming constant specific volume"
W_p=W_p_s/Eta_p
h[2]=h[1]+W_p   "SSSF First Law for the pump"
v[2]=volume(Fluid$,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$,s=s_s[4],P=P[4])
Eta_t=(h[3]-h[4])/(h[3]-hs[4])"Definition of turbine efficiency"
T[4]=temperature(Fluid$,P=P[4],h=h[4])
s[4]=entropy(Fluid$,h=h[4],P=P[4])
v[4]=volume(Fluid$,s=s[4],P=P[4])
h[3] =W_t_hp+h[4]"SSSF First Law for the high pressure turbine"

"Low Pressure Turbine analysis"
P[5]=P[4]
s[5]=entropy(Fluid$,T=T[5],P=P[5])
h[5]=enthalpy(Fluid$,T=T[5],P=P[5])
s_s[6]=s[5]
hs[6]=enthalpy(Fluid$,s=s_s[6],P=P[6])
Ts[6]=temperature(Fluid$,s=s_s[6],P=P[6])
vs[6]=volume(Fluid$,s=s_s[6],P=P[6])
Eta_t=(h[5]-h[6])/(h[5]-hs[6])"Definition of turbine efficiency"
```

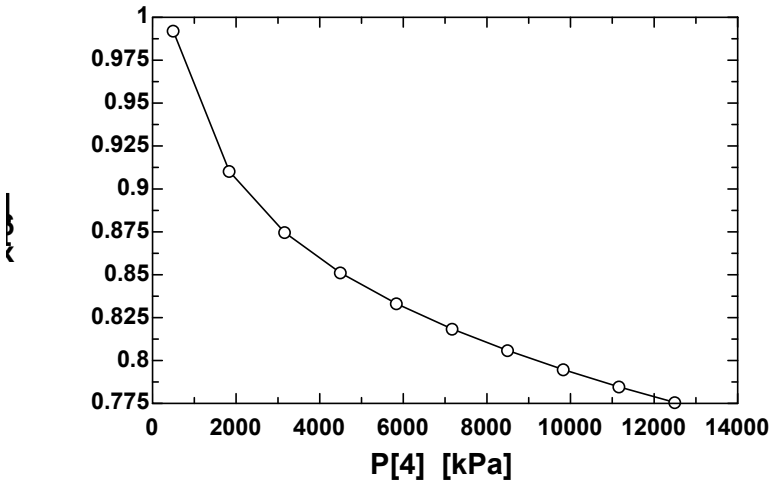
```
h[5]=W_t_lp+h[6]"SSSF First Law for the low pressure turbine"
x[6]=quality(Fluid$,h=h[6],P=P[6])

"Boiler analysis"
Q_in + h[2]+h[4]=h[3]+h[5]"SSSF First Law for the Boiler"

