ENGINEERING COUNCIL

CERTIFICATE LEVEL

THERMODYNAMIC, FLUID AND PROCESS ENGINEERING C106

TUTORIAL 5 – STEAM POWER CYCLES

When you have completed this tutorial you should be able to do the following.

- Explain and solve the Carnot steam cycle.
- Explain and solve the Rankine steam power cycle.

It is unlikely that the syllabus intends you to study advanced steam cycles but these may be found in other tutorials on the web site.

You must fully understand the properties of steam and how to use the thermodynamic tables and charts. This is covered in previous tutorials.

1. STEAM CYCLES

1.1 THE CARNOT STEAM CYCLE

In previous tutorials you learned that a Carnot cycle gave the highest thermal efficiency possible for an engine working between two temperatures. The cycle consisted of isothermal heating and cooling and reversible adiabatic expansion and compression.

Consider a cycle that uses vapour throughout. Evaporation and condensation at constant pressure is also constant temperature. Isothermal heating and cooling is theoretically possible. The cycle would consist of the same 4 processes as before only this time each process would be carried out in a separate steady flow plant item with the vapour flowing from one to the other in a closed loop as shown below.

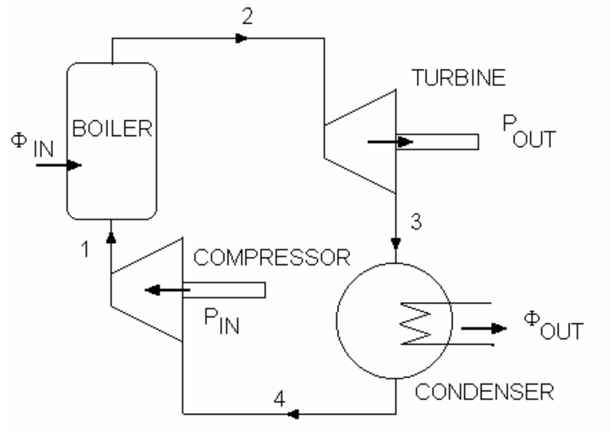

Fig. 1

The four processes are:

1 - 2 Evaporation at constant pressure and temperature requiring heat input.
2 - 3 Reversible adiabatic expansion in the turbine giving power output.
3 - 4 Cooling and condensing at constant pressure and temperature in the condenser requiring heat output.
4 - 1 Reversible adiabatic compression requiring power input.

In order that no temperature changes occur in the evaporator and condenser, the vapour must be wet at inlet and outlet. Over-cooling will produce liquid at temperatures below the saturation temperature and over-heating will superheat it beyond the saturation temperature. The cycle will be a rectangle on the T-s diagram and as shown on the h-s diagram.

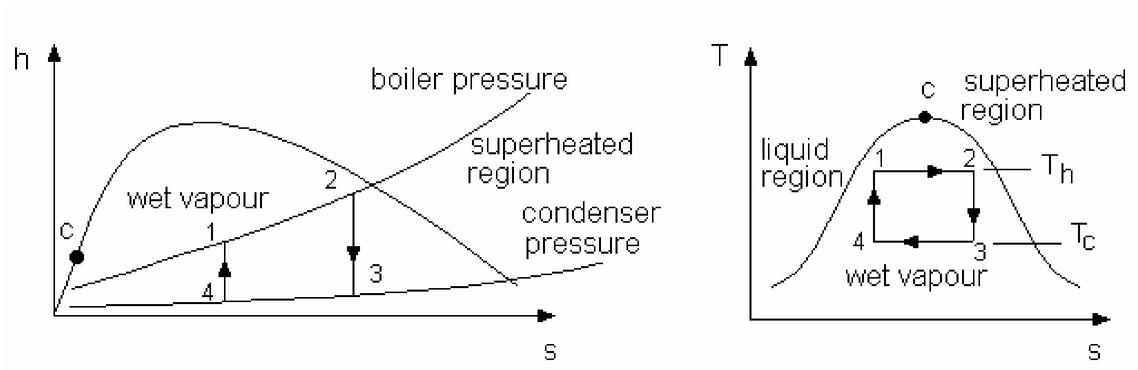

Fig.2

The limits are that at point (2) it may be dry saturated vapour but not superheated. At point 1 it may be saturated water but not under-cooled. If these limits are not used, then the vapour has a dryness fraction at each point. Since heat transfer only occurs at the evaporator and condenser the heat transfer rates are given by the following expressions.

