Review

Steam Tables

Throughout the thermodynamics temperature and pressure range, the properties of changeable phase materials (i.e water and refrigerant fluids) cannot be calculated by using mathematical relationships or correlations. Therefore, the properties should tabulated.

For the water vapor (steam), there are two types of tables. Saturated steam tables (Blue zone in figure (1)) used concerned on the mixed (liquid and gas) states. Superheated steam tables (Red zone in Figure (1)) are dealing with the steam on the gaseous state.

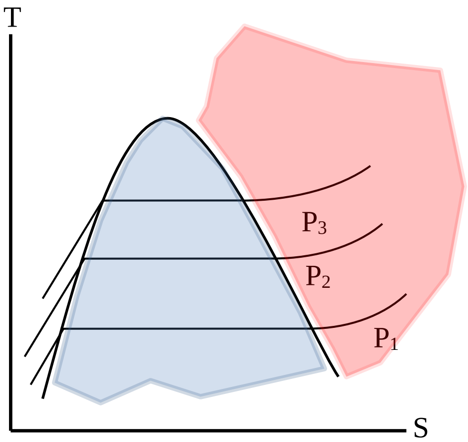


Figure (1)

Dryness Fraction

The state of the fluid can defined by the knowledge of any two independent properties such as P&T (for the superheated steam). However, in the mixed region, the P&T are unable to define the state of the system (for the saturated steam) and hence a third property is required such as specific volume or DRYNESS FRACTION.

Dryness Fraction can defined as the mass of dry saturated vapor in 1 kg of mixture of liquid and vapor.

$$\boldsymbol{x = \frac{m_v}{m_m} = \frac{m_v}{m_v + m_l}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

$\boldsymbol{m_v}: mass\ of\ steam\ (vapore)$

$\boldsymbol{m_l}: mass\ of\ water\ (liquied)$

$\boldsymbol{m_m}: mass\ of\ mixture$

$\boldsymbol{x}: dryness\ fraction$ without unites

For saturated liquid line $x = 0$

For dry saturated vapor $x = 1$

For mixed region $0 < x < 1$

Wetness Fraction: defined as the mass of liquid in 1 kg of a mixture of liquid and vapor.

$$\boldsymbol{Wetness\ Fraction = 1 - Dryness\ Fraction}. \quad \dots\dots\dots (2)$$

For one kilogram of wet vapor, there are x kg of vapor, and (1-x) kg of liquid. Hence to calculate the specific volume at this point;

$$\boldsymbol{v = v_f(1 - x) + v_g x} \quad \dots\dots\dots (3)$$

The volume of the liquid is negligibly small compared to the volume of dry saturated vapor. Moreover, for practical problem;

$$\boldsymbol{v = x v_g} \quad \dots\dots\dots\dots\dots (4)$$

The enthalpy of a wet vapor given by the sum of the enthalpy of the liquid plus the enthalpy of the dry vapor;

$$\boldsymbol{h = (1 - x)h_f + x h_g}$$

$$\boldsymbol{h = h_f + x(h_g - h_f)}$$

$$\boldsymbol{h = h_f + x h_{fg}} \quad \dots\dots\dots\dots\dots\dots (5)$$

Similarly the entropy equation is;

$$\boldsymbol{s = s_f + x s_{fg}} \quad \dots\dots\dots\dots\dots\dots (6)$$

Example (1): Find the dryness fraction, specific volume and, internal energy *of* steam at 7 bar and enthalpy of 2600 kj/kg.

Solution:

from steam tables at P=7 bar

From steam tables:
h_f=697.34 kj/kg
h_{fg}=2064 kj/kg
h_g=2763.5 kj/kg
v_g=0.273 m^3/kg
u_f=696.56 kj/kg
u_g=2572.5 kj/kg

h=2600 kj/kg

Thus $h < h_g$ and the steam is wet

$$\boldsymbol{h = h_f + x h_{fg}} \qquad \dots\dots\dots\dots\dots\dots (5)$$

From equation (5) $x = \frac{h-h_f}{h_{fg}} = \frac{2600-697.34}{2064} = 0.92$

From equation (4) $V = x \times V_g = 0.92 \times 0.273 = 0.251 \ {m^3}/{kg}$

Superheated Vapor (Steam)

For superheated steam, the pressure and temperature are two independent properties. When these properties given then the state of steam fully defined. For example, steam at 2 bar and 200°C is superheated, since the saturation temperature at 2 bar is 120.2°C which is less than the temperature of steam. The degree of superheat is the difference between the saturation temperature and the steam temperature.

The steam properties (v, h, u and, s) in the superheated state are given in a range of pressure and for each pressure there is a range of temperature. See figure (2)

- For constant pressure line the superheated steam properties like (v,u,h,s) will be changed according to its temperature; pointes 1,2,3.
- In the same manner, for constant temperature line the superheated steam properties like (v,u,h,s) will be changed according to its pressure; pointes 4,5,6.

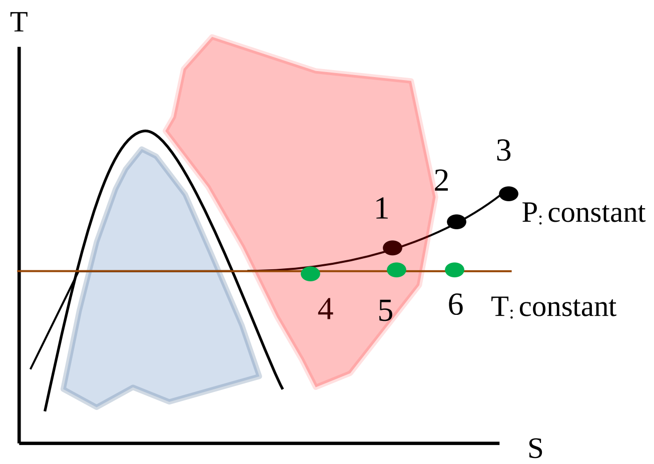


Figure (2)

The heat required to change of phase from the saturated liquid to saturated vapor called LATENT HEAT OF VAPORIZATION. It found that the higher the pressure at which heating takes place the lower the latent heat of vaporization. The saturated vapor usually called dry saturated vapor to declare the fact that there is no liquid.

Vapor Tables

There are three types of vapor:

1. Wet vapor (blue zone).
2. Superheated vapor (red zone).
3. Dry saturated vapor (line separates between blue and red zones).

T-S diagram for Vapor

The T-S diagram of a vapor shown in the figure (3). Lines P_1, P_2, P_3…..P_n are lines of **constant pressure. These lines are incident with** the saturated liquid line in the liquid region. The constant pressure lines are horizontal in the mixture phase region and curve upward in the superheated region. The lines of constant volume are concave down in the mixed phase region and concave up in the superheated region. The slop of the constant volume lines is greater than slop of constant pressure lines in the superheated region.

The entropy of saturated liquid is given the symbol S_f and the entropy of the saturated vapor is given the symbol S_g. S_f and, S_g are found from the tables according to the quality of vapor. The entropy of the wet vapor calculated as follows;

$$\boldsymbol{s = (1 - x)s_f + xs_g}$$

For isentropic process;

$$\boldsymbol{s_1 = s_2}$$

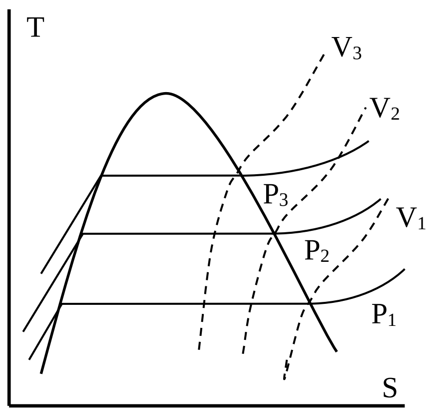


Figure (3)

Tutorial: With the aid of steam tables, complete the following table:

point	P(kpa)	T(°C)	x	v(m³/kg)	h(kj/kg)	s(kj/kg.K)
1		200	0.65			
2	50		1.0			
3	800	500	***			
4	400		***			8.4557
5		1300	***	72.603		
6	75		0.8			

Answer: The completed table is

point	P(kpa)	T(C)	x	v(m³/kg)	h(kj/kg)	s(kj/kg.K)
1	155.38	200	0.65	0.082784	2113.8	4.9967
2	50	81	1.0	3.24	2645.9	7.5939
3	800	500	***	0.44331	3480.6	7.8672
4	400	600	***	1.00555	3702.4	8.4557
5	10	1300	***	72.603	5409.7	11.5810
6	75	91.77	0.8	1.7736	2207.24	6.2076

On the other hand, the above table can completed with the aid of any steam table application for mobile or computer.