"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
```

P_4 [kPa]	η_{th}	W_{net} [kJ/kg]	X_6
500	0.4128	1668	0.9921
1833	0.4253	1611	0.9102
3167	0.4283	1567	0.8747
4500	0.4287	1528	0.8511
5833	0.428	1492	0.8332
7167	0.4268	1458	0.8184
8500	0.4252	1426	0.8058
9833	0.4233	1395	0.7947
11167	0.4212	1366	0.7847
12500	0.4189	1337	0.7755




1700
1650
1600
1550
1500
1450
1400
1350
1300
0
2000
4000
6000
8000
10000
12000
14000
P[4] [kPa]


0.43
0.428
0.426
0.424
0.422
0.42
0.418
0.416
0.414
0.412
0
2000
4000
6000
8000
10000
12000
14000
P[4] [kPa]


1
0.975
0.95
0.925
0.9
0.875
0.85
0.825
0.8
0.775
0
2000
4000
6000
8000
10000
12000
14000
P[4] [kPa]

10-108 EES The effect of number of reheat stages on the performance an ideal Rankine cycle is to be investigated.

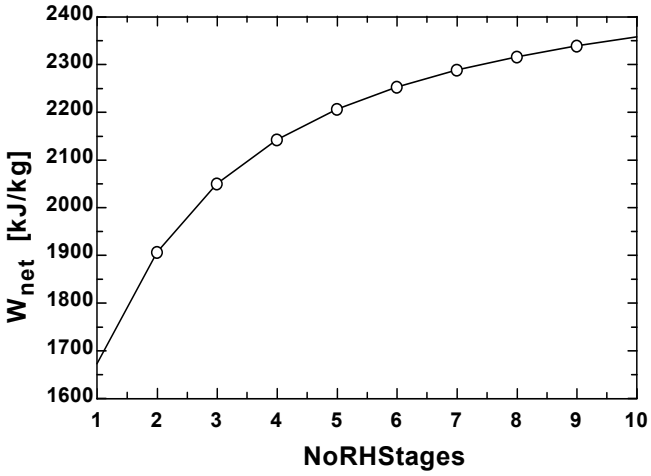
Analysis The problem is solved using EES, and the solution is given below.

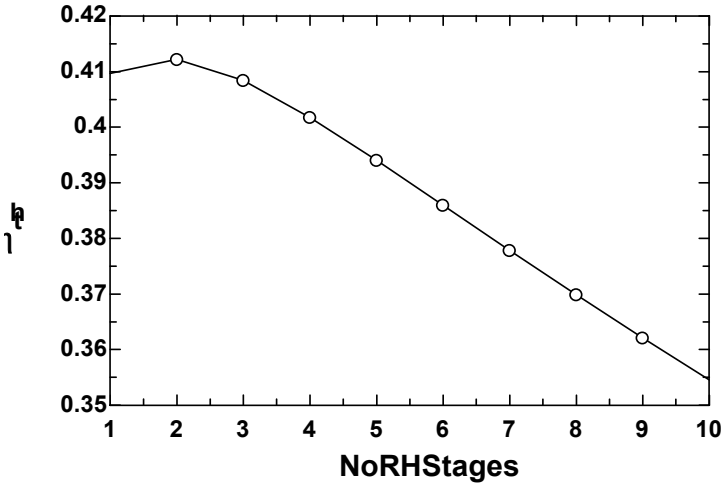
```
function x6$(x6) "this function returns a string to indicate the state of steam at point 6"
        x6$=''
        if (x6>1) then x6$='(superheated)'
        if (x6<0) then x6$='(subcooled)'
end

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$,T=T5,P=P5)
s_s6=s5
hs6=enthalpy(Fluid$,s=s_s6,P=P6)
Ts6=temperature(Fluid$,s=s_s6,P=P6)
vs6=volume(Fluid$,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
```

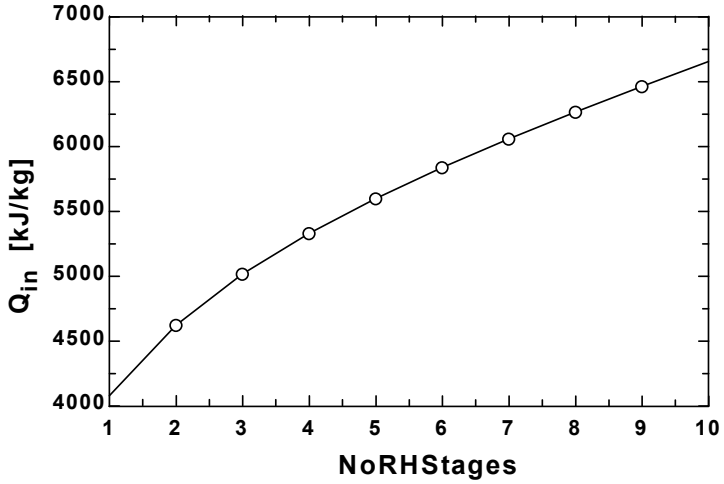
```
P[4] = P[3]*(1/Pratio)^(1/(NoRHStages+1))"kPa"

Fluid$='Steam_IAPWS'