$\Phi_{in} = m(h_2 - h_1) = T_h \; \Delta S$ (Boiler)

$\Phi_{out} = m(h_3 - h_4) = T_c \, \Delta S$ (Condenser)

T_h is the boiler temperature and T_c is the condenser temperature.

The thermal efficiency may be found from the 1st. Law. $\eta_{th} = 1 - \Phi_{out}/\Phi_{in} = 1 - T_c / T_h$

This expression is the same as for the gas version.

WORKED EXAMPLE No. 1

A Carnot cycle is conducted on steam as follows. The evaporator produces dry saturated steam at 10 bar. The steam is expanded reversibly and adiabatically in a turbine to 1 bar. The exhaust steam is partially condensed and then compressed back to 10 bar. As a result of the compression, the wet steam is changed completely into saturated water.

Assuming a flow rate of 1 kg/s throughout determine the condition and specific enthalpy at each point in the cycle.
Calculate the energy transfers for each stage.
Show that the efficiency is correctly predicted by the expression η_{th}= T(cold)/T(hot)

SOLUTION We will refer to the previous diagrams throughout.

EVAPORATOR

$h_2 = h_g$ at 10 bar (since it is dry saturated) = 2778 kJ/kg.
$s_2 = s_g$ at 10 bar (since it is dry saturated) = 6.586 kJ/kg K.
$h_1 = h_f$ at 10 bar (since it is saturated water) = 763 kJ/kg.
Φ_{in} = 1 (2778 - 763) = 2015 kW

TURBINE
Since the expansion is isentropic then $s_2 = s_3$ = 6.586 kJ/kg K
$s_3 = 6.586 = s_f + x_3 s_{fg}$ at 1 bar
$6.586 = 1.303 + x_3(6.056)$ hence x_3=0.872
$h_3 = h_f + x_3 h_{fg}$ at 1 bar = 417 + (0.872)(2258) = 2387 kJ/kg
P(output) = 1(2778 - 2387) = 391.2 kW

COMPRESSOR
Since the compression is isentropic then $s_4 = s_1$
$s_1 = s_f$ at 10 bar (since it is saturated water) = 2.138 kJ/kg K.
$s_4 = s_1 = 2.138 = s_f + x_4 s_{fg}$ at 1 bar
$2.138 = 1.303 + x_4(6.056)$ hence x_4 = 0.138
$h_4 = h_f + x_4 h_{fg}$ at 1 bar = 417 + (0.139)(2258) = 728.3 kJ/kg
Power Input = 1(763 - 728.3) = 34.7 kW

CONDENSER
Heat output = 1(2387 - 728.3) = 1658.7 kW
Energy Balances rounded off to nearest kW.
Total energy input = 34.7 + 2015 = 2050 kW

Total energy output = 391.2 + 1658.7 = 2050 kW
Net Power output = 391.2 - 34.7 = 356 kW
Net Heat input = 2015 - 1658.7 = 356 kW
Thermal efficiency = P_{nett}/Φ_{in} = 356/2015 = 17.7%
Thermal Efficiency = 1 - Φ_{out} / Φ_{in} = 1 - 1658.7/2015 = 17.7%
The hottest temperature in the cycle is t_s at 10 bar = 179.9 ^oC or 452.9 K
The coldest temperature in the cycle is t_s at 1 bar = 99.6 ^oC or 372.6 K
The Carnot efficiency = 1 - 372.6/452.9 = 17.7%

SELF ASSESSMENT EXERCISE No.1

1. A steam power plant uses the Carnot cycle. The boiler puts 25 kW of heat into the cycle and produces wet steam at 300°C. The condenser produces wet steam at 50°C.

