Department of Air Conditioning and Refrigeration Engineering Technology

# Class: 2nd

# Subject: Thermodynamics

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# The Ideal Reheat Rankine Cycle

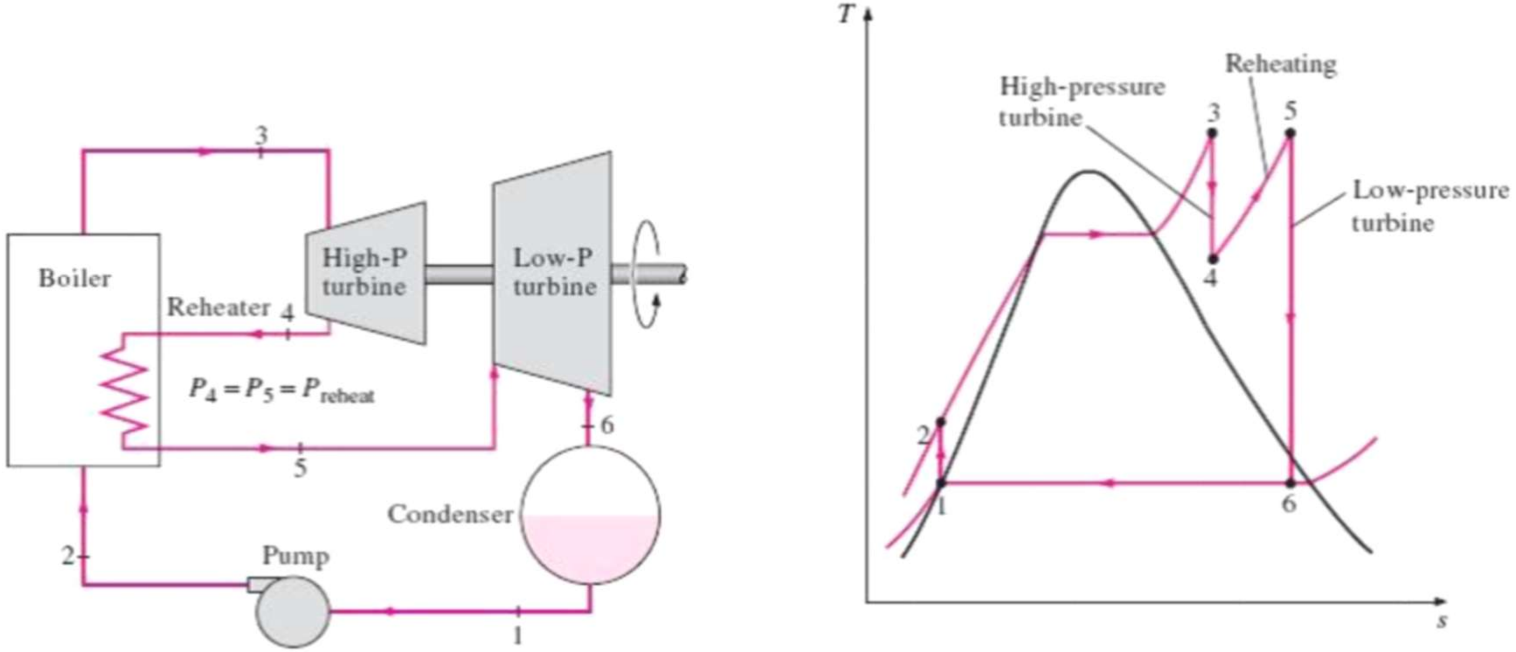
Increasing the boiler pressure increases the thermal efficiency of the Rankine cycle, but it also increases the moisture content of the steam to unacceptable levels. Therefore, the desirable approach is expanding the steam in the turbine in two stages, and reheats it in between.

In other words, modify the simple ideal Rankine cycle with a reheat process. Reheating is a practical solution to the excessive moisture problem in turbines, and it is commonly used in modern steam power plants

The figure below explains the (T-S) diagram of the ideal reheat Rankine cycle and the schematic of the power plant operating on this cycle.

