

## **UNIT 61: ENGINEERING THERMODYNAMICS**

---

Unit code: D/601/1410

QCF level: 5

Credit value: 15

---

### **OUTCOME 4** **STEAM AND GAS TURBINE POWER PLANT**

#### **TUTORIAL No. 8 – STEAM CYCLES**

#### **4 Understand the operation of steam and gas turbine power plant**

*Principles of operation:* impulse and reaction turbines; condensing; pass-out and back pressure steam turbines; single and double shaft gas turbines; regeneration and re-heat in gas turbines; combined heat and power plants

*Circuit and property diagrams:* circuit diagrams to show boiler/heat exchanger; superheater; turbine; condenser; condenser cooling water circuit; hot well; economiser/feedwater heater; condensate extraction and boiler feed pumps; temperature entropy diagram of Rankine cycle

*Performance characteristics:* Carnot, Rankine and actual cycle efficiencies; turbine isentropic efficiency; power output; use of property tables and enthalpy-entropy diagram for steam

When you have completed tutorial 8 you should be able to do the following.

- Explain the Carnot steam cycle.
- Explain the Rankine steam power cycle.
- Describe improvements to the Rankine cycle.

# 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.

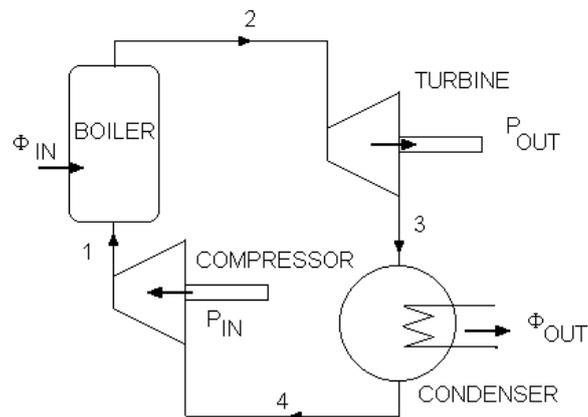


Fig. 1

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.

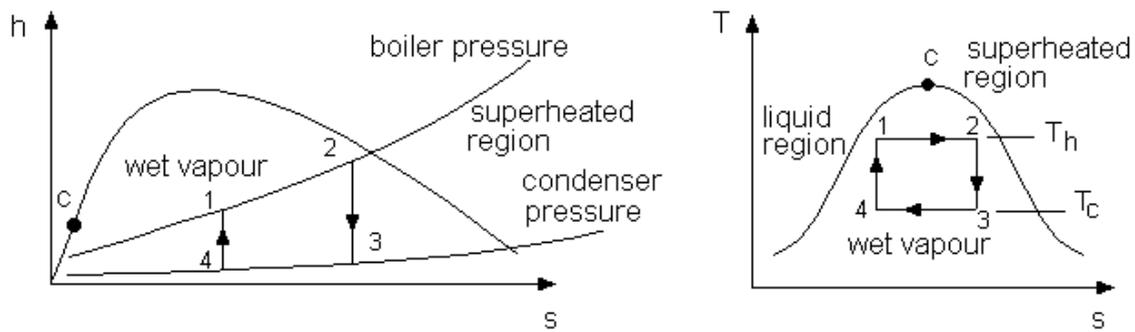


Fig.2

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.