"Pump analysis"
P[1] = P[6]
P[2]=P[3]
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
h[2]=h[1]+W_p   "SSSF First Law for the pump"
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$,s=s_s[4],P=P[4])
Eta_t=(h[3]-h[4])/(h[3]-hs[4])"Definition of turbine efficiency"
T[4]=temperature(Fluid$,P=P[4],h=h[4])
s[4]=entropy(Fluid$,h=h[4],P=P[4])
v[4]=volume(Fluid$,s=s[4],P=P[4])
h[3] =W_t_hp+h[4]"SSSF First Law for the high pressure turbine"

"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

{P[5]=P[4]
s[5]=entropy(Fluid$,T=T[5],P=P[5])
h[5]=enthalpy(Fluid$,T=T[5],P=P[5])
s_s[6]=s[5]
hs[6]=enthalpy(Fluid$,s=s_s[6],P=P[6])
Ts[6]=temperature(Fluid$,s=s_s[6],P=P[6])
vs[6]=volume(Fluid$,s=s_s[6],P=P[6])
Eta_t=(h[5]-h[6])/(h[5]-hs[6])"Definition of turbine efficiency"
h[5]=W_t_lp+h[6]"SSSF First Law for the low pressure turbine"
x[6]=QUALITY(Fluid$,h=h[6],P=P[6])
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$,h=h[6],P=P[6])
x6s$=x6$(x[6])

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

η_{th}	NoRH Stages	Q_{in} [kJ/kg]	W_{net} [kJ/kg]
0.4097	1	4085	1674
0.4122	2	4628	1908
0.4085	3	5020	2051
0.4018	4	5333	2143
0.3941	5	5600	2207
0.386	6	5838	2253
0.3779	7	6058	2289
0.3699	8	6264	2317
0.3621	9	6461	2340
0.3546	10	6651	2358






7000
6500
6000
5500
5000
4500
4000
Q_{in} [kJ/kg]
1
2
3
4
5
6
7
8
9
10
NoRHStages

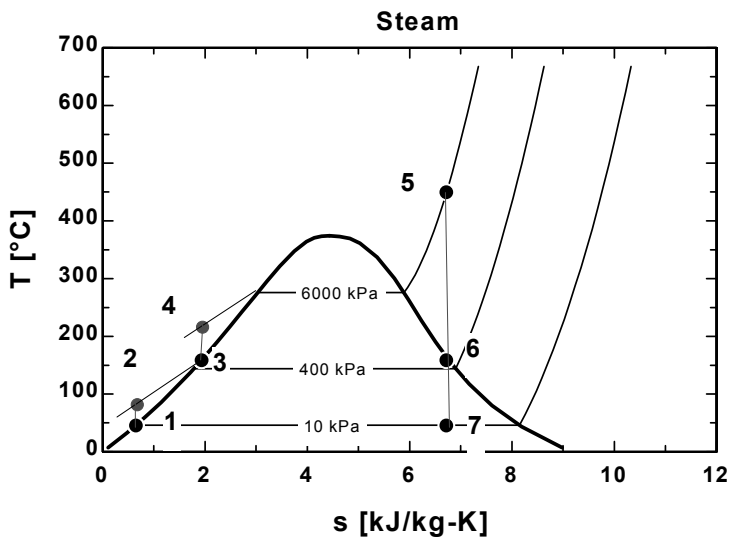
10-109 EES The effect of extraction pressure on the performance an ideal regenerative Rankine cycle with one open feedwater heater is to be investigated.

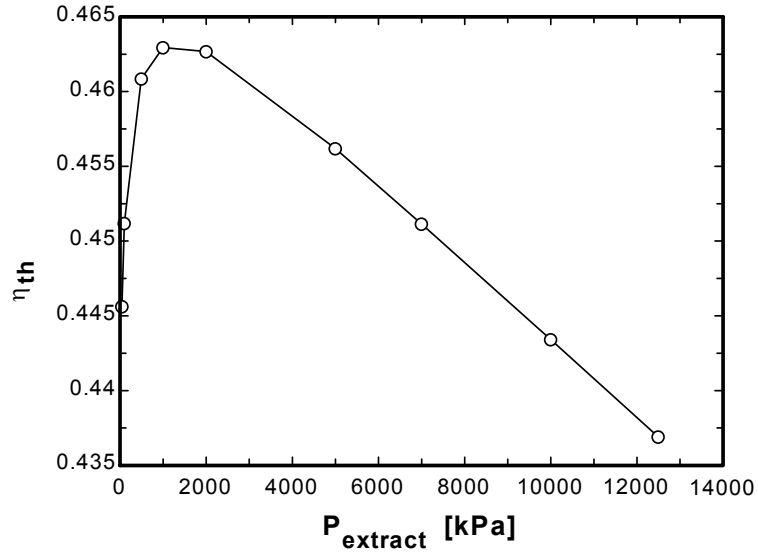
Analysis The problem is solved using EES, and the solution is given below.