Chapter 1: Steam Power Cycles

The heat engines are cyclic devices and that the working fluid of a heat engine returns to its initial state at the end of each cycle. Work done by the working fluid during one part of the cycle and on the working fluid during another part. The difference between these two is the net work delivered by the heat engine. The efficiency of a heat-engine cycle greatly depends on how the individual processes that make up the cycle executed. The net work, thus the cycle efficiency, can maximized by using processes that require the least amount of work and deliver the most that is, by using reversible processes.

Reversible cycles cannot achieved in practice because the irreversibilities associated with each process cannot eliminated. However, reversible cycles provide upper limits on the performance of real cycles. Heat engines that work on reversible cycles serve as models to which actual heat engines can compared. Reversible cycles also serve as starting points in the development of actual cycles and modified as needed to meet certain requirements.

1.1 Rankine Cycle

Rankine cycle was the ideal cycle for vapor power plants. The ideal Rankine cycle does not involve any internal irreversibilities and consists of the following four processes, see figure (2.1):

Isentropic compression in a pump, Process (1-2): Water enters the pump at state 1 as saturated liquid and is compressed isentropically to the operating pressure of the boiler. The water temperature increases somewhat during this isentropic compression process.

Constant pressure heat addition in a boiler, Process (2-3): Water enters the boiler as a compressed liquid at state 2 and leaves as a superheated vapor at state 3. The boiler basically a large heat exchanger where the heat originating from heat source is transferred to the water at constant pressure. The boiler, together with the section where the steam is superheated (the super heater), is often called the steam generator.

Isentropic expansion in a turbine, Process (3-4): The superheated vapor at state 3 enters the turbine, where it expands isentropically and produces work by rotating the connected shaft. The pressure and the temperature of steam drop during this process to the values at state 4, where steam enters the condenser. At this state, steam is usually a saturated liquid–vapor mixture with a high quality.

Constant pressure heat rejection in a condenser, Process (4-1): State 4, steam condensed at constant pressure in the condenser, by rejecting heat to a cooling medium. Steam leaves the condenser as saturated liquid state 1 and enters the pump, to completing the cycle.

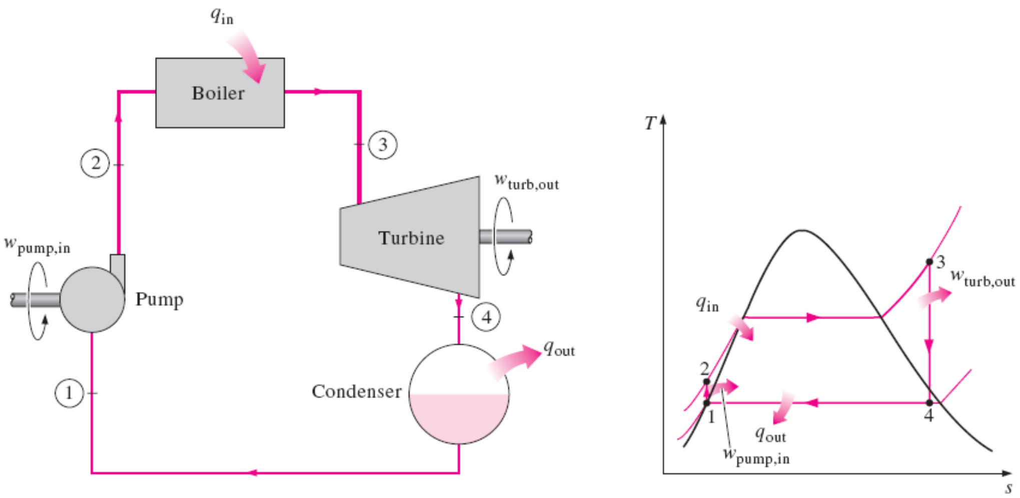


Figure (1.1): Simple Ideal Rankine Cycle

The area under the process curve on a *T-s* diagram represents the heat transfer for internally reversible processes, it can see that the area under process curve 2-3 represents the heat transferred to the water in the boiler and the area under the process curve 4-1 represents the heat rejected in the condenser. The difference between these two (the area enclosed by the cycle curve) is the net work produced during the cycle.

1.2. Energy Analysis of the Cycle

All four components associated with the Rankine cycle (pump, boiler, turbine, and condenser) are steady-flow devices, and thus all four processes that make up the Rankine cycle can be analyzed as steady-flow processes. The kinetic and potential energy changes of the steam are usually small relative to the work and heat transfer terms and therefore usually neglected. Then the steady-flow energy equation per unit mass of steam can applied for every element in the cycle as follows:

$$Q_{add} + h_{in} = W_{done} + h_{out}$$

- For pump: $Q = 0$ & $\boldsymbol{W_{pump} = h_2 - h_1}$ kj/kg
  Or $\boldsymbol{W_{pump} = v_1(P_2 - P_1)}$ kj/kg
  Where $h_1 = h_f$ & $v_1 = v_f$ @ $P = P_1$
- For boiler: $W = 0$ & $\boldsymbol{Q_{in} = h_3 - h_2}$
- For turbine: $Q = 0$ & $\boldsymbol{W_{turbine} = h_3 - h_4}$
- For condenser: $W = 0$ & $\boldsymbol{Q_{out} = h_4 - h_1}$

$$W_{net} = W_{turbine} - W_{pump} = Q_{in} - Q_{out}$$

$$\eta_{th} = \frac{W_{net}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}$$

Example (1.1) Steam power plant operates on a simple ideal Rankine cycle between the pressure limits of **3 MPa** and **50 kPa**. The temperature of the steam at the turbine inlet is **300°C**, and the mass flow rate of steam through the cycle is **35 kg/s**. Show the cycle on a T-s diagram with respect to saturation lines, and determines (a) the thermal efficiency of the cycle and (b) the net power output of the power plant.

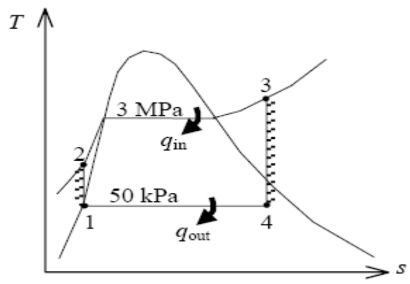
Solution:

$h_1 = h_f = 340.54 \quad kj/kg \quad at \quad P = 50\ kpa$
$v_1 = v_f = 0.00103 \quad m^3/kg \quad at \quad P = 50\ kpa$
$W_{pump} = v(P_2 - P_1) = 0.00103 \times (3000 - 50) \times 1000 = 3.04\ \ kj/kg$
$W_{pump} = h_2 - h_1 \rightarrow h_2 = h_1 + W_{pump} = 340.54 + 3.04\ \ kj/kg$
At $P_3 = 3\ \ Mpa$ & $T_3 = 300\ °C \rightarrow h_3 = 2994.3\ \frac{kj}{kg}$ & $s_3 =$
$6.5412\ \frac{kj}{kg.K}$
At $P_4 = 50\ \ kpa$ & $s_4 = s_3 \quad \rightarrow X_4 = \frac{S_4 - S_f}{S_{fg}} = \frac{6.5412 - 1.0912}{6.5019} =$
0.8382
$h_4 = h_f + X_4 h_{fg} = 340.54 + 0.8382 \times 2304.7 = 2272\ \ kj/kg$
$Q_{in} = h_3 - h_2 = 2994.3 - 343.58 = 2650.6 \qquad kj/kg$
$Q_{out} = h_4 - h_1 = 2272.3 - 340.54 = 1931.8 \qquad kj/kg$

$$W_{net} = Q_{in} - Q_{out} = 2650.6 - 1931.8 = 718.9 \quad kj/kg$$

$$\eta_{th} = 1 - \frac{Q_{out}}{Q_{in}} = 1 - \frac{1931.8}{2650.7} = 27.1 \ \%$$

$$power = m^{\circ} \times W_{net} = 35 \times 718.9 = 25.2 \quad MW$$



1.3. The 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 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 commonly used in modern steam power plants.