$$q_{add} = q_{primary} + q_{reheat} = (h_3 - h_2) + (h_5 - h_4)$$

$$w_{out} = w_{turbine\ 1} + w_{turbine\ 2} = (h_3 - h_4) + (h_5 - h_6)$$



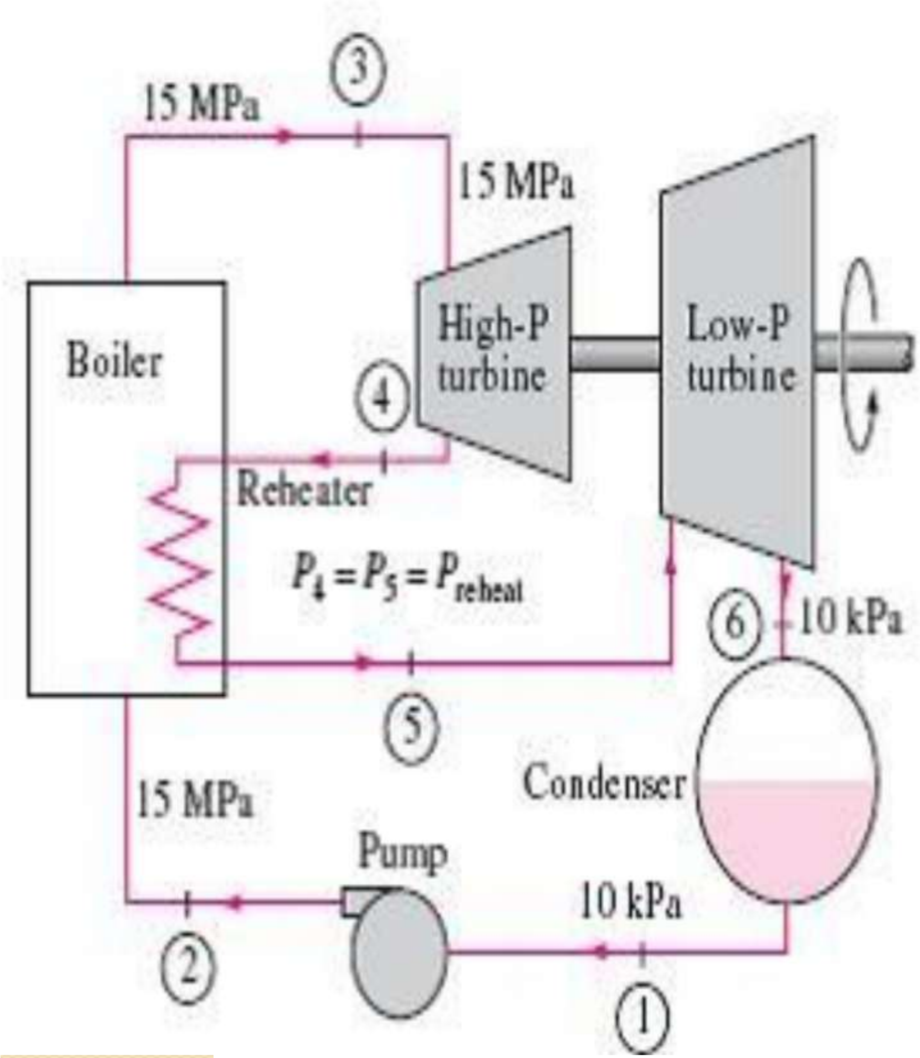
The Ideal Reheat Rankine Cycle

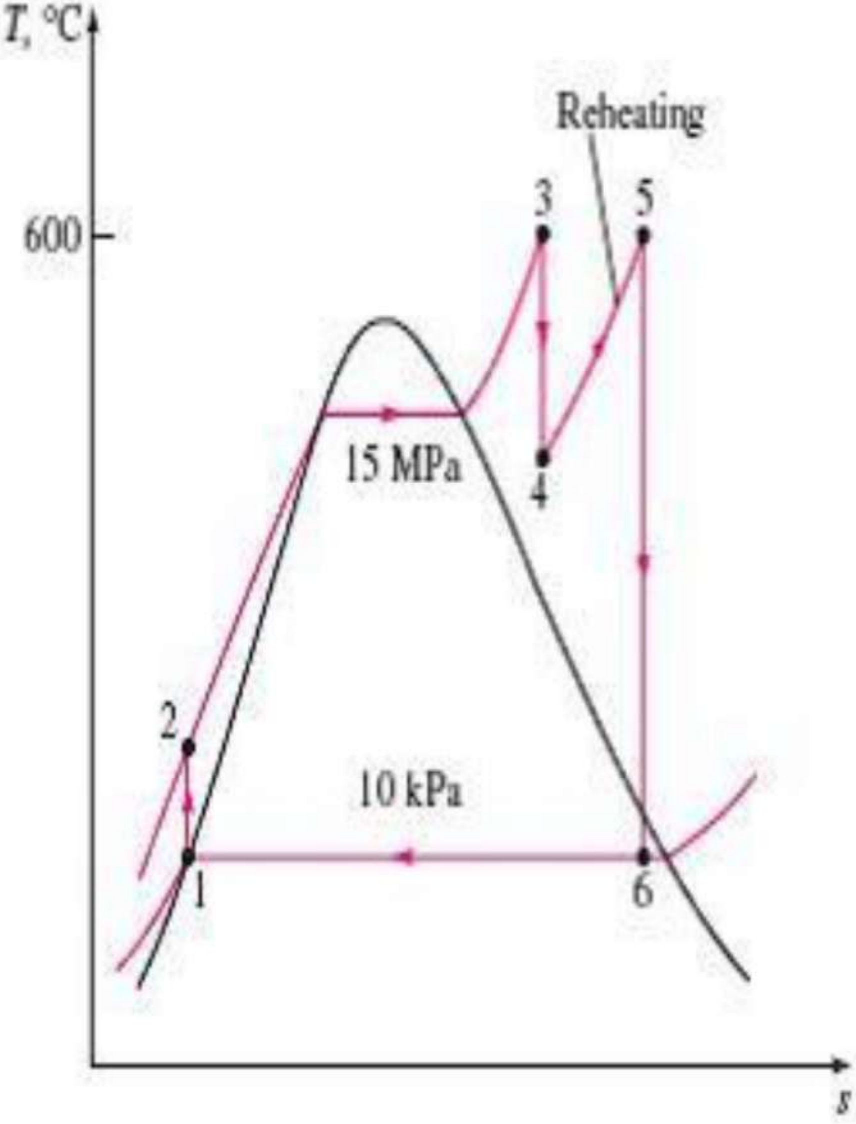
**Example (5.4)** Consider a steam power plant operating on the ideal reheat Rankine cycle. Steam enters the high-pressure turbine at 15 MPa and 600°C and is condensed in the condenser at a pressure of 10 kPa. If the moisture content of the steam at the exit of the low-pressure turbine is not to exceed 10.4%, determine:

(a) the pressure at which the steam should be reheated

(b) the thermal efficiency of the cycle. Assume the steam is reheated to the inlet temperature of the high-pressure turbine.

Solution:


15 MPa
③
15 MPa
Boiler
High-P turbine
Low-P turbine
④
Reheater
$P_4 = P_5 = P_{reheat}$
⑥
10 kPa
⑤
Condenser
15 MPa
Pump
10 kPa
②
①


T, °C
600
Reheating
3
5
15 MPa
4
2
10 kPa
1
6
s

$a)\ State\ 6\ at:\ P_6 = 10\text{kPa And } x_6 = 0.896$

$$s_6 = s_f + x_6 s_{fg} = 0.6492 + 0.896 \times (7.34996) = 7.3688\text{kJ/kg. K}$$

$$h_6 = h_f + x_6 h_{fg} = 191.8 + 0.896 \times (2392.1) = 2335.1\text{kJ/kg}$$

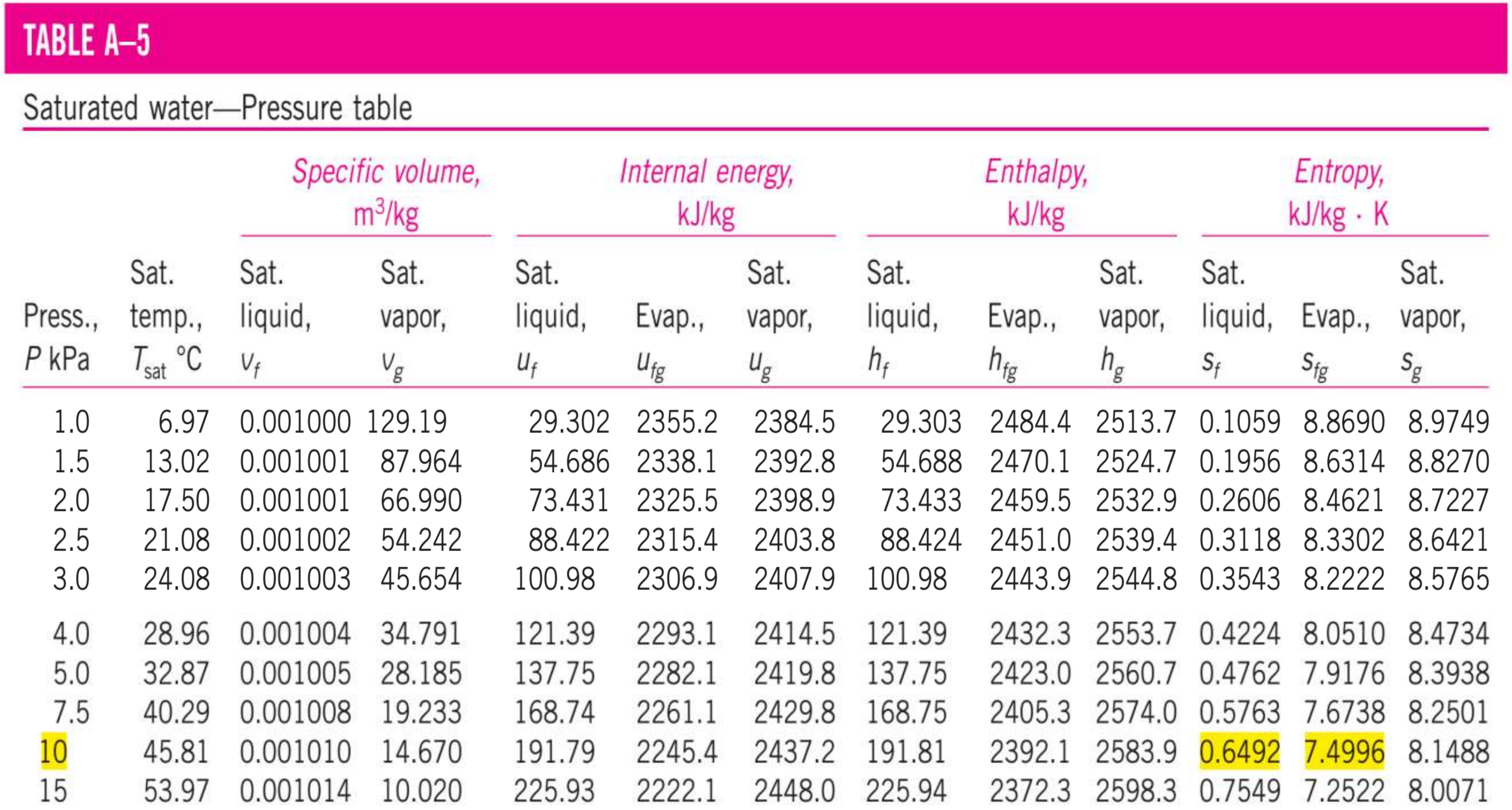


**TABLE A–5**

Saturated water—Pressure table

| | | Specific volume, $m^3/kg$ | | Internal energy, kJ/kg | | | Enthalpy, kJ/kg | | | Entropy, kJ/kg · K | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Press., $P$ kPa | Sat. temp., $T_{sat}$ °C | Sat. liquid, $v_f$ | Sat. vapor, $v_g$ | Sat. liquid, $u_f$ | Evap., $u_{fg}$ | Sat. vapor, $u_g$ | Sat. liquid, $h_f$ | Evap., $h_{fg}$ | Sat. vapor, $h_g$ | Sat. liquid, $s_f$ | Evap., $s_{fg}$ | Sat. vapor, $s_g$ |
| 1.0 | 6.97 | 0.001000 | 129.19 | 29.302 | 2355.2 | 2384.5 | 29.303 | 2484.4 | 2513.7 | 0.1059 | 8.8690 | 8.9749 |