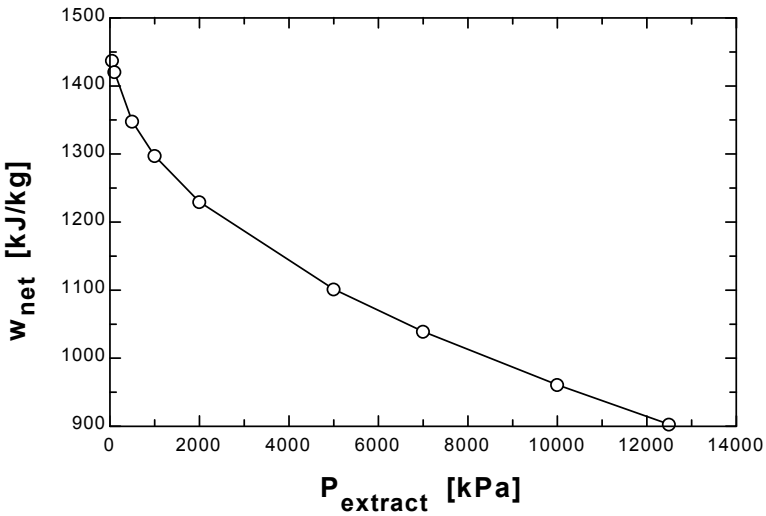
```
"Input Data"
P[5] = 15000 [kPa]
T[5] = 600 [C]
P_extract=1400 [kPa]
P[6] = P_extract
P_cond=10 [kPa]
P[7] = P_cond
Eta_turb= 1.0 "Turbine isentropic efficiency"
Eta_pump = 1.0 "Pump isentropic efficiency"
P[1] = P[7]
P[2]=P[6]
P[3]=P[6]
P[4] = P[5]

"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:"
y*h[6]  + (1- y)*h[2] = 1*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)

"Boiler condensate pump  or Pump 2 analysis"
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])

"Boiler analysis"
q_in + h[4]=h[5]"SSSF conservation of energy for the Boiler"
h[5]=enthalpy(Fluid$, T=T[5], P=P[5])
s[5]=entropy(Fluid$, T=T[5], P=P[5])

"Turbine analysis"
ss[6]=s[5]
hs[6]=enthalpy(Fluid$,s=ss[6],P=P[6])
Ts[6]=temperature(Fluid$,s=ss[6],P=P[6])
h[6]=h[5]-Eta_turb*(h[5]-hs[6])"Definition of turbine efficiency for high pressure stages"
T[6]=temperature(Fluid$,P=P[6],h=h[6])
s[6]=entropy(Fluid$,P=P[6],h=h[6])
```