Figure (1.2) shows T-s diagram of the ideal reheat Rankine cycle and the schematic of the power plant operating on this cycle. The ideal reheat Rankine cycle differs from the simple ideal Rankine cycle in that the expansion process takes place in two stages. In the first stage (the high-pressure turbine), steam is expanded isentropically to an intermediate pressure and sent back to the boiler where it is reheated at constant pressure, usually to the inlet temperature of the first turbine stage. Steam then expands isentropically in the second stage (low-pressure turbine) to the condenser pressure. Thus, the total heat input and the total turbine work output for a reheat cycle become:

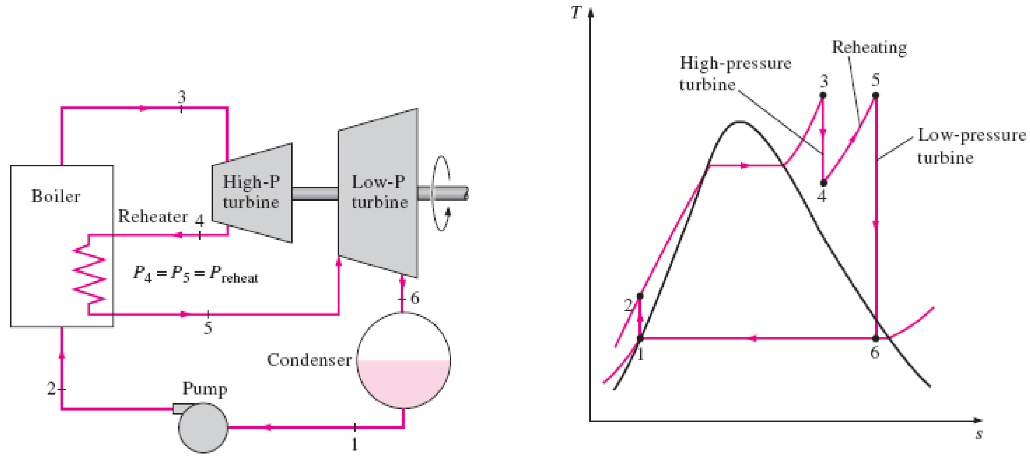


Figure (1.2):Re-heat Rankine Cycle

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

$$W_{out} = W_{turbinI} + W_{turbinII} = (h_3 - h_4) + (h_5 - h_6)$$

The incorporation of the single reheat in a modern power plant improves the cycle efficiency by 4 to 5 percent by increasing the average temperature at which heat transferred to the steam.

The reheat temperatures are very close or equal to the turbine inlet temperature. The optimum reheat pressure is about one-fourth of the maximum cycle pressure. For example, the optimum reheat pressure for a cycle with a boiler pressure of 12 MPa is about 3 MPa.

Example (1.2) 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, 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 and (b) the thermal efficiency of the cycle. Assume the steam reheated to the inlet temperature of the high-pressure turbine.

Solution:

a) State 6: @ 10 kpa & $X_6 = 0.896$

$$S_6 = S_f + X_6 S_{fg} = 0.6492 + 0.896(7.34996) = 7.3688 \quad \frac{kJ}{kg.K}$$

$h_6 = h_f + X_6 h_{fg} = 191.8 + 0.896(2392.1) = 2335.1\ \frac{kJ}{kg}$

Thus, $T_5 = 600$ °C & $S_5 = S_6$

And, $P_5 = 4.0\ Mpa$ & $h_5 = 3674.9\ \frac{kJ}{kg}$

From that steam should be reheated at a pressure of 4 Mpa to prevent a moisture content greater than 10.4 %.

b) The thermal efficiency calculated as follows:

State 1: @ $10\ kpa$

$h_1 = h_f = 191.81\ \frac{kJ}{kg}$ & $v_1 = v_f = 0.00101\ \frac{m^3}{kg}$

State 2: @$15\ Mpa$ & $S_2 = S_1$

$W_{pump} = v_1(P_2 - P_1) = 0.00101 \times (15 \times 10^6 - 10 \times 10^3) = 15.14\ \frac{kj}{kg}$

$W_{pump} = h_2 - h_1 \rightarrow h_2 = 191{,}81 + 15.14 = 206.96\ \frac{kj}{kg}$

State 3: @$15\ Mpa$ & $T_3 = 600$ °C

From steam tables $h_3 = 3583.1\ \frac{kJ}{kg}$ & $S_3 = 6.6796\ \frac{kJ}{kg.K}$

State 4:

@ $4\ Mpa$ & $S_3 = S_4$

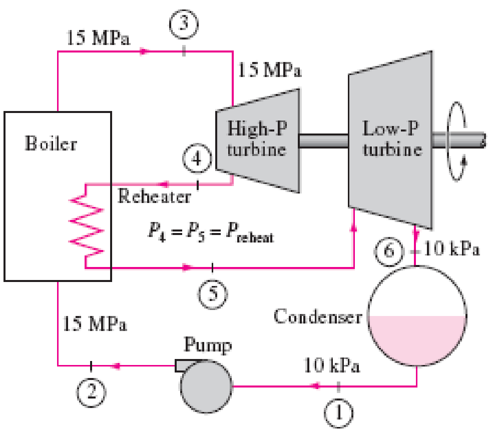
From steam tables $h_4 = 3155.0\ \frac{kJ}{kg}$ & $T_4 = 375.5$ °C

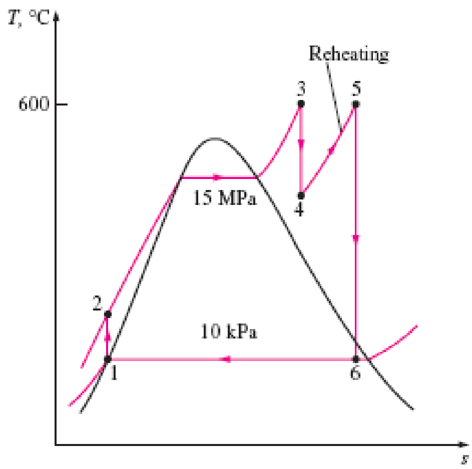
$Q_{in} = (h_3 - h_2) + (h_5 - h_4)$

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

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

$\eta_{th} = 1 - \frac{Q_{out}}{Q_{in}} = 1 - \frac{2143.3}{3896.1} = 45\ \%$

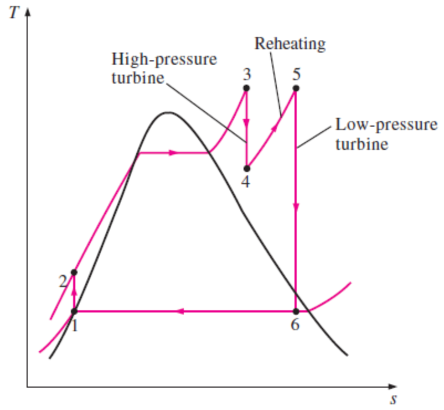




1.3.1. Optimum Efficiency of Re-heat Rankine Cycle

The conditions for optimum efficiency of Reheat Rankine cycle are:

1. The reheat temperature must be equal the maximum temperature in the cycle.
2. The reheat pressure equals one-fourth of the maximum pressure in the cycle.