| 1.5 | 13.02 | 0.001001 | 87.964 | 54.686 | 2338.1 | 2392.8 | 54.688 | 2470.1 | 2524.7 | 0.1956 | 8.6314 | 8.8270 |
| 2.0 | 17.50 | 0.001001 | 66.990 | 73.431 | 2325.5 | 2398.9 | 73.433 | 2459.5 | 2532.9 | 0.2606 | 8.4621 | 8.7227 |
| 2.5 | 21.08 | 0.001002 | 54.242 | 88.422 | 2315.4 | 2403.8 | 88.424 | 2451.0 | 2539.4 | 0.3118 | 8.3302 | 8.6421 |
| 3.0 | 24.08 | 0.001003 | 45.654 | 100.98 | 2306.9 | 2407.9 | 100.98 | 2443.9 | 2544.8 | 0.3543 | 8.2222 | 8.5765 |
| 4.0 | 28.96 | 0.001004 | 34.791 | 121.39 | 2293.1 | 2414.5 | 121.39 | 2432.3 | 2553.7 | 0.4224 | 8.0510 | 8.4734 |
| 5.0 | 32.87 | 0.001005 | 28.185 | 137.75 | 2282.1 | 2419.8 | 137.75 | 2423.0 | 2560.7 | 0.4762 | 7.9176 | 8.3938 |
| 7.5 | 40.29 | 0.001008 | 19.233 | 168.74 | 2261.1 | 2429.8 | 168.75 | 2405.3 | 2574.0 | 0.5763 | 7.6738 | 8.2501 |
| 10 | 45.81 | 0.001010 | 14.670 | 191.79 | 2245.4 | 2437.2 | 191.81 | 2392.1 | 2583.9 | 0.6492 | 7.4996 | 8.1488 |
| 15 | 53.97 | 0.001014 | 10.020 | 225.93 | 2222.1 | 2448.0 | 225.94 | 2372.3 | 2598.3 | 0.7549 | 7.2522 | 8.0071 |

$a)$ $State\ 6\ at:$ $P_6 = 10\text{kPa}$ And $x_6 = 0.896$

$$s_6 = s_f + x_6 s_{fg} = 0.6492 + 0.896 \times (7.34996) = 7.3688\text{kJ/kg.K}$$
$$h_6 = h_f + x_6 h_{fg} = 191.8 + 0.896 \times (2392.1) = 2335.1\text{kJ/kg}$$