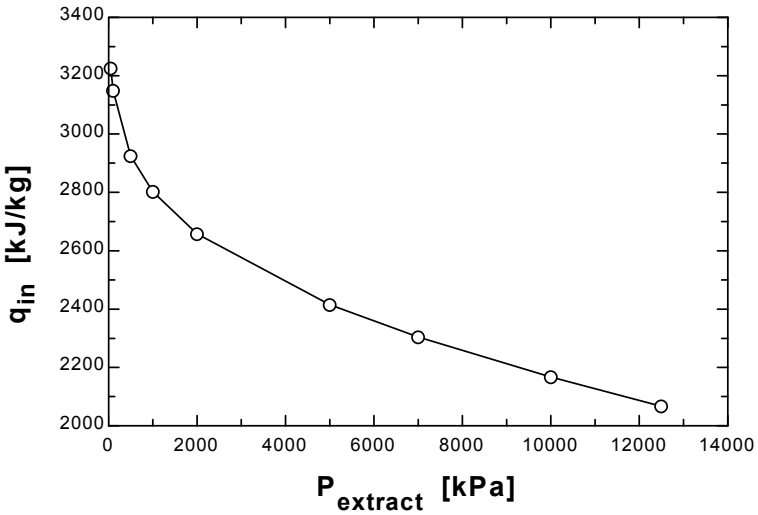
```
ss[7]=s[6]
hs[7]=enthalpy(Fluid$,s=ss[7],P=P[7])
Ts[7]=temperature(Fluid$,s=ss[7],P=P[7])
h[7]=h[6]-Eta_turb*(h[6]-hs[7])"Definition of turbine efficiency for low pressure stages"
T[7]=temperature(Fluid$,P=P[7],h=h[7])
s[7]=entropy(Fluid$,P=P[7],h=h[7])
h[5] =y*h[6] + (1- y)*h[7] + w_turb "SSSF conservation of energy for turbine"

"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
```

η_{th}	$P_{extract}$ [kPa]	w_{net} [kJ/kg]	q_{in} [kJ/kg]
0.4456	50	1438	3227
0.4512	100	1421	3150
0.4608	500	1349	2927
0.4629	1000	1298	2805
0.4626	2000	1230	2659
0.4562	5000	1102	2416
0.4511	7000	1040	2305
0.4434	10000	961.4	2168
0.4369	12500	903.5	2068




0.465
0.46
0.455
0.45
0.445
0.44
0.435
η_{th}
0
2000
4000
6000
8000
10000
12000
14000
$P_{extract}$ [kPa]


1500
1400
1300
1200
1100
1000
900
w_{net} [kJ/kg]
0
2000
4000
6000
8000
10000
12000
14000
$P_{extract}$ [kPa]


3400
3200
3000
2800
2600
2400
2200
2000
q_{in} [kJ/kg]
0
2000
4000
6000
8000
10000
12000
14000
$P_{extract}$ [kPa]

10-110 EES The effect of number of regeneration stages on the performance an ideal regenerative Rankine cycle with one open feedwater heater is to be investigated.

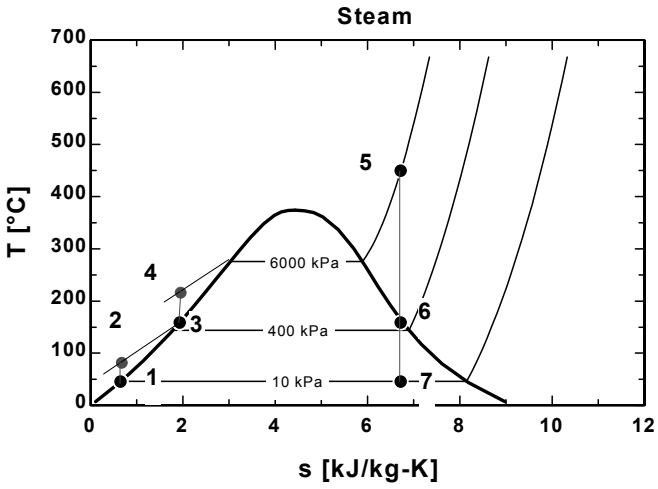
Analysis The problem is solved using EES, and the solution is given below.