1.3.2. Advantages Effects of Re-heating:

1. Network done increases.
2. Heat supply increases.
3. Thermal efficiency increases.
4. The turbine exit steam dryness fraction increases, thus moisture decreases, therefore blade erosion becomes minimum, and that lead to increase the life of the turbine.
5. Erosion and corrosion problems in the steam turbine are eliminated /or may be avoided.

1.3.3. Disadvantages of Reheating:

1. Reheating requires more maintenance.
2. The increase in thermal efficiency is not appreciable in comparison to the expenditure incurred in reheating.

1.4. The Regenerative Rankine Cycle

A practical regeneration process in steam power plants accomplished by extracting, or "bleeding," steam from the turbine at various points. This steam, which could have produced more work by expanding further in the turbine, used to heat the feed water instead. The device where the feed water heated by regeneration is called a **regenerator,** or a **feed water heater (FWH).**

Regeneration not only improves cycle efficiency, but also provides a convenient means of deaerating the feed water (removing the air that leaks in at the condenser) to prevent corrosion in the boiler. It also helps control the large volume flow rate of the steam at the final stages of the turbine (due to the large specific volumes at low pressures). Therefore, regeneration has used in all modern steam power plants since its introduction in the early 1920s.

A feed water heater is a heat exchanger, where heat transferred from the steam to the feed water either, by mixing the two fluid streams (open feed water heaters) or without mixing; them (closed feed water heaters).

1.4.1. Open Feed water Heaters: It is an open (or direct-contact) feed water heaters is basically a mixing chamber, where the steam extracted from the turbine mixes with the feed water exiting the pump. Ideally, the mixture leaves the heater as a **saturated liquid** at the heater pressure. The schematic of a steam power plant with one open feed water heater (also called single-stage regenerative cycle) and the T-s diagram of the cycle shown in figure (1.4).

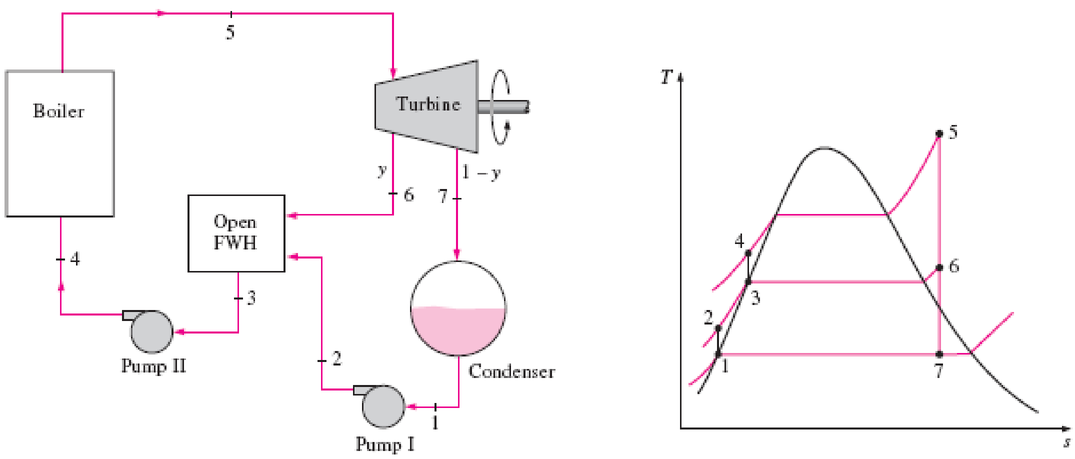


Figure (1.4): Regenerative Rankine Cycle (open feed water heater)

In an ideal regenerative Rankine cycle, steam enters the turbine at the boiler pressure (state 5) and expands isentropically to an intermediate pressure (state 6). Some steam extracted at this state and routed to the feed water heater, while the remaining steam continues to expand isentropically to the condenser pressure (state 7). This steam leaves the condenser as a saturated liquid at the condenser pressure (state 1). The condensed water, which also called the *feed water*, then enters an isentropic pump, where it compressed to the feed water heater pressure (state 2) and routed to the feed water heater, where it mixes with the steam extracted from the turbine. The fraction of the steam extracted is such that the mixture leaves the heater as a saturated liquid at the heater pressure (state 3). A second pump raises the pressure of the water to the boiler pressure (state 4). The cycle completed by heating the water in the boiler to the turbine inlet state (state 5).

In the analysis of steam power plants, it is more convenient to work with quantities expressed per unit mass of the steam flowing through the boiler. For each 1 kg of steam leaving the boiler, (y) kg expands partially in the turbine and is extracted at state 6. The remaining (1-y) kg expands completely to the condenser pressure. Therefore, the mass flow rates are different in different components. If the mass flow rate through the boiler is m°, for example, it is $(1-y)\times m^{\circ}$ through the condenser. This aspect of the regenerative Rankine cycle should considered in the analysis of the cycle as well as in the interpretation of the areas on the T-s diagram. The heat and work interactions of a regenerative Rankine cycle with one feed water heater can expressed per unit mass of steam flowing through the boiler as follows:

$$Q_{add} = h_5 - h_4$$
$$Q_{rej} = (1-y)\times(h_7 - h_1)$$
$$W_{tur,out} = W_{Tur,\mathrm{I}} + (1-y)\times W_{Tur,II}$$
$$W_{tur,out} = (h_5 - h_6) + (1-y)\times(h_6 - h_7)$$

Where,

$$W_{Tur,\mathrm{I}} = h_5 - h_6$$
$$W_{Tur,\mathrm{II}} = h_6 - h_7$$

$$W_{pump,in} = (1-y)\times W_{pump,\mathrm{I}} + W_{pump,\mathrm{II}}$$
$$W_{pump,in} = (1-y)\times(h_2 - h_1) + (h_4 - h_3)$$

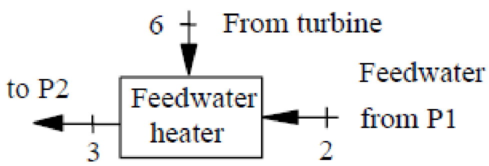
Where,

$$W_{pump,\text{I}} = v_1(P_2 - P_1) = h_2 - h_1$$
$$W_{pump,\text{II}} = v_3(P_4 - P_3) = h_4 - h_3$$

$$y = \mathring{m}_6/\mathring{m}_5$$

The thermal efficiency of the Rankine cycle increases because of regeneration. The cycle efficiency increases further as the number of feed water heaters is increased. The optimum number of feed water heaters is determined from economic considerations.

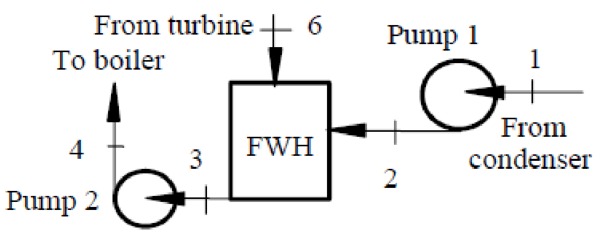
Example: (1.3) An open feed water heater in a regenerative steam power cycle receives 20 kg/s of water at 100°C, 2 MPa. The extraction steam from the turbine enters the heater at 2 MPa, 275°C, and all the feed water leaves as saturated liquid. What is the required mass flow rate of the extraction steam?



Solution:

$$\mathring{m}_2 + \mathring{m}_6 = \mathring{m}_3$$
$$\mathring{m}_2 h_2 + \mathring{m}_6 h_6 = \mathring{m}_3 h_3 = (\mathring{m}_2 + \mathring{m}_6) h_3$$
$$h_2 = 420.45\ kj/kg\ \ ,\ \ h_3 = 908.77\ \ kj/kg\quad \&\ \ h_6 = 2963\ kj/kg$$
$$\mathring{m}_6 = \mathring{m}_2 \times \frac{h_3 - h_2}{h_6 - h_3} = 20 \times \frac{908.77 - 420.45}{2963 - 908.77} = 4.754\ kg/s$$

Example: (1.4) A power plant with one open feed water heater has a condenser temperature of **45°C**, a maximum pressure of **5 MPa**, and boiler exit temperature of **900°C**. Extraction steam at **1 MPa** to the feed water heater is mixed with the feed water line so the exit is saturated liquid into the second pump. Find the fraction of extraction steam flow and the two specific pump work inputs.