   Calculate the following.

   i. The efficiency of the plant. (43.6%)
   ii. The net power output. (10.9 kW)
   iii. The heat removed by the condenser. (14 kW)

2. A steam power plant is based on the Carnot cycle. The boiler is supplied with saturated water at 20 bar and produces dry saturated steam at 20 bar. The condenser operates at 0.1 bar. Assuming a mass flow rate of 1 kg/s calculate the following.

   i. The thermal efficiency. (34.3%)
   ii. The power output of the turbine. (792 kW)
   iii. The heat transfer rate into the boiler. (1.89 MW)

1.2 THE RANKINE CYCLE

The Rankine Cycle is a practical cycle and most steam power plants are based on it. The problems with the Carnot Cycle are as follows.

- It produces only small net power outputs for the plant size because dry saturated steam is used at inlet to the turbine.
- It is impractical to compress wet steam because the water content separates out and fills the compressor.
- It is impractical to control the condenser to produce wet steam of the correct dryness fraction.

In order to get around these problems, the Rankine Cycle uses superheated steam from the boiler to the turbine. The condenser completely condenses the exhaust steam into saturated water. The compressor is replaced with a water (feed) pump to return the water to the boiler. The result of this is reduced efficiency but greater quantities of power.

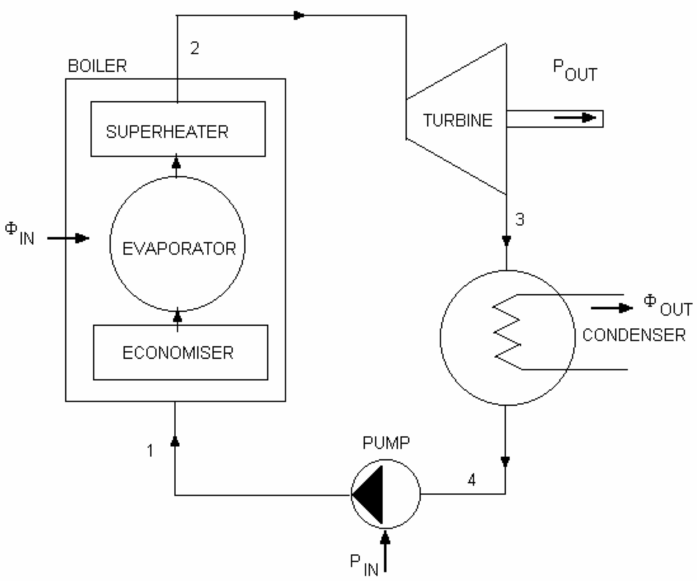

Fig.3

The plant layout is shown above. First let's briefly examine the boiler.

BOILER
For reasons of combustion efficiency (which you do not have to study), a practical boiler is made up of three sections.

a) Economiser
This is a water heater inside the boiler that raises the water temperature at the boiler pressure to just below the saturation temperature at that pressure.

b) Evaporator
This is a unit usually consisting of a drum and tubes in which the water is evaporated and the steam driven off.

c) Super-heater
This is a heater placed in the hottest part of the boiler that raises the temperature of the steam well beyond the saturation temperature.

There are many boiler designs and not all of them have these features. The main point is that a heat transfer rate is needed into the boiler unit in order to heat up the water, evaporate it and superheat it. The overall heat transfer is

$$\Phi_{in} = m\,(h_2 - h_1)$$

Next let's look at some other practical aspects of a steam power plant.

EXTRACTION PUMP AND HOTWELL.

In a practical steam cycle the condensate in the condenser is extracted with an extraction pump and the water produced is the coldest point in the steam cycle. This is usually placed into a vessel where it can be treated and extra added to make up for leaks. This point is called the HOTWELL because it contains hot water. The main feed pump returns this water to the boiler at high pressure. In the following work, extraction pumps and hotwells are not shown.