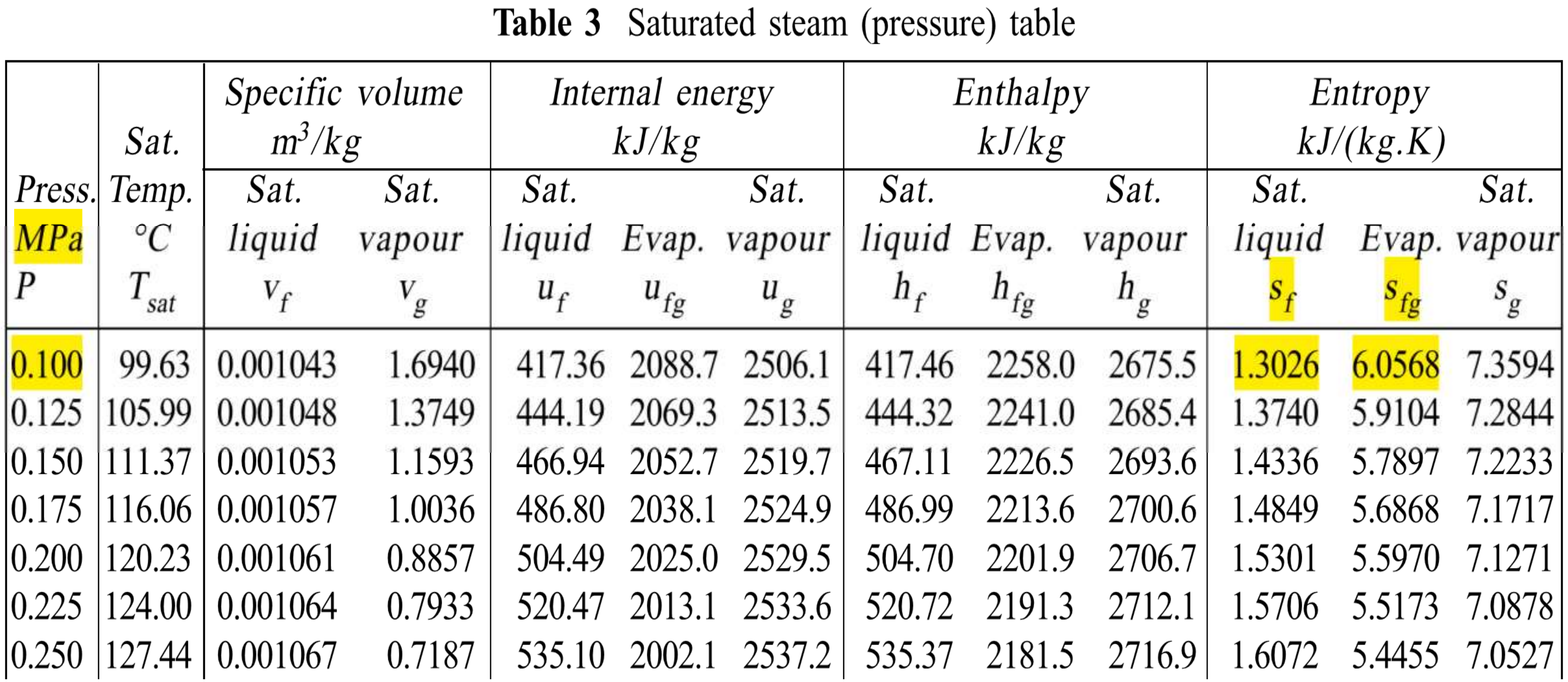


**Table 3** Saturated steam (pressure) table

| Press. MPa P | Sat. Temp. °C $T_{sat}$ | Specific volume m³/kg Sat. liquid $v_f$ | Sat. vapour $v_g$ | Internal energy kJ/kg Sat. liquid $u_f$ | Evap. $u_{fg}$ | Sat. vapour $u_g$ | Enthalpy kJ/kg Sat. liquid $h_f$ | Evap. $h_{fg}$ | Sat. vapour $h_g$ | Entropy kJ/(kg.K) Sat. liquid $s_f$ | Evap. $s_{fg}$ | Sat. vapour $s_g$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.100 | 99.63 | 0.001043 | 1.6940 | 417.36 | 2088.7 | 2506.1 | 417.46 | 2258.0 | 2675.5 | 1.3026 | 6.0568 | 7.3594 |
| 0.125 | 105.99 | 0.001048 | 1.3749 | 444.19 | 2069.3 | 2513.5 | 444.32 | 2241.0 | 2685.4 | 1.3740 | 5.9104 | 7.2844 |
| 0.150 | 111.37 | 0.001053 | 1.1593 | 466.94 | 2052.7 | 2519.7 | 467.11 | 2226.5 | 2693.6 | 1.4336 | 5.7897 | 7.2233 |
| 0.175 | 116.06 | 0.001057 | 1.0036 | 486.80 | 2038.1 | 2524.9 | 486.99 | 2213.6 | 2700.6 | 1.4849 | 5.6868 | 7.1717 |
| 0.200 | 120.23 | 0.001061 | 0.8857 | 504.49 | 2025.0 | 2529.5 | 504.70 | 2201.9 | 2706.7 | 1.5301 | 5.5970 | 7.1271 |
| 0.225 | 124.00 | 0.001064 | 0.7933 | 520.47 | 2013.1 | 2533.6 | 520.72 | 2191.3 | 2712.1 | 1.5706 | 5.5173 | 7.0878 |
| 0.250 | 127.44 | 0.001067 | 0.7187 | 535.10 | 2002.1 | 2537.2 | 535.37 | 2181.5 | 2716.9 | 1.6072 | 5.4455 | 7.0527 |