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

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

$T_h$  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

$$\eta_{th} = T(\text{cold})/T(\text{hot})$$

**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.

$$\Phi_{in} = 1(2778 - 763) = 2015 \text{ kW}$$

### **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

$$6.586 = 1.303 + x_3(6.056) \text{ hence } x_3 = 0.872$$

$h_3 = h_f + x_3 h_{fg}$  at 1 bar =  $417 + (0.872)(2258) = 2387$  kJ/kg

$$P(\text{output}) = 1(2778 - 2387) = 391.2 \text{ kW}$$

### **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

$$2.138 = 1.303 + x_4(6.056) \text{ hence } x_4 = 0.138$$

$h_4 = h_f + x_4 h_{fg}$  at 1 bar =  $417 + (0.138)(2258) = 728.3$  kJ/kg

$$\text{Power Input} = 1(763 - 728.3) = 34.7 \text{ kW}$$

### **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 =  $P_{\text{nett}} / \Phi_{in} = 356 / 2015 = 17.7\%$

Thermal Efficiency =  $1 - \Phi_{out} / \Phi_{in} = 1 - 1658.7 / 2015 = 17.7\%$

The hottest temperature in the cycle is  $t_g$  at 10 bar =  $179.9$  °C or  $452.9$  K

The coldest temperature in the cycle is  $t_g$  at 1 bar =  $99.6$  °C 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.

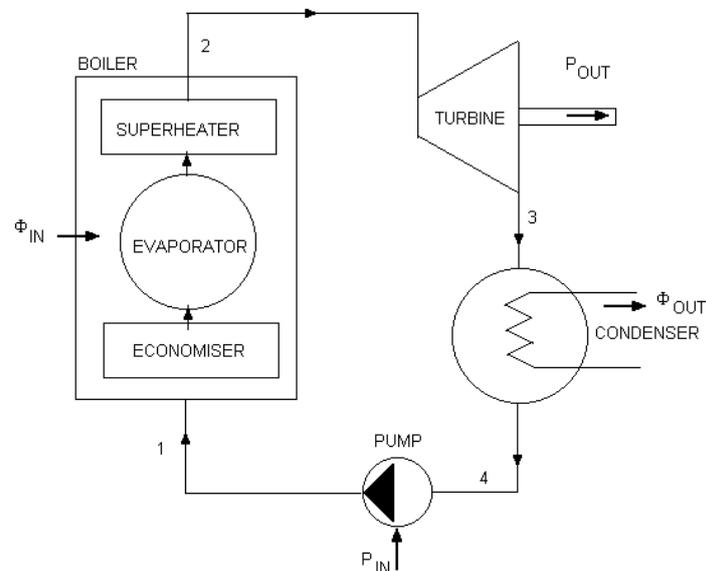


Fig.3

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.