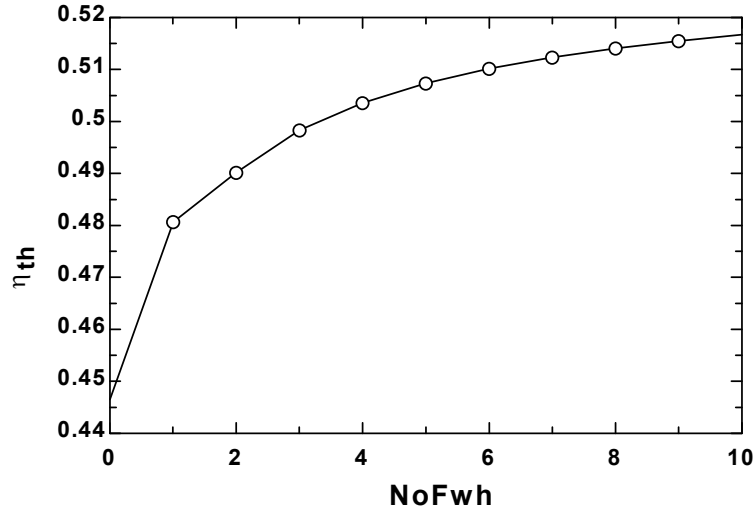
```
Procedure Reheat(NoFwh,T[5],P[5],P_cond,Eta_turb,Eta_pump:q_in,w_net)

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)

P4[1] = P[5]  "NOTICE THIS IS P4[i] WITH i = 1"

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
```

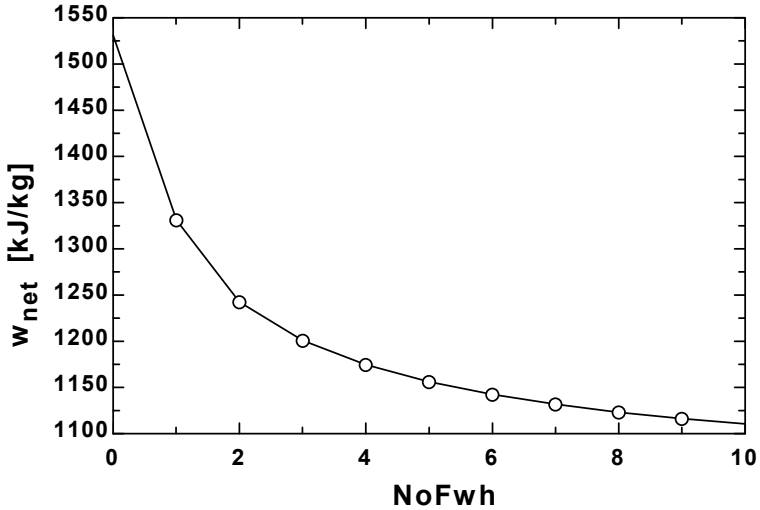
```
i=0
REPEAT
i=i+1
"Open Feedwater Heater analysis:"
{h2[i] = h6[i]}
s5[i] = s[5]
ss6[i]=s5[i]
hs6[i]=enthalpy(Fluid$,s=ss6[i],P=P6[i])
Ts6[i]=temperature(Fluid$,s=ss6[i],P=P6[i])
h6[i]=h[5]-Eta_turb*(h[5]-hs6[i])"Definition of turbine efficiency for high pressure stages"
If i=1 then y[1]=(h3[1] - h4[2])/(h6[1]  - h4[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)*(h3[i] - h4[i+1])/(h6[i]  - h4[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]=h6[i]-Eta_turb*(h6[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"
```

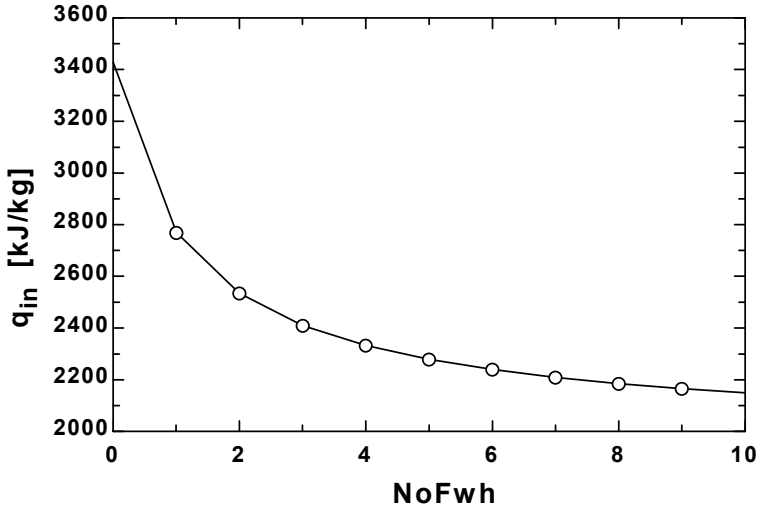
```
h[2]=w_pump1+ h[1]  "Steady-flow conservation of energy"
s[2]=entropy(Fluid$,P=P[2],h=h[2])
T[2]=temperature(Fluid$,P=P[2],h=h[2])

"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
P[4] = P[5]

"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
```