Thus, $T_5 = 600°\mathrm{C}$ *and* $s_5 = s_6 = 7.3688\mathrm{kJ/kg.K}$

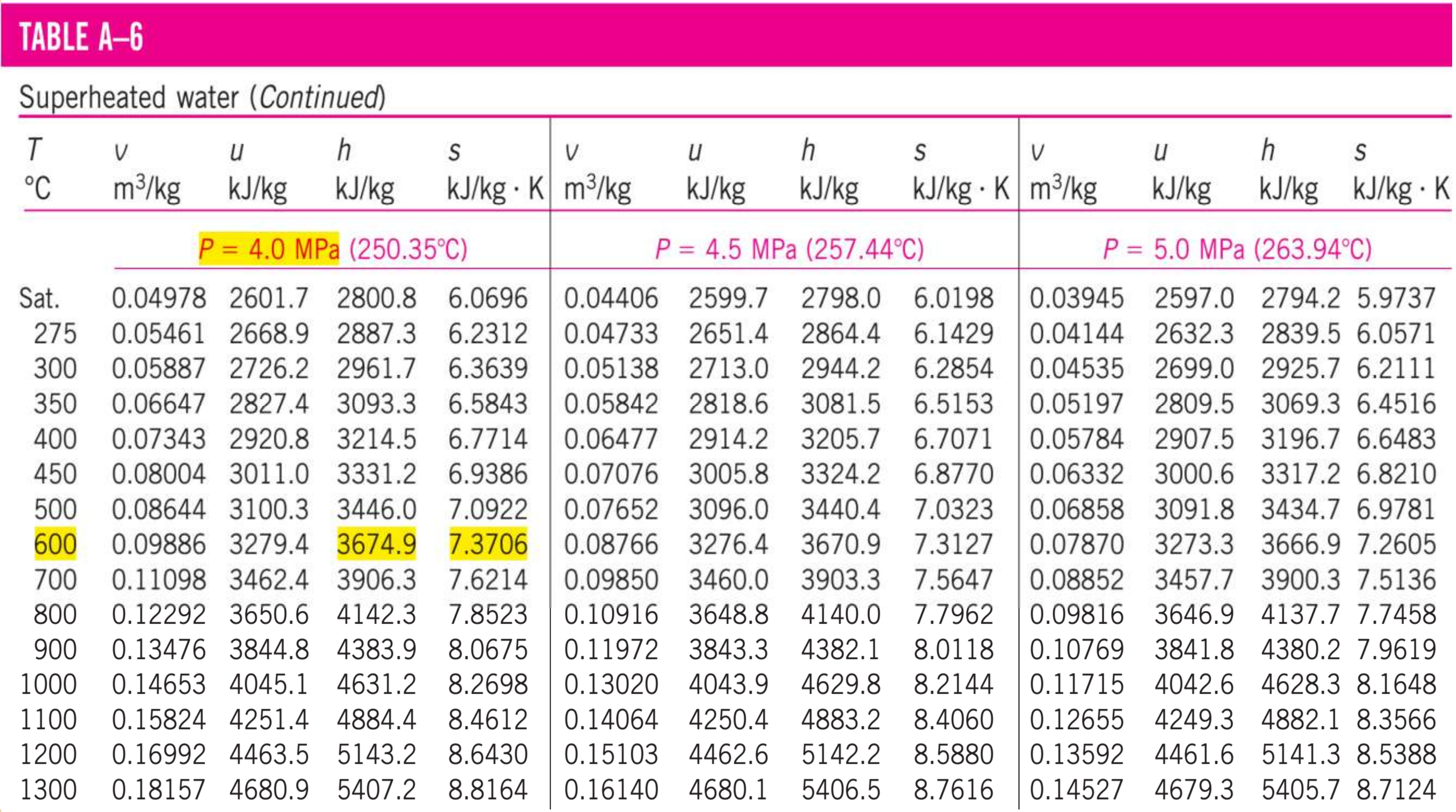


**TABLE A–6**

Superheated water (*Continued*)