State out of boiler 5: $h_5 = 4378.82 \quad kJ/kg, \quad s_5 = 7.9593 \ kJ/kg.K$

C.V. Turbine reversible, adiabatic: $s_7 = s_6 = s_5$

State 6: P6 , s_6 => $h_6 = 3640.6 \frac{kJ}{kg}, \quad T_6 = 574$ °C

Pump P1

$$W_{P1} = h_2 - h_1 = v_1(P_2 - P_1) = 0.00101 \times (1000 - 9.6) = 1.0 \ kJ/kg$$

=> $h_2 = h_1 + W_{P1} = 188.42 + 1.0 = 189.42 \quad kJ/kg$

Feedwater heater: Call $\frac{\mathring{m}_6}{\mathring{m}} = y$ (the extraction fraction)

Energy Eq.: $(1 - y) \times h_2 + y\, h_6 = 1 \times h_3$

$$y = \frac{(h_3 - h_2)}{(h_6 - h_2)} = \frac{(762.79 - 189.42)}{(3640.6 - 189.42)} = 0.1661$$

Pump P2

$$W_{P2} = h_4 - h_3 = v_3(P_4 - P_3) = 0.001127 \times (5000 - 1000) = 4.5 \ kJ/kg$$

Example: (1.5) Consider a steam power plant operating on the ideal regenerative Rankine cycle with one open feed water heater. Steam enter the turbine at **15 MPa** and, **600°C** and, condensed in the condenser at a pressure of **10 kPa**. Some steam leaves the turbine at a pressure of **1.2 MPa** and enters the open feed water heater. Determine the fraction of steam extracted from the turbine and the thermal efficiency of the cycle.

Solution:

State 1:

$$@10 \ kPa \ \& \ saturated \ liquid \ h_1 = h_f = 191.81 \ \frac{kJ}{kg} \ \& \ V_1 = v_f = 0.00101 \ \frac{m^3}{kg}$$

State 2:

$@1.2 \ MPa \ \& \ S_2 = S_1$

$$W_{pump,\mathrm{I}} = v_1(P_2 - P_1) = 0.00101 \times (1.2 \times 10^6 - 10 \times 10^3) = 1.2 \ kJ/kg$$

$$W_{pump,\mathrm{I}} = h_2 - h_1 \rightarrow h_2 = 191.81 + 1.2 = 193.01 \ kJ/kg$$

State 3: $@1.2\ Mpa\ \&\ saturated\ liquid$

$v_3 = v_f = 0.001138\ m^3/kg\ \ \&\ h_3 = h_f = 798.33\ \frac{\text{kJ}}{\text{kg}}$

State 4: $@15\ Mpa\ \&\ S_4 = S_3$

$$W_{pump,\text{II}} = v_3(P_4 - P_3) = 0.001138 \times (15 \times 10^6 - 1.2 \times 10^6)$$
$$= 15.7\ \ kJ/kg$$

$$W_{pump,\text{II}} = h_4 - h_3 \rightarrow h_4 = 798.33 + 15.7 = 814.03\ \ kJ/kg$$

State 5: $@15\ Mpa\ \&\ T_5 = 600\ ℃$

Thus, $h_5 = 3583.1 \frac{kJ}{kg}\ \ \&\ \ S_5 = 6.6796\ \frac{kJ}{kg.K}$

State 6: $@\ 1.2\ Mpa\ \&\ S_6 = S_5$

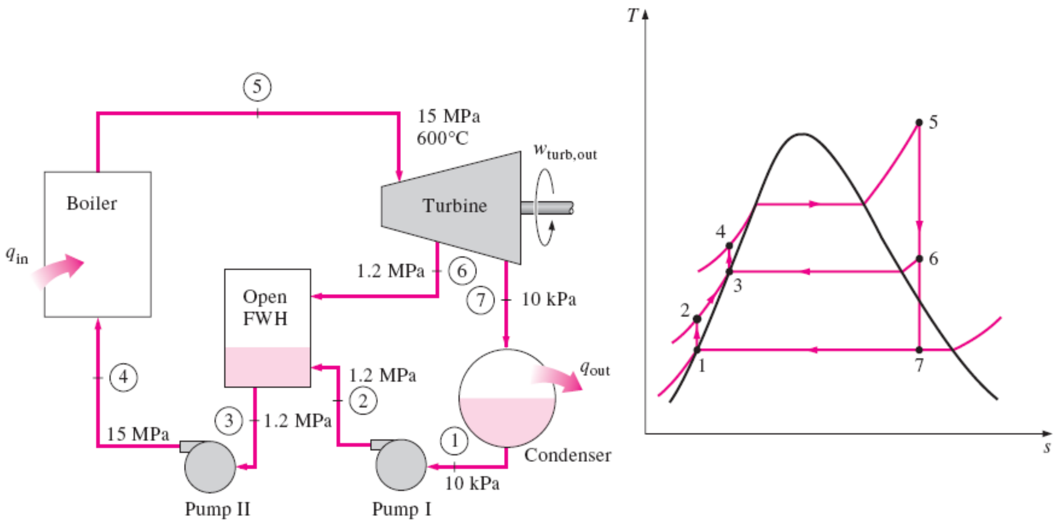
Thus, $h_6 = 2860.2\ \frac{kJ}{kg}\ \ \ \&\ T_6 = 218.4\ ℃$

State 7: $@10\ kpa\ \ \&\ S_7 = S_5$

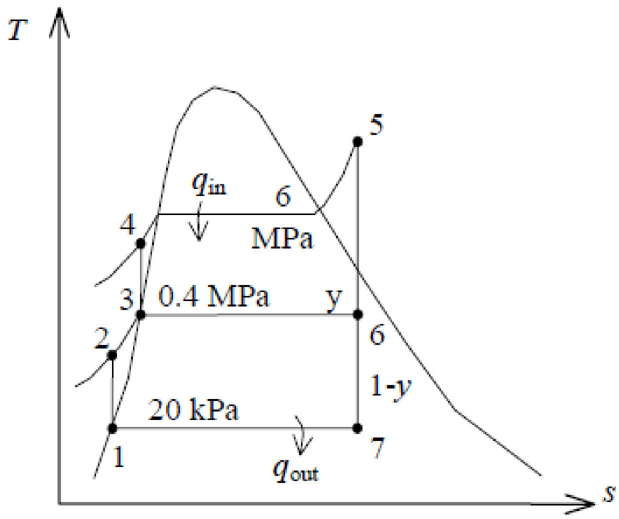
$$X_7 = \frac{S_7 - S_f}{S_{fg}} = \frac{6.679 - 0.6492}{7.4996} = 0.8041$$
$$h_7 = h_f + X_7 h_{fg} = 191.81 + 0.8041 \times 2392.1 = 2115.3\ \ kJ/kg$$

The energy analysis of open feed water heaters is identical to the energy analysis of mixing chambers. The feed water heaters generally well insulated($Q = 0$), and they do not involve any work interactions($W = 0$). The energy balance of the feed water heater is:

$$E_{in} = E_{out} \rightarrow \sum\nolimits_{in} m^o h = \sum\nolimits_{out} m^o h$$
$$yh_6 + (1 - y) \times h_2 = 1 \times h_3 \rightarrow y = \frac{h_3 - h_2}{h_6 - h_2} = \frac{798.33 - 193.01}{2860.2 - 193.01} = 0.227$$
$$Q_{add} = h_5 - h_4 = 3583.1 - 814.03 = 2769.1\ \ kJ/kg$$
$$Q_{rej} = (1 - y)(h_7 - h_1) = (1 - 0.227) \times (2115.3 - 191.81)$$
$$= 1486.9\ \ kJ/kg$$
$$\eta_{th} = 1 - \frac{Q_{rej}}{Q_{add}} = 1 - \frac{1486.9}{2769.1} = 46.29\ \%$$



Example (1.6): A steam power plant operates on an ideal regenerative Rankine cycle. Steam enter the turbine at **6 MPa** and, **450°C** and, condensed in the condenser at **20 kPa**. Steam extracted from the turbine at **0.4 MPa** to heat the feed water in an open feed water heater. Water leaves the feed water heater as a saturated liquid. Show the cycle on a *T*-*s* diagram, and determine (*a*) the net work output per kilogram of steam flowing through the boiler and (*b*) the thermal efficiency of the cycle.