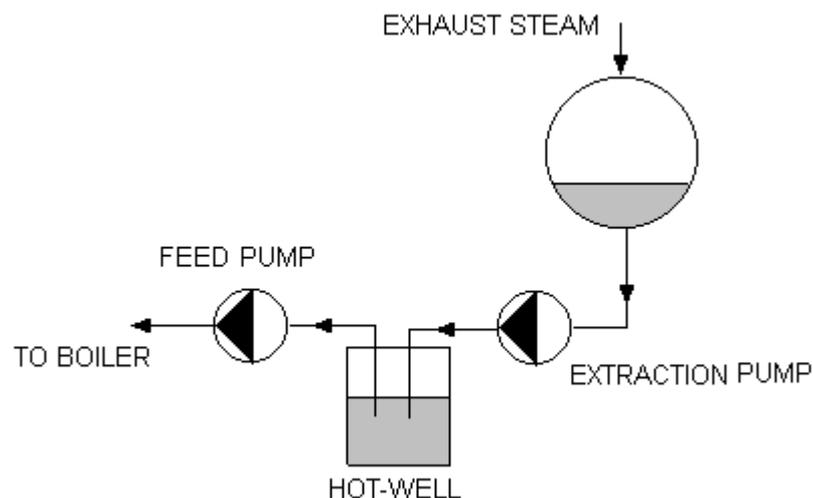


Fig.4

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

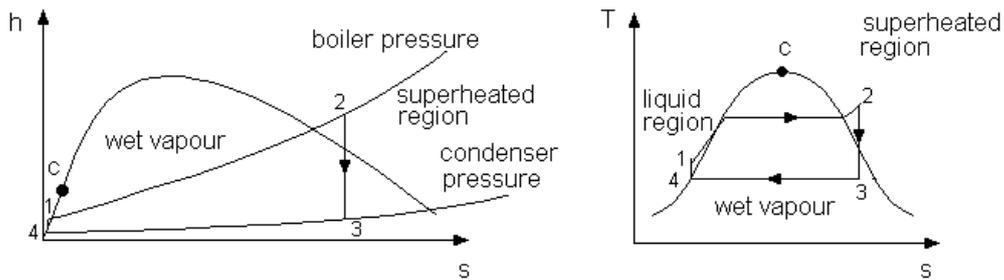


Fig.5

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**

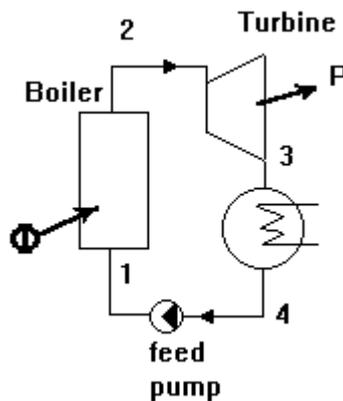


Figure 6

#### **Turbine**

$h_2 = 3214 \text{ kJ/kg}$  at 40 bar and 400°C.

Since the expansion is isentropic then

$$s_2 = 6.769 \text{ kJ/kg K} = s_3 = 0.391 + 8.13 x \quad x = 0.785$$

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

#### **Condenser**

$$h_4 = h_f \text{ at } 0.035 \text{ bar} = 112 \text{ kJ/kg}$$

#### **Boiler**

If the power input to the pump is neglected then

$$h_4 = h_1 = 112 \text{ kJ/kg}$$

$$\Phi_{in} = h_2 - h_1 = 3102 \text{ kJ/kg.}$$

$$P(\text{output}) = h_2 - h_3 = 1189.4 \text{ kJ/kg}$$

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

### **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<sup>3</sup>/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**

$$P_{in} = 1 \text{ kg/s}(40 - 0.035) \times 10^{-1} = 4 \text{ kW}$$

$$4 = 1 \text{ kg/s}(h_1 - h_4) = (h_1 - 112)$$

$$h_1 = 116 \text{ kJ/kg}$$

Reworking the energy transfers gives

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

$$P_{net} = P_{out} - P_{in} = 1189.4 - 4 = 1185.4 \text{ kJ/kg}$$

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

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°C
Mass flow rate	55 kg/s

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

## **SOLUTION**

### **Turbine**

$h_2 = 3097 \text{ kJ/kg}$  at 100 bar and  $400^\circ\text{C}$ .

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

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

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

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

### **Condenser**

$$h_4 = h_f \text{ at } 0.07 \text{ bar} = 163 \text{ kJ/kg}$$

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

### **PUMP**

Ideal power input = Flow Energy change =  $mv(\Delta p)$

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

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

### **Boiler**

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

### **EFFICIENCY**

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

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

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

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

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

### **SPECIFIC STEAM CONSUMPTION**

This is given by

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

## **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°C
Condenser pressure	0.07 bar

Assuming isentropic expansion and pumping, determine the following.

- The power output of the turbine. (44.9 MW)
  - The power input to the pump. (225 kW)
  - The heat input to the boiler. (124 MW)
  - The heat rejected in the condenser. (79 MW)
  - 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°C
Condenser pressure	0.04 bar

Assuming isentropic expansion and pumping, determine the following.

- The power output of the turbine. (4.6 MW)
  - The power input to the pump. (30 kW)
  - The heat input to the boiler. (10.5 MW)
  - The heat rejected in the condenser. (5.9 MW)
  - 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°C
Condenser pressure	0.1 bar
Net Power Output	1.1 MW

Calculate the following.

- The cycle efficiency. (29.7 %)
- The steam flow rate. (1.3 kg/s)

## 2. BACK-PRESSURE AND PASS-OUT TURBINES

If an industry needs sufficient quantities of process steam (e.g. for sugar refining) and electric power, it becomes economical to use the steam for both purposes. This is done with a steam turbine and generator and the process steam is obtained in two ways as follows.

