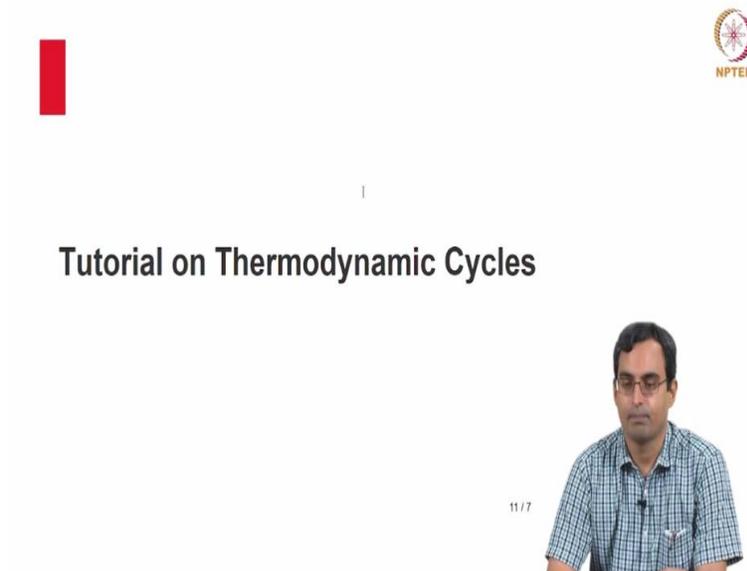


Gmail
Thermodynamics
Professor Anand T N C
Department of Mechanical Engineering
Indian Institute of Technology, Madras
Lecture – 85
Tutorial Problem (1 number)

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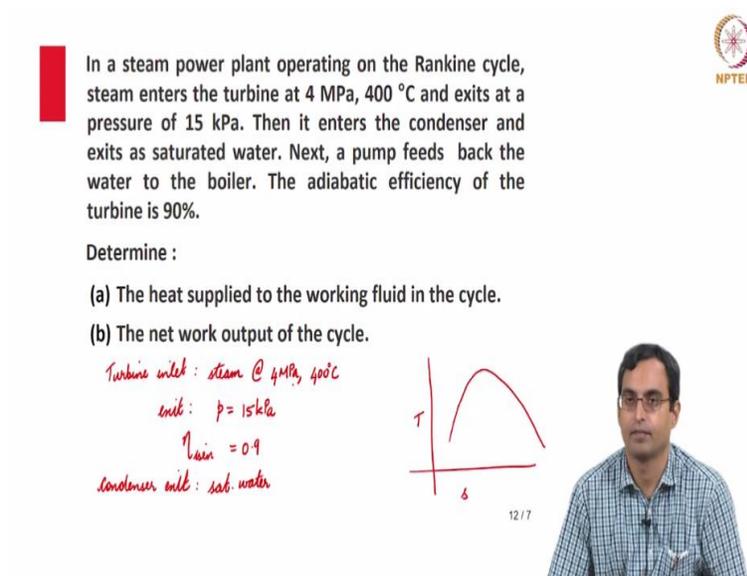


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Tutorial on Thermodynamic Cycles

The slide features a red vertical bar on the left, the NPTEL logo in the top right, and a video inset of Professor Anand T N C on the right side. The main title is centered on the slide.

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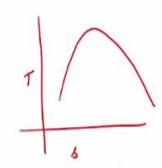
In a steam power plant operating on the Rankine cycle, steam enters the turbine at 4 MPa, 400 °C and exits at a pressure of 15 kPa. Then it enters the condenser and exits as saturated water. Next, a pump feeds back the water to the boiler. The adiabatic efficiency of the turbine is 90%.

Determine :

(a) The heat supplied to the working fluid in the cycle.

(b) The net work output of the cycle.

Turbine inlet : steam @ 4MPa, 400°C
exit : p = 15kPa
 $\eta_{\text{turb}} = 0.9$
condenser exit : sat. water



The slide includes a red vertical bar on the left, the NPTEL logo in the top right, and a video inset of Professor Anand T N C on the right side. The text describes a Rankine cycle problem. A handwritten note lists the turbine inlet conditions (4 MPa, 400 °C), exit pressure (15 kPa), and adiabatic efficiency (0.9). It also notes the condenser exit is saturated water. A T-s diagram is shown with temperature (T) on the vertical axis and entropy (s) on the horizontal axis, depicting a cycle with a superheated vapor expansion curve.

Figure 1.

Solution of the problem in Fig. 1:

Turbine inlet: $p = 4 \text{ MPa}, T = 400 \text{ }^\circ\text{C}$

Turbine exit: $p = 15 \text{ kPa}$

$$\eta_{isen,turbine} = 0.9$$

We have saturated water at the condenser exit. It would help in solving the problem if we draw this cycle on a T-S diagram. Hence, we need to know the states.