Solution:

(a) From steam tables:

$@\,p = 20\ kPa \qquad h_1 = h_f = 251.42\ kj/kg \qquad \&\ v_1 = v_f = 0.001017\ m^3/kg$

$W_{p1} = v_1(p_2 - p_1) = (0.001017) \times (0.4 \times 10^6 - 20 \times 10^3) = 0.39\ kj/kg$

$h_2 = h_1 + W_{p1} = 251.42 + 0.39 = 251.81\ kj/kg$

$@p_3 = 0.4\ Mpa \ \Longrightarrow h_3 = h_f = 604.66\ kj/kg \quad \& \ v_3 = v_f = 0.001084\ m^3/kg$

$W_{p2} = v_3(p_4 - p_3) = (0.001084) \times (6 \times 10^6 - 0.4 \times 10^6) = 6.07\ kj/kg$

$h_4 = h_3 + W_{p2} = 604.66 + 6.07 = 610.73\ kj/kg$

$@p_5 = 6\ Mpa\ \& \ T_5 = 450℃ \ \Longrightarrow h_5 = 3302.9\ kj/kg \quad \& \ s_5 = 6.7219\ kj/kg\,.K$

$@p_6 = 0.4\ Mpa\ \&\ s_6 = s_5 \quad \Longrightarrow x_6 = \frac{s_6 - s_f}{s_{fg}} = \frac{6.7219 - 1.7765}{5.1191} = 0.9661$

Also, $h_6 = h_f + x_6 . h_{fg} = 604.66 + (0.9661) \times (2133.4) = 2665.7\ \ kj/kg$

$@p_7 = 20\ kPa\ \&\ s_7 = s_5 \quad \Longrightarrow x_7 = \frac{s_7 - s_f}{s_{fg}} = \frac{6.7219 - 0.832}{7.0752} = 0.8325$

Also, $h_7 = h_f + x_7 . h_{fg} = 251.42 + (0.8325) \times (2357.5) = 2214.0\ \ kj/kg$

The fraction of steam extracted is determined from the steady flow energy balance equation applied to the feed water heater.

$\sum E_{in} = \sum E_{out} \quad \Rightarrow \quad m_6^\circ h_6 + m_2^\circ h_2 = m_3^\circ h_3 \quad \Rightarrow \quad y h_6 + (1-y) h_2 = 1 \times h_3$

Where y is the fraction of steam extracted from the turbine $y = \frac{m_6^\circ}{m_5^\circ}$

$y = \frac{h_3 - h_2}{h_6 - h_2} = \frac{601.73 - 251.81}{2665.7 - 251.81} = 0.145$

$Q_{in} = h_5 - h_4 = 3302.9 - 610.73 = 2692.2\ kj/kg$

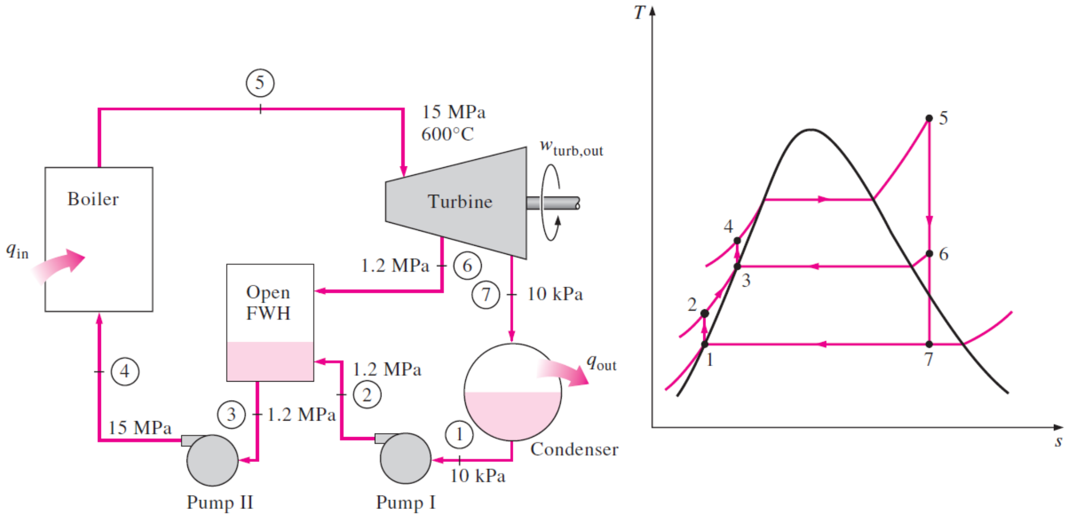
$Q_{out} = (1-y)(h_7 - h_1) = (1 - 0.145)(2214 - 251.42) = 1678\ \ kj/kg$

$W_{net} = Q_{in} - Q_{out} = 2692.2 - 1675.4 \ = 1016.8\ \ kj/kg$

(b) The thermal efficiency is determined as:

$\eta_{th} = 1 - \frac{Q_{out}}{Q_{in}} = 1 - \frac{1678}{2692.2} = 37.7\ \%$

Example (1.7): Consider a steam power plant operating on the ideal regenerative Rankine cycle with one open feed water heater. Steam enters the turbine at 15 MPa and, 600°C and, condensed in the condenser at a pressure of 10 kPa. Some steam leaves the turbine at a pressure of 1.2 MPa and enters the open feed water heater. Determine the fraction of steam extracted from the turbine and the thermal efficiency of the cycle.



Solution:

State 1: @ $P_1 = 10\,kPa$ & *saturated liquid* $h_1 = h_f = 191.81\ kj/kg$

And $v_1 = v_f = 0.00101\ \ m^3/kg$

State 2: @ $P_2 = 1.2\,MPa$ & $s_2 = s_1$

$$W_{p1} = v_1(P_2 - P_1) = (0.00101) \times (1.2 \times 10^6 - 10 \times 10^3)$$
$$= 1.2\ kj/kg$$
$$h_2 = h_1 + W_{p1} = 191.81 + 1.2 = 193.01\ \ kj/kg$$

State 3: @ $P_3 = 1.2\,MPa$ & *saturated liquid* $h_3 = h_f = 798.33\ kj/kg$

And $v_3 = v_f = 0.001138\ \ m^3/kg$

State 4: @ $P_4 = 15\,MPa$ & $s_4 = s_3$

$$W_{p2} = v_3(P_4 - P_3) = (0.001138) \times (15 \times 10^6 - 1.2 \times 10^6)$$
$$= 15.7\ kj/kg$$
$$h_4 = h_3 + W_{p2} = 798.33 + 15.7 = 814.03\ \ kj/kg$$

State 5: @ $P_5 = 15\,MPa$ & $T_5 = 600\,℃$ $h_5 = 3583.1\ \ kj/kg$

and $s_5 = 6.6796\ \ kj/kg.K$

State 6: @ $P_6 = 1.2\,MPa$ & $s_6 = s_5$

$h_6 = 2860.2\ kj/kg$ & $T_6 = 218.4℃$

State 7: @ $P_7 = 10\,kPa$ & $s_7 = s_5$

$$x_7 = \frac{s_7 - s_f}{s_{fg}} = \frac{6.6796 - 0.6492}{7.4996} = 0.8041$$

$$h_7 = h_f + x_7 \times h_{fg} = 191.81 + 0.8041 \times 2392.1 = 2115.3\ kj/kg$$