- A) By exhausting the steam at the required pressure (typically 2 bar) to the process instead of to the condenser.

A turbine designed to do this is called a **BACK-PRESSURE TURBINE**.

- B) By bleeding steam from an intermediate stage in the expansion process.

A turbine designed to do this is called a **PASS-OUT TURBINE**.

The steam cycle is standard except for these modifications.

### 2.1. BACK-PRESSURE TURBINES

Back-pressure turbines are designed to operate with a back pressure, unlike normal turbines that operate with a vacuum at the exhaust. The diagram shows the basic circuit.

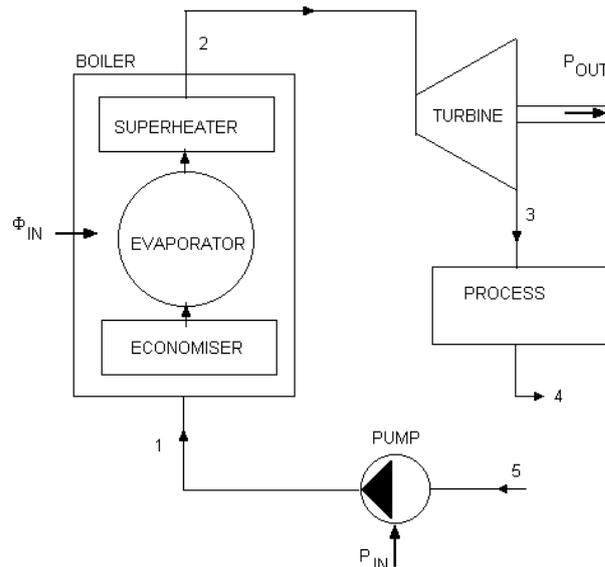


Fig.7

### **WORKED EXAMPLE No.5**

For a steam circuit as shown previously, the boiler produces superheated steam at 50 bar and 400°C. This is expanded isentropically to 3 bar. The exhaust steam is used for a process. The returning feed water is at 1 bar and 40°C. This is pumped to the boiler. The water leaving the pump is at 40°C and 50 bar. The net power output of the cycle is 60 MW. Calculate the mass flow rate of the steam.

### **SOLUTION**

Referring to the previous cycle sketch for location points we find

$$h_2 = 3196 \text{ kJ/kg} \quad s_2 = 6.646 \text{ kJ/kg K}$$

For an ideal expansion

$$s_1 = s_2 = 6.646 = s_f + x s_{fg} \text{ at 3 bar}$$

$$6.646 = 1.672 + x (5.321)$$

$$x = 0.935$$

$$h_4 = h_f + x h_{fg} \text{ at 3 bar}$$

$$h_4 = 561 + 0.935(2164)$$

$$h_4 = 2584 \text{ kJ/kg}$$

$$\text{Change in enthalpy} = 2584 - 3196 = -612 \text{ kJ/kg}$$

The power output of the turbine is found from the steady flow energy equation so

$$P = m(-612) \text{ kW}$$

$$P = -612 m \text{ kW (output)}$$

Next we examine the enthalpy change at the pump.

$$h_1 = 168 \text{ kJ/kg at 1 bar and } 40^\circ\text{C}$$

$$h_2 = 172 \text{ kJ/kg at 50 bar and } 40^\circ\text{C.}$$

$$\text{Change in enthalpy} = 172 - 169 = 3 \text{ kJ/kg}$$

The power input to the pump is found from the steady flow energy equation so :

$$P = -m(3) \text{ kW}$$

$$P = -3 m \text{ kW(input)}$$

Net Power output of the cycle = 60 MW hence

$$60\,000 = 612 m - 3 m$$

$$m = 98.5 \text{ kg/s}$$

### **SELF ASSESSMENT EXERCISE No.3**

1. A steam cycle is performed as follows. The boiler produces 3 kg/s of superheated steam at 60 bar and 400°C. The steam is supplied to a turbine that it expands it isentropically and with no friction to 1.5 bar. The exhaust steam is supplied to a process. The feed water is supplied to the pump at 1.013 bar and 100°C and delivered to the boiler at 60 bar. The pump may be considered as ideal.