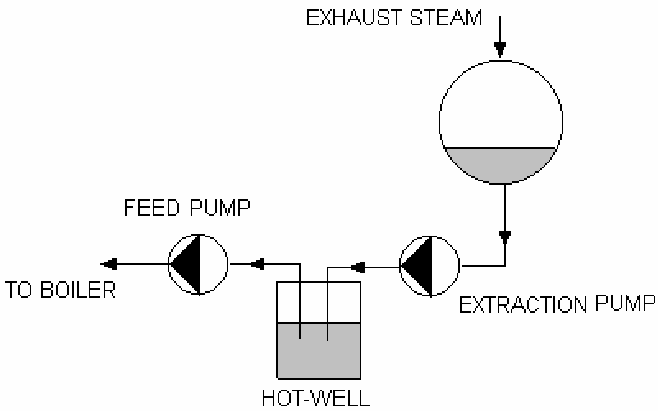

Fig.4

Now let's examine the cycle with the aid of property diagrams.

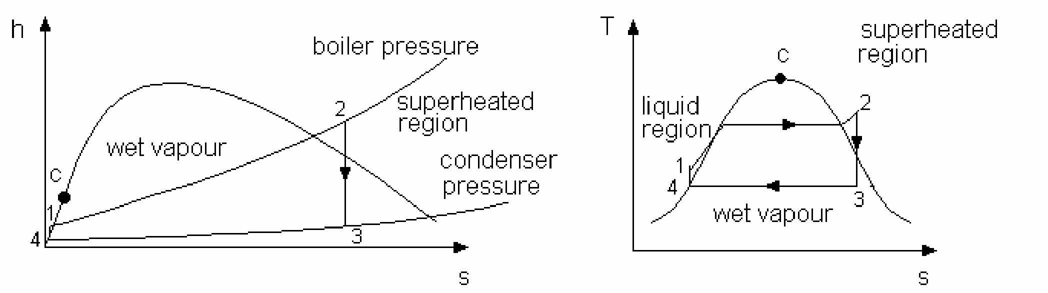

Fig.5

The process 4 to 1 is cramped into the corner of the h-s diagram and is not clear.

BOILER PROCESS (1) to (2) HEAT INPUT

The water at point 1 is below the saturation temperature at the boiler pressure. The economiser first heats it up raising the temperature, enthalpy and entropy until it reached the saturation curve. The water is then evaporated and finally, the temperature is raised by superheating the steam to point 2.

$$\Phi_{in} = m (h_2 - h_1)$$

TURBINE PROCESS (2) to (3) POWER OUTPUT

The second process is the expansion in the turbine and this is ideally reversible and adiabatic and is represented by a vertical line on the diagrams.

$$P_{out} = m(h_2 - h_3)$$

Turbines in real plant are often in several stages and the last stage is specially designed to cope with water droplets in the steam that becomes wet as it gives up its energy. You must use the isentropic expansion theory in order to calculate the dryness fraction and enthalpy of the exhaust steam.

CONDENSER PROCESS (3) to (4) HEAT OUTPUT

The third process is the condenser where the wet steam at point 3 is ideally turned into saturated water at the lower pressure (point 4). Condensers usually work at very low pressures (vacuums) in order to make the turbine give maximum power. The heat removed is given by

$$\Phi_{out} = m (h_3 - h_4)$$

Since the condenser produces condensate (saturated water) then $h_4 = h_f$ at the condenser pressure.

PUMP PROCESS (4) to (1) POWER INPUT

The final process which completes the cycle is the pumping of the water (point 4) from the low condenser pressure to the boiler at high pressure (point 1). In reality there are many things which are done to the feed water before it goes back into the boiler and the pressure is often raised in several stages. For the Rankine Cycle we assume one stage of pumping which is adiabatic and the power input to the pump is

$$P_{in} = m (h_1 - h_4)$$

The power required to pump the water is much less than that required to compress the vapour (if it was possible). The power input to the feed pump is very small compared to the power output of the turbine and you can often neglect it altogether. In this case we assume $h_1=h_4$.