At 4 MPa, $T_{sat} = 250 \text{ }^\circ\text{C}$. Since $400 \text{ }^\circ\text{C} > T_{sat}$, the steam is in superheated zone at the inlet of the turbine. At the turbine inlet, $h = 3214.5 \text{ kJ/kg}$ and $s = 6.771 \text{ kJ/kg}\cdot\text{K}$

The condensation process happens at 15 kPa. If the expansion process in the turbine is isentropic (from 4 MPa to 15 kPa), the entropy at the inlet of the condenser is $s = 6.771 \text{ kJ/kg}\cdot\text{K}$.

At 15 kPa, $s_g = 8.007 \text{ kJ/kg}\cdot\text{K}$. As $6.771 < 8.007$, the inlet to the condenser lies inside the liquid-vapor dome. Now, we can qualitatively draw the Rankine cycle on a T-S diagram as shown in Fig. 2.

The processes are:

Process 1-2: isentropic compression in a pump

Process 2-3-4-5: constant pressure heat addition in a boiler

Process 5-6: isentropic expansion in a turbine

Process 6-1: constant pressure heat rejection in a condenser

Heat supplied to the working fluid in a boiler, $q = h_5 - h_2$ (enthalpy at the inlet of the turbine – enthalpy at the exit of the pump)

The state 2 has the same entropy as state 1. We also know the pressure at state 2. Knowing pressure and entropy values at state 2, we can get h_2 from the tables for subcooled liquids. However, we don't have those tables here.

We can also get h_2 through the expression $w_p = h_1 - h_2$, where w_p is the work input to the pump. If we consider the isentropic compression, $w_p = h_1 - h_2 = -v_1(p_2 - p_1) = -0.001014(4 \times 10^6 - 15 \times 10^3) = -4.04 \frac{kJ}{kg}$

$$\text{Hence, } h_2 = h_1 - w_p = 225.8 - (-4.04) = 229.84 \frac{kJ}{kg}$$

Hence, heat supplied to the working fluid in a boiler, $q = h_5 - h_2 = 3214.5 - 229.84 = 2984.66 \frac{kJ}{kg}$

Net work output on a unit mass basis = $w_{net} = w_t + w_p = |w_t| - |w_p|$ (w_t is the turbine work output)

$$w_t = h_5 - h_6$$

For calculating h_6 , we need the quality x_6 . We know that $s_5 = s_6 = 6.771 = [s_f + x_6 s_{fg}]_{15 \text{ kPa}} \rightarrow x_6 = 0.829 \rightarrow h_6 = [h_f + x_6 h_{fg}]_{15 \text{ kPa}} = 2192.5 \frac{kJ}{kg}$

$$\text{Hence, } w_t = h_5 - h_6 = 1022 \frac{kJ}{kg}$$

Hence, net work output on a unit mass basis = $w_{net} = w_t + w_p = |w_t| - |w_p| = 1022 - 4.04 = 1017.96 \frac{kJ}{kg}$ (considering isentropic processes)

$$\eta_{isen,turbine} = 0.9 = \frac{w_{t,act}}{w_{t,ideal}} = \frac{w_{t,act}}{1022} \rightarrow w_{t,act} = 919.8 \frac{kJ}{kg}$$

$$\text{Hence, } w_{net} = w_{t,act} + w_p = 915.76 \frac{kJ}{kg}$$

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P-13 (MPS) (2) (1)				P-13 (MPS) (2) (2)				P-13 (MPS) (2) (3)				P-13 (MPS) (2) (4)			
Temp	Volume	Enthalpy	Entropy												
0.01	0.0001	0.0001	0.0001	0.01	0.0001	0.0001	0.0001	0.01	0.0001	0.0001	0.0001	0.01	0.0001	0.0001	0.0001



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4 MPa 400°C
 $h_5 = 3214.5 \text{ kJ/kg}$
 $s_5 = 6.771 \text{ kJ/kgK}$

$s_g @ 15 \text{ kPa} = 8.007 \text{ kJ/kgK}$

Isentropic expansion:
 $dS = 0 = \dot{m} [h_i + c_p \ln(T_i/T_f)] - \dot{m} [h_c + c_p \ln(T_c/T_f)]$
 $0 = h_c - h_i$

2 = point on the 4 MPa line

Wp = ?
 $dS = \dot{m} [h_i + c_p \ln(T_i/T_c)] - \dot{m} [h_c + c_p \ln(T_c/T_c)]$
 $W = \dot{m} [h_i - h_c] \text{ or } W = \dot{m} (h_i - h_c)$
 $h_2 = h_1 + |W|$

$dS = \dot{m} c_p \ln(T_c/T_i)$



Figure 2.