Calculate the following.

- i. The power output of the turbine. (2.2 MW)
  - ii. The heat input to the boiler. (8.3 MW)
  - iii. The power input to the pump. (17.7 kW)
  - iv. The thermal efficiency of the cycle. (26.3%)
2. A back pressure steam cycle works as follows. The boiler produces 8 kg/s of steam at 40 bar and 500°C. This is expanded isentropically to 2 bar. The pump is supplied with feed water at 0.5 bar and 30°C and delivers it to the boiler at 31°C and 40 bar.

Calculate the following.

- i. The net power output. (6 MW)
- ii. The heat input to the boiler. (26.5 MW)
- iii. The thermal efficiency of the cycle. (22.5%)

## 2.2 PASS-OUT TURBINES

The circuit of a simple pass-out turbine plant is shown below. Steam is extracted between stages of the turbine for process use. The steam removed must be replaced by make up water at point 6.

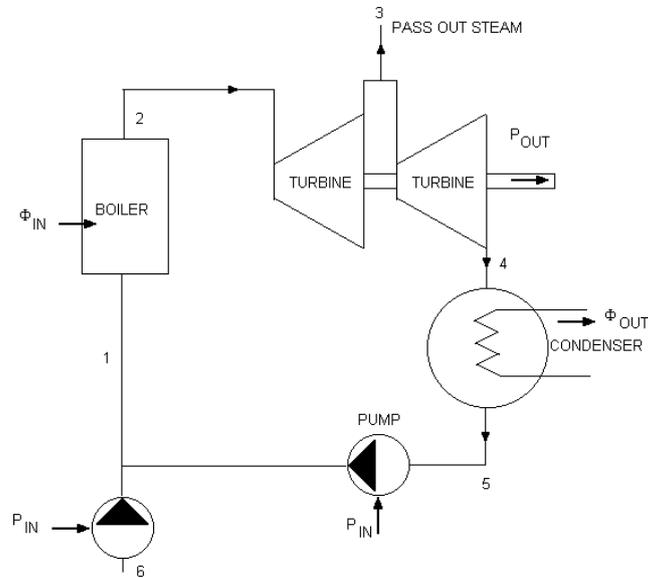


Fig. 8

In order to solve problems you need to study the energy balance at the feed pumps more closely so that the enthalpy at inlet to the boiler can be determined. Consider the pumps on their own as below.

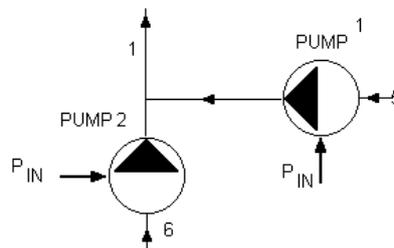


Fig. 9

The balance of power is as follows.  $P_1 + P_2 = \text{increase in enthalpy per second.}$

$$P_1 + P_2 = m_1 h_1 - m_6 h_6 - m_5 h_5$$

From this the value of  $h_1$  or the mass  $m$  may be determined. This is best shown with a worked example.

### WORKED EXAMPLE No.6

The circuit below shows the information normally available for a feed pump circuit. Determine the enthalpy at entry to the boiler.