To get the fraction of steam extracted from the open feed water heater apply the energy-balanced equation across it as follows:

$$\sum E_{in} = \sum E_{out}$$
$$y \times h_6 + (1 - y) \times h_2 = 1 \times h_3$$

Where $y = \frac{\mathring{m}_6}{\mathring{m}_5}$

$y = \frac{h_3 - h_2}{h_6 - h_2} = \frac{798.33 - 193.01}{2860.2 - 193.01} = 0.227$

Then $Q_{in} = h_5 - h_4 = 3583.1 - 814.03 = 2769.1\ kj/kg$

$Q_{out} = (1 - y) \times (h_7 - h_1)$

$Q_{out} = (1 - 0.227) \times (2115.3 - 191.81) = 1486.9\ kj/kg$

$$\eta_{th} = 1 - \frac{Q_{out}}{Q_{in}} = 1 - \frac{1486.9}{2769.1} = 46.3\ \%$$

1.4.2. Closed Feed water Heaters: It is another type of feed water heater used in steam power plants, in which heat transferred from the extracted steam to the feed water without any mixing taking place. The two streams now can be at different pressures, since they do not mix. The schematic of a steam power plant with one closed feed water heater and the *T-s* diagram of the cycle shown in figure (1.5).

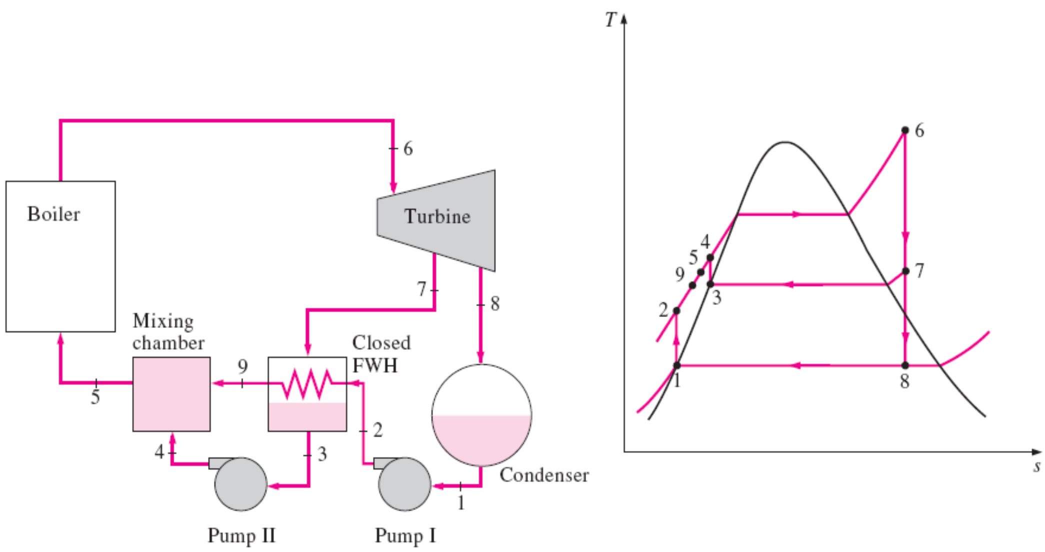


Figure (1.5): Regenerative Rankine Cycle (closed feedwater heater)

Comparison between the Open and Closed Feed Water Heater

The open and closed feedwater heaters can compared as follows:

- Open feedwater heaters are simple and inexpensive and have good heat transfer characteristics.
- The closed feedwater heaters are more complex because of the internal tubing network, and thus they are more expensive.

- Heat transfer in closed feedwater heaters is also less effective since the two streams are not allowed to be in direct contact.
- Closed feedwater heaters do not require a separate pump for each heater since the extracted steam and the feedwater can be at different pressures.

Most steam power plants use a combination of open and closed feedwater heaters.

Exercises (1)

Problem (1.1) Consider a solar-energy-powered ideal Rankine, see figure (1), this cycle uses water as the working fluid. Saturated vapor leaves the solar collector at **175°C**, and the condenser pressure is **10 kPa**. Determine the thermal efficiency of this cycle. [reference: Fundamentals of Thermodynamics by Borgnakke & Sonntag prob.11.14,p-460].(Ans.26.1 %).

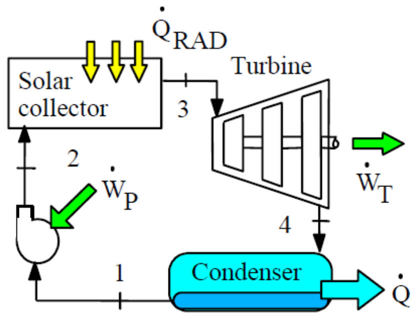


Figure (1): Simple Rankine Cycle.

Problem (1.2) A steam power plant working according to simple Rankine cycle. It has a high pressure of **3 MPa** and it maintains **60ºC** in the condenser. A condensing turbine is used, but the quality should not be lower than **90%** at any state in the turbine. Find the cycle efficiency. [reference: Fundamentals of Thermodynamics by Borgnakke & Sonntag prob.11.18,p-460].(Ans.33.2 %).

Problem (1.3) A smaller power plant as shown in figure (2), produces steam at **3 MPa**, **600ºC** in the boiler. It keeps the condenser at **45ºC** by transfer of **10 MW** out as heat transfer. The first turbine section expands to **500 kPa** and then flow reheated followed by the expansion in the low-pressure turbine. Find the reheat temperature so the turbine output is saturated vapor. For this reheat, find the total turbine power output and the boiler heat transfer. [reference: Fundamentals of Thermodynamics by Borgnakke & Sonntag prob.11.33,p-462].(Ans.529 ºC, 6487 kW, 16475 kW).

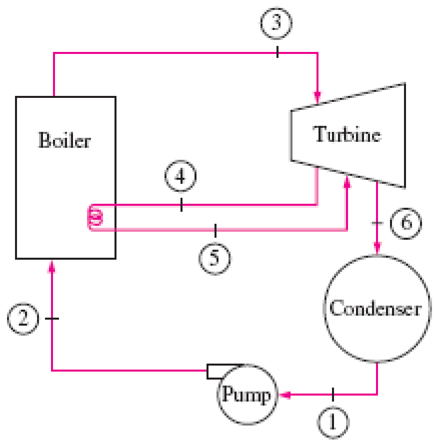
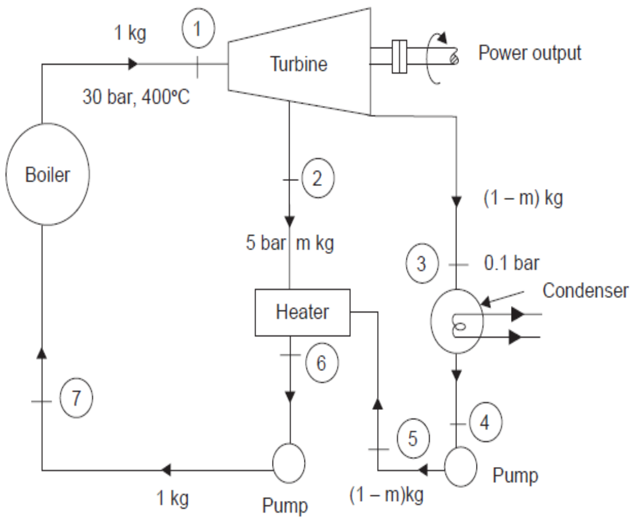


Figure (2): Rankine with Re-heat Cycle.

Problem (1.4) Consider an ideal steam reheat cycle, see figure (2), where steam enters the high-pressure turbine at **3.0 MPa**, **400°C**, and then expands to **0.8 MPa**. Its then reheated to **400°C** and expands to **10 kPa** in the low-pressure turbine. Calculate the cycle thermal efficiency and the moisture content of the steam leaving the low-pressure turbine. [reference: Fundamentals of Thermodynamics by Borgnakke & Sonntag prob.11.36,p-462].(Ans.36.2 %, 0.923).