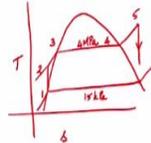


In a steam power plant operating on the Rankine cycle, steam enters the turbine at 4 MPa, 400 °C and exits at a pressure of 15 kPa. Then it enters the condenser and exits as saturated water. Next, a pump feeds back the water to the boiler. The adiabatic efficiency of the turbine is 90%.

Determine :

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Turbine inlet : steam @ 4MPa, 400°C
 exit : p = 15kPa
 $\eta_{turb} = 0.9$
 condenser exit : sat. water



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Properties of Saturated Water - Pressure Table											
Pressure	Temp	Volume	Enthalpy	Entropy	Volume	Enthalpy	Entropy	Volume	Enthalpy	Entropy	
MPa	°C	v_f	v_g	v_{fg}	u_f	u_g	u_{fg}	h_f	h_g	s_f	s_g
0.001	0.01	0.001000	206.13	206.13	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	5	0.001000	206.98	206.98	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	10	0.001000	207.83	207.83	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	15	0.001000	208.68	208.68	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	20	0.001000	209.53	209.53	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	25	0.001000	210.38	210.38	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	30	0.001000	211.23	211.23	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	35	0.001000	212.08	212.08	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	40	0.001000	212.93	212.93	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	45	0.001000	213.78	213.78	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	50	0.001000	214.63	214.63	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	55	0.001000	215.48	215.48	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	60	0.001000	216.33	216.33	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	65	0.001000	217.18	217.18	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	70	0.001000	218.03	218.03	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	75	0.001000	218.88	218.88	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	80	0.001000	219.73	219.73	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	85	0.001000	220.58	220.58	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	90	0.001000	221.43	221.43	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	95	0.001000	222.28	222.28	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	100	0.001000	223.13	223.13	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	105	0.001000	223.98	223.98	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	110	0.001000	224.83	224.83	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	115	0.001000	225.68	225.68	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	120	0.001000	226.53	226.53	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	125	0.001000	227.38	227.38	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	130	0.001000	228.23	228.23	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	135	0.001000	229.08	229.08	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	140	0.001000	229.93	229.93	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	145	0.001000	230.78	230.78	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	150	0.001000	231.63	231.63	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	155	0.001000	232.48	232.48	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	160	0.001000	233.33	233.33	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	165	0.001000	234.18	234.18	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	170	0.001000	235.03	235.03	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	175	0.001000	235.88	235.88	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	180	0.001000	236.73	236.73	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	185	0.001000	237.58	237.58	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	190	0.001000	238.43	238.43	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	195	0.001000	239.28	239.28	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	200	0.001000	240.13	240.13	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	205	0.001000	240.98	240.98	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	210	0.001000	241.83	241.83	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	215	0.001000	242.68	242.68	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	220	0.001000	243.53	243.53	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	225	0.001000	244.38	244.38	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	230	0.001000	245.23	245.23	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	235	0.001000	246.08	246.08	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	240	0.001000	246.93	246.93	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	245	0.001000	247.78	247.78	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	250	0.001000	248.63	248.63	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	255	0.001000	249.48	249.48	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	260	0.001000	250.33	250.33	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	265	0.001000	251.18	251.18	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	270	0.001000	252.03	252.03	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	275	0.001000	252.88	252.88	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	280	0.001000	253.73	253.73	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	285	0.001000	254.58	254.58	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	290	0.001000	255.43	255.43	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	295	0.001000	256.28	256.28	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	300	0.001000	257.13	257.13	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	305	0.001000	257.98	257.98	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	310	0.001000	258.83	258.83	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	315	0.001000	259.68	259.68	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	320	0.001000	260.53	260.53	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	325	0.001000	261.38	261.38	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	330	0.001000	262.23	262.23	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	335	0.001000	263.08	263.08	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	340	0.001000	263.93	263.93	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	345	0.001000	264.78	264.78	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	350	0.001000	265.63	265.63	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	355	0.001000	266.48	266.48	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	360	0.001000	267.33	267.33	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	365	0.001000	268.18	268.18	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	370	0.001000	269.03	269.03	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	375	0.001000	269.88	269.88	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	380	0.001000	270.73	270.73	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	385	0.001000	271.58	271.58	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	390	0.001000	272.43	272.43	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	395	0.001000	273.28	273.28	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	400	0.001000	274.13	274.13	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	405	0.001000	274.98	274.98	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	410	0.001000	275.83	275.83	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	415	0.001000	276.68	276.68	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	420	0.001000	277.53	277.53	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	425	0.001000	278.38	278.38	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	430	0.001000	279.23	279.23	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	435	0.001000	280.08	280.08	0.000000	0.01	0.01	0.01	0.01	0.000000	0.01
0.001	440	0.001000	280.93	280.93	0.000000	0.01	0.01	0.01	0.01</		