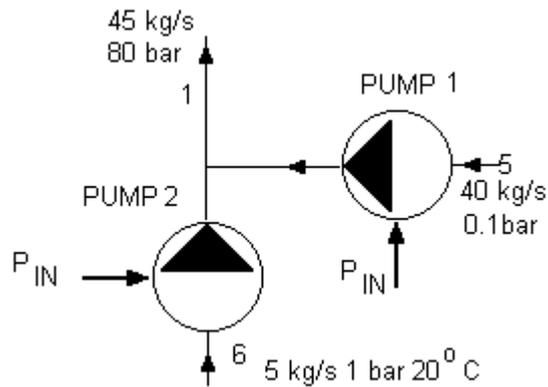


Fig. 10

### SOLUTION

If no other details are available the power input to the pump is  $m v \Delta p$   
Assume  $v = 0.001 \text{ m}^3/\text{kg}$

$$P = m v \Delta p = m \times 0.001 \times \Delta p \text{ (bar)} \times 10^5 \times 10^{-3} = m \Delta p \times 10^{-1} \text{ kW}$$

$$\text{PUMP1} \quad P_1 = m v \Delta p = (40)(80 - 0.1)(10^{-1}) = 319.6 \text{ kW}$$

$$\text{PUMP2} \quad P_2 = m v \Delta p = (5)(80-1)(10^{-1}) = 39.5 \text{ kW}$$

$$\text{Total power input} = 319.6 + 39.5 = 359.1 \text{ kW}$$

$$h_5 = h_f = 192 \text{ kJ/kg at } 0.1 \text{ bar}$$

$$h_6 = 84 \text{ kJ/kg (from water tables or approximately } h_f \text{ at } 20^\circ\text{C)}$$

Balancing energy we have the following.

$$359.1 = 45 h_1 - 40 h_5 - 5h_6$$

$$359.1 = 45 h_1 - 40(192) - 5(84)$$

$$h_1 = 188 \text{ kJ/kg}$$

### WORKED EXAMPLE No.7

A pass-out turbine plant works as shown in fig. 11 The boiler produces steam at 60 bar and 500°C and this is expanded through two stages of turbines. The first stage expands to 3 bar where 4 kg/s of steam is removed. The second stage expands to 0.09 bar. Assume that the expansion is a straight line on the h - s chart.

The condenser produces saturated water. The make up water is supplied at 1bar and 20°C. The net power output of the cycle is 40 MW. Calculate the following.

- i. The flow rate of steam from the boiler.
- ii The heat input to the boiler.
- iii. The thermal efficiency of the cycle.

### SOLUTION

#### TURBINE EXPANSION

$h_2 = 3421$  kJ/kg from tables.

$h_3 = 2678$  kJ/kg using isentropic expansion and entropy.

$h_4 = 2166$  kJ/kg using isentropic expansion and entropy.

These results may be obtained from the h-s chart.

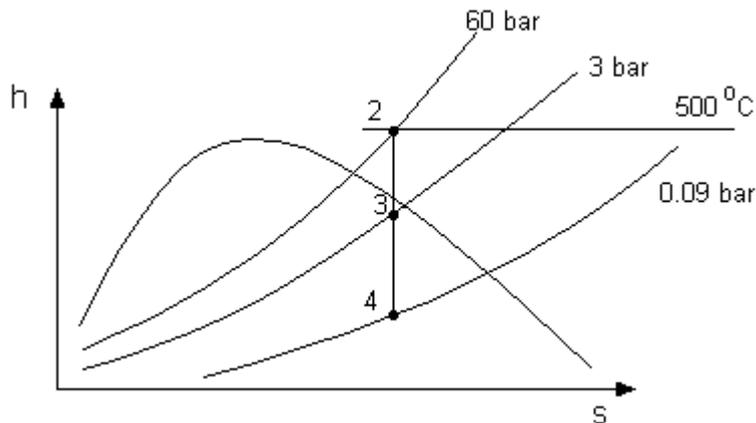


Fig. 11

#### POWER OUTPUT

$$P_{\text{out}} = m(h_3 - h_2) + (m - 4)(h_3 - h_4)$$

$$P_{\text{out}} = m(3421 - 2678) + (m - 4)(2678 - 2166)$$

$$P_{\text{out}} = 743 m + 512 m - 2048$$

### POWER INPUT

The power input is to the two feed pumps.