Problem (1.5) In a single-heater regenerative cycle the steam enters the turbine at **30 bar**, **400°C** and the exhaust pressure is **0.10** bar. The feed water heater is a direct contact type which operates at **5 bar**. Find:
(i) The efficiency and the steam rate of the cycle.
(ii) The increase in mean temperature of heat addition, efficiency and steam rate as compared to the Rankine cycle (without regeneration).
Pump work may neglected.

Ans.: (i) $\eta_{th} = 36.08\%$.



Problem (1.6) A steam power plant operates on an ideal regenerative Rankine cycle. Steam enters the turbine at **6 MPa** and **450°C** and is condensed in the condenser at **20 kPa**. Steam is extracted from the turbine at **0.4 MPa** to heat the feedwater in an open feedwater heater. Water leaves the feedwater heater as a saturated liquid. Show the cycle on a *T-s* diagram, and determine (*a*) the net work output per kilogram of steam flowing through the boiler and (*b*) the thermal efficiency of the cycle. [*reference: Thermodynamics an Engineering Approach, by Michael A. Boles, prob. 10-44,p-594*].

Ans.*:* (*a*) 1017 kJ/kg, (*b*) 37.8 %

Problem (1.7) 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 saturation lines, and determine (*a*) the thermal efficiency of the cycle, and (*b*) the mass flow rate of the steam. [*reference: Thermodynamics an Engineering Approach, by Michael A. Boles, prob. 10-22,p-591*].

Ans.*:* (*a*) 38.9 percent, (*b*) 36 kg/s

Problem (1.8) Consider a regenerative cycle using steam as the working fluid. Steam leaves the boiler and enters the turbine at **4 MPa**, **400ºC**. After expansion to **400 kPa**, some of the steam is extracted from the turbine for the purpose of heating the feedwater in an open feedwater heater. The pressure in the feedwater heater is **400 kPa** and the water leaving it is saturated liquid at **400 kPa**. The steam not extracted expands to **10 kPa**. Determine the cycle efficiency.

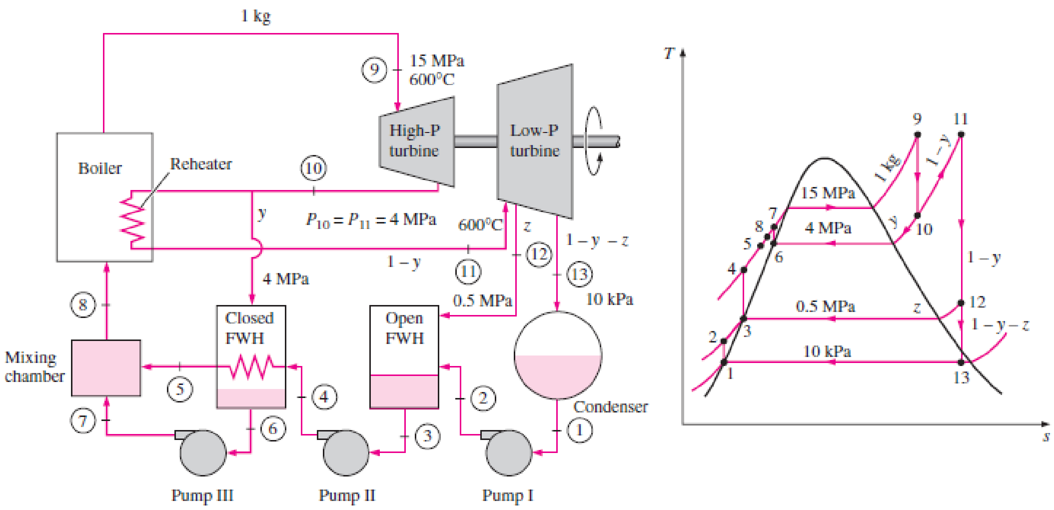
Ans.: 37.5%

Test Example

ايضاح: الطالب الذي لديه القدرة على حل هذا النوع من المسائل يكون مؤهل لخوض الاختبار بمادة الفصل.

The Ideal Reheat–Regenerative Rankine Cycle

Solved problem: Consider a steam power plant that operates on an ideal reheat–regenerative Rankine cycle with one open feed water heater, one closed feed water heater, and one reheated. Steam enters the turbine at **15 MPa** and, **600°C** and, condensed in the condenser at a pressure of **10 kPa**. Some steam is extracted from the turbine at **4 MPa** for the closed feed water heater, and the remaining steam is reheated at the same pressure to **600°C**. The extracted steam completely condensed in the heater and pumped to **15 MPa** before it mixes with the feed water at the same pressure. Steam for the open feed water heater extracted from the low-pressure turbine at a pressure of **0.5 MPa**. Determine the fractions of steam extracted from the turbine as well as the thermal efficiency of the cycle.



The enthalpies at the various states and the pump work per unite mass of the fluid following through them are:

h_1=191.81 kj/kg	h_6=1087.4 kj/kg	h_{12}=3014.8 kj/kg
h_2=192.3 kj/kg	h_7=1101.2 kj/kg	h_{13}=2335.7 kj/kg
h_3=640.09 kj/kg	h_8= kj/kg	W_{P1}=0.49 kj/kg
h_4=643.92 kj/kg	h_9=3155 kj/kg	W_{P2}=3.83 kj/kg
h_5=1087.4 kj/kg	h_{10}=3155 kj/kg	W_{P3}=13.77 kj/kg

The fractions extracted are determined from the mass and energy balanced of the feed water heaters:

1. **For closed feed water heater**:

$\sum E_{in} = \sum E_{out} \implies yh_{10} + (1-y)h_4 = (1-y)h_5 + yh_6$

$y = \frac{h_5 - h_4}{(h_{10}-h_6)+(h_5-h_4)} = \frac{1087.4-643.92}{(3155-1087.4)+(1087.4-643.92)} = 0.1766$

2. **For open feed water heater**:

$\sum E_{in} = \sum E_{out} \implies yh_{12} + (1-y-z)h_2 = (1-y)h_3$

$z = \frac{(1-y)(h_3-h_2)}{(h_{12}-h_2)} = \frac{(1-0.1766)(640.09-192.3)}{3014.8-192.3} = 0.1306$

The enthalpy at state 8 is determined by applying the mass and energy equation to the mixing chamber:

$\sum E_{in} = \sum E_{out} \implies 1 \times h_8 = (1-y)h_5 + yh_7$

$h_8 = (1-0.1766) \times 1087.4 + 0.1766 \times 1101.2 = 1089.8\ kj/kg$

$Q_{in} = (h_9 - h_8) + (1-y)(h_{11} - h_{10})$

$Q_{in} = (3583.1 - 1089.8) + (1-0.1766)(3674.9-3155) = 2921.4\ kj/kg$

$Q_{out} = (1-y-z) \times (h_{13} - h_1)$

$Q_{out} = (1-0.1766-0.1306)(2335.7-191.81) = 1485.3\ kj/kg$

Finally

$$\eta_{th} = 1 - \frac{Q_{out}}{Q_{in}} = 1 - \frac{1485.3}{2921.4} = 49.2\ \%$$

Problem (1.9) A steam power plant operates on the reheat regenerative Rankine cycle with a closed feed water heater. Steam enter the turbine at 12.5 MPa and, 550°C at a rate of 24 kg/s and, condensed in the condenser at a pressure of 20 kPa. Steam is reheated at 5 MPa to 550°C. Some steam extracted from the low-pressure turbine at 1.0 MPa, then completely condensed in the closed feed water heater, and pumped to 12.5 MPa before it mixes with the feed water at the same pressure. Assuming an isentropic efficiency of 88 percent for both the turbine and the pump, determine (*a*) the temperature of the steam at the inlet of the closed feed water heater, (*b*) the mass flow rate of the steam extracted from the turbine for the closed feed water heater, (*c*) the net power output, and (*d*) the thermal efficiency.

Ans.: (*a*) 328°C, (*b*) 4.29 kg/s, (*c*) 28.6 MW, (*d*) 39.3 %