| *T* °C | *v* m³/kg | *u* kJ/kg | *h* kJ/kg | *s* kJ/kg · K | *v* m³/kg | *u* kJ/kg | *h* kJ/kg | *s* kJ/kg · K | *v* m³/kg | *u* kJ/kg | *h* kJ/kg | *s* kJ/kg · K |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *P* = 4.0 MPa (250.35°C) | | | | *P* = 4.5 MPa (257.44°C) | | | | *P* = 5.0 MPa (263.94°C) | | | |
| Sat. | 0.04978 | 2601.7 | 2800.8 | 6.0696 | 0.04406 | 2599.7 | 2798.0 | 6.0198 | 0.03945 | 2597.0 | 2794.2 | 5.9737 |
| 275 | 0.05461 | 2668.9 | 2887.3 | 6.2312 | 0.04733 | 2651.4 | 2864.4 | 6.1429 | 0.04144 | 2632.3 | 2839.5 | 6.0571 |
| 300 | 0.05887 | 2726.2 | 2961.7 | 6.3639 | 0.05138 | 2713.0 | 2944.2 | 6.2854 | 0.04535 | 2699.0 | 2925.7 | 6.2111 |
| 350 | 0.06647 | 2827.4 | 3093.3 | 6.5843 | 0.05842 | 2818.6 | 3081.5 | 6.5153 | 0.05197 | 2809.5 | 3069.3 | 6.4516 |
| 400 | 0.07343 | 2920.8 | 3214.5 | 6.7714 | 0.06477 | 2914.2 | 3205.7 | 6.7071 | 0.05784 | 2907.5 | 3196.7 | 6.6483 |
| 450 | 0.08004 | 3011.0 | 3331.2 | 6.9386 | 0.07076 | 3005.8 | 3324.2 | 6.8770 | 0.06332 | 3000.6 | 3317.2 | 6.8210 |
| 500 | 0.08644 | 3100.3 | 3446.0 | 7.0922 | 0.07652 | 3096.0 | 3440.4 | 7.0323 | 0.06858 | 3091.8 | 3434.7 | 6.9781 |
| 600 | 0.09886 | 3279.4 | 3674.9 | 7.3706 | 0.08766 | 3276.4 | 3670.9 | 7.3127 | 0.07870 | 3273.3 | 3666.9 | 7.2605 |
| 700 | 0.11098 | 3462.4 | 3906.3 | 7.6214 | 0.09850 | 3460.0 | 3903.3 | 7.5647 | 0.08852 | 3457.7 | 3900.3 | 7.5136 |
| 800 | 0.12292 | 3650.6 | 4142.3 | 7.8523 | 0.10916 | 3648.8 | 4140.0 | 7.7962 | 0.09816 | 3646.9 | 4137.7 | 7.7458 |
| 900 | 0.13476 | 3844.8 | 4383.9 | 8.0675 | 0.11972 | 3843.3 | 4382.1 | 8.0118 | 0.10769 | 3841.8 | 4380.2 | 7.9619 |
| 1000 | 0.14653 | 4045.1 | 4631.2 | 8.2698 | 0.13020 | 4043.9 | 4629.8 | 8.2144 | 0.11715 | 4042.6 | 4628.3 | 8.1648 |
| 1100 | 0.15824 | 4251.4 | 4884.4 | 8.4612 | 0.14064 | 4250.4 | 4883.2 | 8.4060 | 0.12655 | 4249.3 | 4882.1 | 8.3566 |
| 1200 | 0.16992 | 4463.5 | 5143.2 | 8.6430 | 0.15103 | 4462.6 | 5142.2 | 8.5880 | 0.13592 | 4461.6 | 5141.3 | 8.5388 |
| 1300 | 0.18157 | 4680.9 | 5407.2 | 8.8164 | 0.16140 | 4680.1 | 5406.5 | 8.7616 | 0.14527 | 4679.3 | 5405.7 | 8.7124 |

*And* $P_5 = 4\mathrm{MPa}$ and $h_5 = 3674.9\mathrm{kJ/kg}$

So the steam should be reheated at a pressure of 4 MPa to prevent a moisture content greater than 10.4%.

b) The thermal efficiency is calculated as follows:

State 1: at $P_1 = 10$ kPa

$h_1 = h_f = 191.81$ kJ/kg and $v_1 = v_f = 0.00101\ \text{m}^3/\text{kg}$

State 2: at $P_2 = 15$ MPa and $s_2 = s_1$

$w_{pump} = v_1(P_2 - P_1) = 0.00101 \times (15 \times 10^3 - 10) = 15.14$ kJ/kg

$w_{pump} = h_2 - h_1 \rightarrow h_2 = 191.81 + 15.14 = 206.96$ kJ/kg

State 3: at $P_3 = 15$ MPa and $T_3 = 600°\text{C}$

From superheated steam tables: $h_3 = 3583.1\ \text{kJ/kg}$ and $s_3 = 6.6796\ \text{kJ/kg.K}$