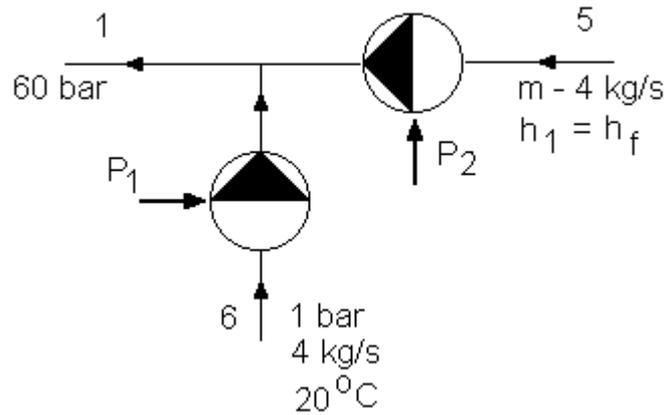


Fig. 12

$h_6 = 84 \text{ kJ/kg}$  (water at 1 bar and  $20^\circ\text{C}$ )

$h_5 = h_f$  at 0.09 bar = 183 kJ/kg.

$$P_1 = mv\Delta p = 4 \times (60 - 1) \times 10^{-1} = 23.6 \text{ kW}$$

$$P_2 = -mv\Delta p = (m-4) \times (60 - 0.09) \times 10^{-1} = 5.99m - 23.96 \text{ kW}$$

### NET POWER

$$40\,000 \text{ kW} = P_{\text{out}} - P_1 - P_2$$

$$40\,000 = 743m + 512m - 2048 - 23.6 - 5.99m + 23.96$$

$$40\,000 = 1249m - 2048 \quad \text{hence } m = 33.66 \text{ kg/s}$$

### ENERGY BALANCE ON PUMPS

$$P_1 = 23.6 \text{ kW}$$

$$P_2 = 177.7 \text{ kW (using the value of } m \text{ just found)}$$

$$m h_1 = (m - 4) h_5 + P_1 + P_2$$

$$33.66 h_1 = 29.66 \times 183 + 23.6 + 177.7$$

$$h_1 = 167.2 \text{ kJ/kg}$$

$$\text{HEAT INPUT} \quad \Phi_{\text{in}} = m(h_2 - h_1) = 109523 \text{ kW}$$

$$\text{EFFICIENCY} \quad \text{Efficiency} = \eta = 40/109.523 = 36.5 \%$$

#### **SELF ASSESSMENT EXERCISE No.4**

1. A steam turbine plant is used to supply process steam and power. The plant comprises an economiser, boiler, super-heater, turbine, condenser and feed pump.

The process steam is extracted between intermediate stages in the turbine at 2 bar pressure. The steam temperature and pressure at outlet from the super-heater are 500°C and 70 bar respectively. The turbine exhausts at 0.1 bar.

The make-up water is at 15°C and 1 bar and it is pumped into the feed line to replace the lost process steam.

Assume that the expansion is isentropic.

If due allowance is made for the feed pump-work, the net mechanical power delivered by the plant is 30 MW when the process steam load is 5 kg/s.

Sketch clear T- s and h-s and flow diagrams for the plant.

Calculate the following.

- i. The flow rate of steam flow leaving the super-heater. (25.6 kg/s)
- ii. The rate of heat transfer to the boiler. (83.2 MW)

2. An industrial plant requires 60 MW of process heat using steam at 2.6 bar which it condenses to saturated water. This steam is derived from the intermediate stage of a turbine that produces 30 MW of power to drive the electric generators.

The steam is raised in boilers and supplied to the turbines at 80 bar pressure and 600°C.

The steam is expanded isentropically to the condenser pressure of 0.05 bar.

Calculate the following.

- i. The flow rate of the steam bled to the process. (27.7 kg/s)
- ii. The flow rate of the steam from the boiler. (30.5 kg/s)

### **2.3 REHEATING**

Steam reheating is another way of improving the thermodynamic efficiency by attempting to keep the steam temperature more constant during the heating process.