If you are not ignoring the power input, then you need to find h_1. If you know the exact temperature of the water at inlet to the boiler (outlet from the pump) then you may be able to look it up in tables. The nearest approximation is to look up h_f at the water temperature. Since the water is at high pressure, this figure will not be very accurate and you may correct it by adding the flow energy. We will look at this in greater detail later. Lets first do a simple example with no great complications.

WORKED EXAMPLE No.2

A steam power plant is based on the Rankine cycle. The steam produced by the boiler is at 40 bar and 400°C. The condenser pressure is 0.035 bar. Assume isentropic expansion. Ignore the energy term at the feed pump.

Calculate the Rankine cycle efficiency and compare it to the Carnot efficiency for the same upper and lower temperature limits.

SOLUTION

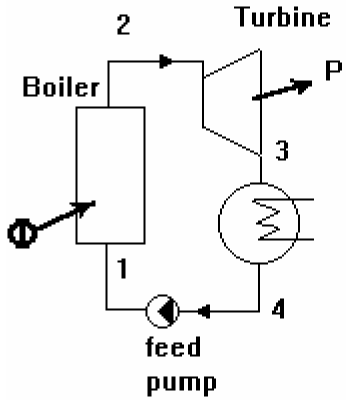

Figure 6

Turbine

h_2 = 3214 kJ/kg at 40 bar and 400°C.

Since the expansion is isentropic then s_2 = 6.769 kJ/kg K =s_3 = 0.391 + 8.13 x   x = 0.785

$h_3 = h_f + x\,h_{fg}$ = 112 + 0.785(2438) = 2024.6 kJ/kg

Condenser

$h_4 = h_f$ at 0.035 bar = 112 kJ/kg

Boiler

If the power input to the pump is neglected then $h_4 = h_1$ =112 kJ/kg

$\Phi_{in} = h_2 - h_1$ = 3102 kJ/kg.   P(output) = $h_2 - h_3$ = 1189.4 kJ/kg

$\eta = P/\Phi_{in}$ = 38.3 %

Carnot Efficiency

The hottest temperature in the cycle is 400°C (673 K) and the coldest temperature is t_s at 0.035 bar and this is 26.7 °C(299.7 K).

The Carnot efficiency is 1 - 299.7/673 = 55.5 % which is higher as expected.

Now let's examine the feed pump in more detail.

FEED PUMP

When water is compressed its volume hardly changes. This is the important factor that is different from the compression of a gas. Because the volume hardly changes, the temperature should not increase and the internal energy does not increase. The Steady flow Energy equation would then tell us that the power input to the pump is virtually equal to the increase in flow energy. We may write

$$P_{in} = m\, v\Delta p$$

Since the volume of water in nearly all cases is 0.001 m^3/kg then this becomes

$$P_{in} = 0.001\, m\, \Delta p = 0.001\, m\, (p_1 - p_2)$$

If we use pressure units of bars then

$$P_{in} = 0.001\, m(p_1 - p_2) \times 10^5 \text{ Watts}$$

Expressed in kilowatts this is

$$P_{in} = m(p_1 - p_2) \times 10^{-1} \text{ kW}$$

From this we may also deduce the enthalpy of the water after the pump.

$$P_{in} = m\,(h_1 - h_4)$$

Hence h_1 may be deduced.

WORKED EXAMPLE No.3

Repeat example 3, but this time do not ignore the feed pump and assume the boiler inlet condition is unknown.

SOLUTION

P_{in} = 1kg/s(40 - 0.035) x 10^{-1} = 4 kW
4 = 1 kg/s(h_1 - h_4) = (h_1 - 112)
h_1 = 116 kJ/kg

Reworking the energy transfers gives

$\Phi_{in} = h_2 - h_1 = 3214 - 116 = 3098$ kJ/kg.