No FWH	η_{th}	w_{net} [kJ/kg]	q_{in} [kJ/kg]
0	0.4466	1532	3430
1	0.4806	1332	2771
2	0.4902	1243	2536
3	0.4983	1202	2411
4	0.5036	1175	2333
5	0.5073	1157	2280
6	0.5101	1143	2240
7	0.5123	1132	2210
8	0.5141	1124	2186
9	0.5155	1117	2167
10	0.5167	1111	2151




0.52
0.51
0.5
0.49
0.48
0.47
0.46
0.45
0.44
η_{th}
0
2
4
6
8
10
NoFwh


1550
1500
1450
1400
1350
1300
1250
1200
1150
1100
w_{net} [kJ/kg]
0
2
4
6
8
10
NoFwh


3600
3400
3200
3000
2800
2600
2400
2200
2000
q_{in} [kJ/kg]
0
2
4
6
8
10
NoFwh

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)
moisture=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"
```

```
P3=P2
P4=P1
T3=600 "C"
s4=s3
Q_rate=800 "kJ/s"
m=Q_rate/q_in
h1=ENTHALPY(Steam_IAPWS,x=0,P=P1)
h2=h1  "pump work is neglected"
"v1=VOLUME(Steam_IAPWS,x=0,P=P1)
w_pump=v1*(P2-P1)
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
W_turb=m*(h3-h4)
"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"
```

10-115 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:"
m_gas*Cp*(T3 -T4)=W1_msteam*4.18*(T2-T1) "Assuming no evaporation of liquid water"
m_gas*Cv*(T3 -T4)=W2_msteam*(h2-h1); Cv=0.718 "Using Cv for air instead of Cp"
W3_msteam = m_gas "Taking the mass flow rates of two fluids to be equal"
m_gas*Cp*(T3 -T4)=W4_msteam*(h2-h11); h11=ENTHALPY(Steam_IAPWS,x=0,P=P1) "Taking
h1=hf@P1"
```

10-116 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-h2)  "Using wrong relation for q_in"
```

10-117 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"
```

10-118 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 trubine 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.

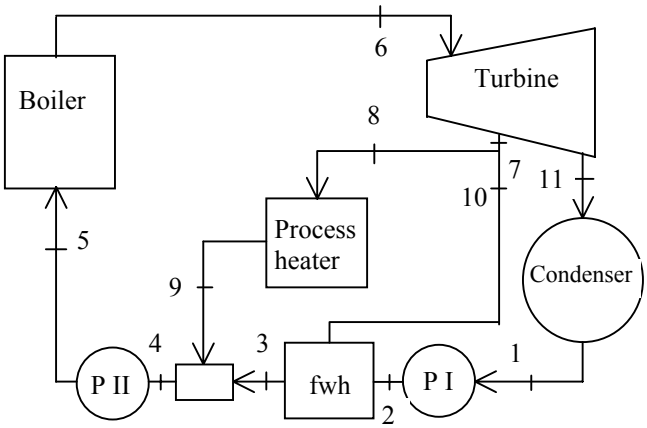
Answer (d) the moisture content at turbine exit will decrease.

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.

10-123 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.



$h_1 = 191.81$
$h_2 = 192.20$
$h_3 = h_4 = h_9 = 604.66$
$h_5 = 610.73$
$h_6 = 3302.9$
$h_7 = h_8 = h_{10} = 2665.6$
$h_{11} = 2128.8$

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_total*(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)
```

10-124 ··· 10-133 Design and Essay Problems