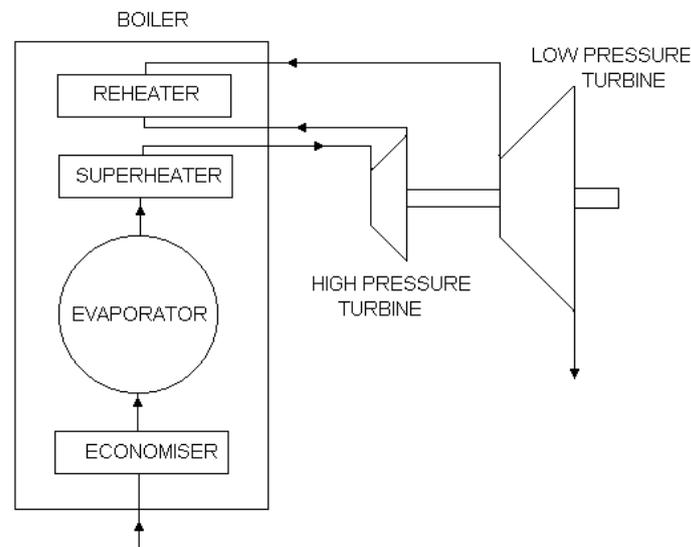


Fig.13

Superheated steam is first passed through a high pressure turbine. The exhaust steam is then returned to the boiler to be reheated almost back to its original temperature. The steam is then expanded in a low pressure turbine. In theory, many stages of turbines and reheating could be done thus making the heat transfer in the boiler more isothermal and hence more reversible and efficient.

### **2.4. FEED HEATING**

Feed heating is another way of improving the efficiency of a steam power plant. The feed water returning to the boiler is heated nearer to the saturation temperature with steam bled from the turbines at appropriate points. There are two types.

- Indirect contact.
- Direct contact.

#### **INDIRECT CONTACT**

The steam does not mix with the feed water at the point of heat exchange. The steam is condensed through giving up its energy and the hot water resulting may be inserted into the feed system at the appropriate pressure.

## DIRECT CONTACT

The bled steam is mixed directly with the feed water at the appropriate pressure and condenses and mixes with the feed water. The diagram shows a basic plant with a single feed heater added.

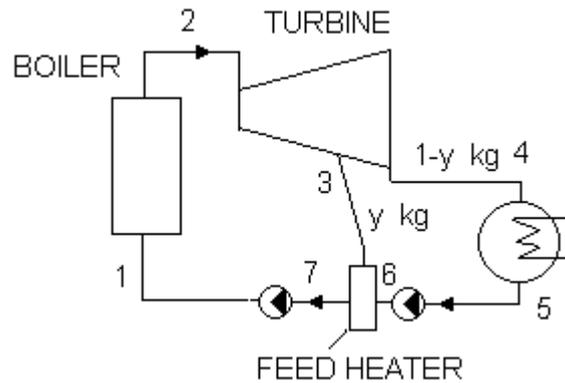


Fig.14

If a steam cycle used many stages of regenerative feed heating and many stages of reheating, the result would be an efficiency similar to that of the Carnot cycle. Although practicalities prevent this happening, it is quite normal for an industrial steam power plant to use several stages of regenerative feed heating and one or two stages of reheating. This produces a significant improvement in the cycle efficiency.

There are other features in advanced steam cycles that further improve the efficiency and are necessary for practical operation. For example air extraction at the condenser, steam recovery from turbine glands, de-super-heaters, de-aerators and so on. These can be found in detail in textbooks devoted to practical steam power plant.

### **SELF ASSESSMENT EXERCISE No.5**

Draw the plant cycle of a steam plant with the following features.

1. Economiser.
2. Evaporator.
3. Super-heater
4. Re-heater.
5. High pressure turbine.
6. Low pressure turbine.
7. Condenser.
8. Direct contact feed heaters fed from the l.p. turbine.
9. Direct contact feed heaters fed from the h.p. turbine.
10. Hot well.
11. High pressure feed pump.
12. Low pressure feed pump.
13. Extraction pump.