$P_{nett} = P_{out} - P_{in} = 1189.4 - 4 = 1185.4$ kJ/kg

$\eta = P_{nett}/\Phi_{in} = 1185.4/3098 = 38.3$ %

Notice that the answers are not noticeably different from those obtained by ignoring the feed pump.

WORKED EXAMPLE No.4

A steam power plant uses the Rankine Cycle. The details are as follows.

Boiler pressure	100 bar
Condenser pressure	0.07 bar
Temperature of steam leaving the boiler	400^oC
Mass flow rate	55 kg/s

Calculate the cycle efficiency, the net power output and the specific steam consumption.

SOLUTION

Turbine

h_2 = 3097 kJ/kg at 100 bar and 400^oC.

For an isentropic expansion we find the ideal condition at point 3 as follows.

s_2 = 6.213 kJ/kg K $=s_3$ = 0.559 + 7.715 x_3 $\quad\quad$ x_3 = 0.733

$h_3 = h_f + x_3 h_{fg}$ = 163 + 0.733(2409) = 1928 kJ/kg

$P_{out} = m(h_2-h_3)$ = 55(3097 - 1928) = 64.3 MW

Condenser

$h_4 = h_f$ at 0.07 bar = 163 kJ/kg

$\Phi_{out} = m(h_3 - h_4)$ = 55(1928 - 163) = 97.1 MW

PUMP

Ideal power input = Flow Energy change = mv(Δp)

$P_{in} = 55(0.001)(100-0.07) \times 10^5$ = 550 kW

$P_{in} = m(h_1 - h_4) = 55(h_1-163)$ hence h_1 = 173 kJ/kg

Boiler

$\Phi_{in} = m(h_2 - h_1)$ = 55(3097 - 173) = 160.8 MW

EFFICIENCY

$P_{nett} = P_{out} - P_{in}$ = 64.3 - 0.55 = 63.7 MW

$\eta = P_{nett} / \Phi_{in}$ = 63.7/160.8 = 39.6 %

Alternatively $\quad\quad$ $P_{nett} = \Phi_{in} - \Phi_{out}$ = 160.8-97.1 = 63.7 MW

This should be the same as P_{nett} since the net energy entering the cycle must equal the net energy leaving.

$\eta = 1 - \Phi_{out} / \Phi_{in}$ = 1 - 97.1/160.8 = 39.6%

SPECIFIC STEAM CONSUMPTION

This is given by

S.S.C. = P_{nett} /mass flow = 63.78/55 = 1.159 MW/kg/s or MJ/kg

SELF ASSESSMENT EXERCISE No.2

1. A simple steam plant uses the Rankine Cycle and the data for it is as follows.

Flow rate	45 kg/s
Boiler pressure	50 bar
Steam temperature from boiler	300^oC
Condenser pressure	0.07 bar

Assuming isentropic expansion and pumping, determine the following.

i. The power output of the turbine. (44.9 MW)
ii. The power input to the pump. (225 kW)
iii. The heat input to the boiler. (124 MW)
iv. The heat rejected in the condenser. (79 MW)
v. The thermal efficiency of the cycle. (36%)

2. A simple steam power plant uses the Rankine Cycle. The data for it is as follows.

Flow rate	3 kg/s
Boiler pressure	100 bar
Steam temperature from boiler	600^oC
Condenser pressure	0.04 bar

Assuming isentropic expansion and pumping, determine the following.

i. The power output of the turbine. (4.6 MW)
ii. The power input to the pump. (30 kW)
iii. The heat input to the boiler. (10.5 MW)
iv. The heat rejected in the condenser. (5.9 MW)
v. The thermal efficiency of the cycle. (44%)

3.
a) Explain why practical steam power plants are based on the Rankine Cycle rather than the Carnot Cycle.

b) A simple steam power plant uses the Rankine Cycle. The data for it is

Boiler pressure	15 bar
Steam temperature from boiler	300^oC
Condenser pressure	0.1 bar
Net Power Output	1.1 MW

Calculate the following.

i. The cycle efficiency. (29.7 %)

ii. The steam flow rate. (1.3 kg/s)