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4 MPa 400°C
 $h_5 = 3214.5 \text{ kJ/kg}$
 $s_5 = 6.771 \text{ kJ/kgK}$
 $s_g @ 15 \text{ kPa} = 8.007 \text{ kJ/kgK}$

Isenthalal = ?
 $\frac{ds}{dt} = \frac{dQ}{dt} + m \left[\frac{dh_i + ke + pe}{t} \right]_i - m \left[\frac{dh_e + ke + pe}{t} \right]_e$
 $q = h_e - h_i$

$h_2 = ?$
 $s_1 = s_g @ 15 \text{ kPa} = 8.007 \text{ kJ/kgK}$
 $s_2 = s_1 = 8.007 \text{ kJ/kgK}$
 2 = point on the 4 MPa line

Work = ?
 $\frac{dW}{dt} = \dot{Q} - \dot{W} + m \left[\frac{dh_i + ke + pe}{t} \right]_i - m \left[\frac{dh_e + ke + pe}{t} \right]_e$
 $\dot{W} = m [h_i - h_e]$ or $\dot{W} = h_i - h_e$
 $h_2 = h_1 + |w|$

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$\int_{p_1}^{p_2} v dp = \int_{p_1}^{p_2} \frac{dh}{v}$
 $\Delta h = \int_{p_1}^{p_2} v dp$ $v = \text{sp. vol. of } h_{g1} @ 15 \text{ kPa}$
 $\Delta h = 0.001014 \times [4 \times 10^4 - 15 \times 10^3] \times 10^{-3}$
 $|w_p| = \Delta h = 4.04 \text{ kJ/kg}$
 $h_2 = h_1 + \Delta h$
 $= 225.8 + 4.04$
 $h_2 = 229.84 \text{ kJ/kg}$
 $q_f = h_5 - h_2 = 3214.5 - 229.84$
 $q_f = 2984.66 \text{ kJ/kg}$

Net work = ?
 For ideal process 5-6, $s_5 = s_6 = 6.771 = s_g + x s_{fg} @ 15 \text{ kPa}$
 $\Rightarrow x = 0.829$
 $h_6 = h_g + x h_{fg} @ 15 \text{ kPa}$
 $= 225.8 + 0.829 \times 2372.4$
 $h_6 = 2192.5$

$$W_T = h_5 - h_6 = 3214.5 - 2192.5$$

$$W_{T,ideal} - W_T = 1022 \text{ kJ/kg}$$

$$\eta = 90\% = \frac{h_5 - h_6'}{h_5 - h_6} = \frac{W_{act}}{W_{T,ideal}}$$

$$\Rightarrow W_{act} = 919.8 \text{ kJ/kg}$$



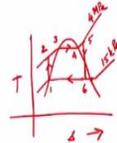
4 MPa 400°C
 $h_5 = 3214.5 \text{ kJ/kg}$
 $s_5 = 6.771 \text{ kJ/kgK}$
 $s_6 @ 15 \text{ kPa} = 8.007 \text{ kJ/kgK}$

Isenthalpic = ?

$$\frac{dE}{dm} = \dot{Q} - \dot{W} + \dot{m} [h_i + k c_i^2]_i - \dot{m} [h_e + k c_e^2]_e$$

$$q = h_e - h_i = h_5 - h_2$$

$$\frac{dW}{dm} = m_i \cdot m_e$$



$h_2 = ?$
 $s_1 = s_2 @ 15 \text{ kPa} = 0.7543 \text{ kJ/kgK}$
 $s_2 = s_1 = 0.7543 \text{ kJ/kgK}$
 2 = point on the 4 MPa line

$W_p = ?$

$$\frac{dE}{dm} = \dot{Q} - \dot{W} + \dot{m} [h_i + k c_i^2]_i - \dot{m} [h_e + k c_e^2]_e$$

$$\dot{W} = \dot{m} [h_i - h_e] \text{ or } W = h_i - h_e$$

$$h_2 = h_1 + |W|$$



In a steam power plant operating on the Rankine cycle, steam enters the turbine at 4 MPa, 400 °C and exits at a pressure of 15 kPa. Then it enters the condenser and exits as saturated water. Next, a pump feeds back the water to the boiler. The adiabatic efficiency of the turbine is 90%.

Determine :

- (a) The heat supplied to the working fluid in the cycle.
- (b) The net work output of the cycle.

*Turbine inlet : steam @ 4MPa, 400°C
exit : p = 15kPa
 $\eta_{\text{turbine}} = 0.9$
condenser exit : sat. water*