State 4: at $P_4 = 4$ MPa and $s_3 = s_4$

From superheated steam tables: $h_4 = 3155\ \text{kJ/kg}$ and $T_4 = 375.5°\text{C}$

$$q_{in} = (h_3 - h_2) + (h_5 - h_4)$$

$$q_{in} = (3583.1 - 206.95) + (3674.9 - 3155.0) = 3896.1\ \text{kJ/kg}$$

$$q_{out} = h_6 - h_1 = 2335.1 - 191.8 = 2143.3\ \text{kJ/kg}$$

$$\eta_{th} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{2143.3}{3896.1}$$

$$\boldsymbol{\eta_{th} = 45\%}$$ **Ans.**

# Exercises

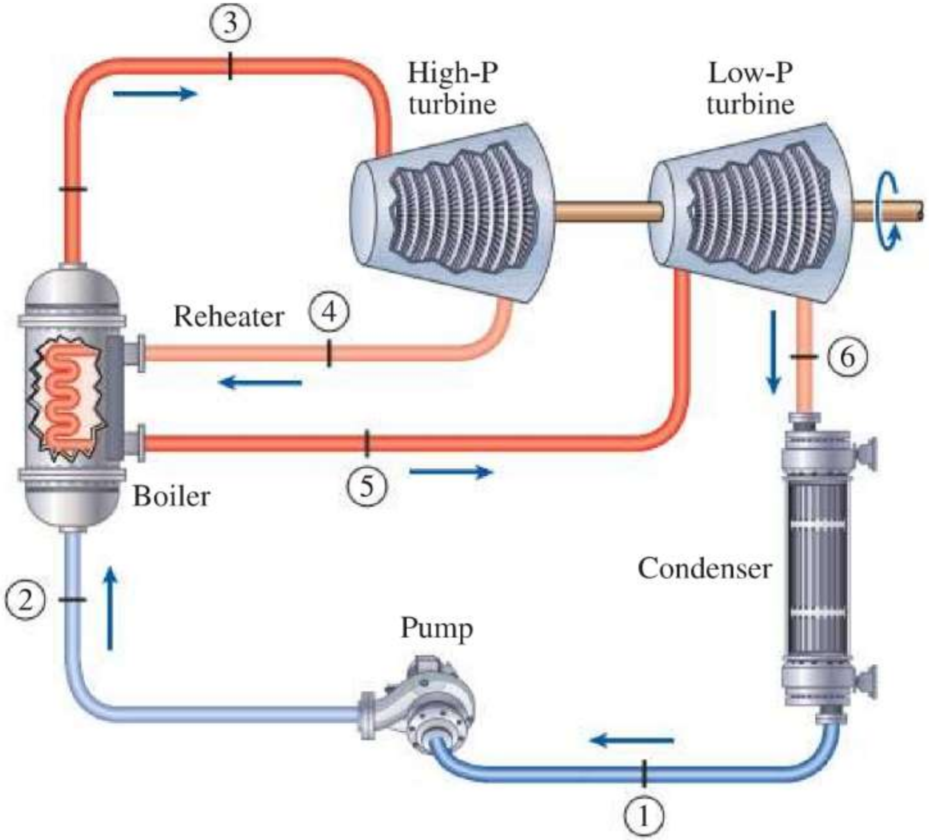
**Problem (5.1):** Consider a steam power plant that operates on a simple ideal Rankine cycle and has a net power output of 45 MW. Steam enters the turbine at 7 MPa and 500°C and is cooled in the condenser at a pressure of 10 kPa by running cooling water from a lake through the tubes of the condenser. Show the cycle on a (*T-S*) diagram with respect to the saturation lines, and determine (a) the thermal efficiency of the cycle (b) the mass flow rate of the steam.

Ans. (38.9%, 36 kg/s)

**Problem (5.2):** A steam power plant operates on the reheat Rankine cycle. Steam enters the high-pressure turbine at 12.5 MPa and 550°C at a rate of 7.7 kg/s and leaves at 2 MPa. Steam is then reheated at constant pressure to 450°C before it expands in the low-pressure turbine. The isentropic efficiencies of the turbine and the pump are 85 percent and 90 percent, respectively. Steam leaves the condenser as a saturated liquid. If the moisture content of the steam at the exit of the turbine is not to exceed 5 percent, determine (a) the condenser pressure (b) the net power output (c) the thermal efficiency.

Ans. (9.73 kPa, 10.2 MW, 36.9%)

problem 5.3 Consider a steam power plant that operates on the ideal reheat Rankine cycle. The plant maintains the boiler at 5000 kPa, the reheat section at 1200 kPa, and the condenser at 20 kPa. The mixture quality at the exit of both turbines is 96 percent. Determine the temperature at the inlet of each turbine and the cycle's thermal efficiency. *Answers:* 327°C, 481°C, 35.0 percent



**Problem (5.4)** Consider a reheat cycle utilizing steam. Steam leaves the boiler and enters the turbine at 4 MPa, 400 °C. After expansion in the turbine to 400 kPa, the steam is reheated to 400 °C and then expanded in the low pressure turbine to 10 kPa. Determine the cycle efficiency. Ans: 35.9%

**Problem (5.5)** Superheated water vapor enters the turbine at 5Mpa and 400 °C. The water leaves the condenser as saturated liquid at a pressure of 30kPa, and the turbine efficiency is 91%. The net power output of the cycle is 100MW. Determine:

a- The thermal efficiency,

b- Mass flow rate of steam in the cycle

**Ans : 29% ; 115.7 kg/sec**