ORISSA SCHOOL OF MINING ENGINEERING, KEONJHAR

DEPARTMENT OF MECHANICAL ENGINEERING

THERMAL ENGINEERING-II
LECTURE NOTES

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CHAPTER-1
PERFORMANCE OF I.C. ENGINE

INTRODUCTION

- With a growing demand for transportation IC engine have gained lot of importance in automobile industry.
- It is therefore necessary to produce efficient and economical engines. While developing an IC engine it is required to take in consideration all the parameters affecting the engines design and performance.
- There are enormous parameters so it becomes difficult to account them while designing an engine. So it becomes necessary to conduct tests on the engine and determine the measures to be taken to improve the engines performance.

OBJECTIVE

- To understand the performance parameters in evaluation of IC engine performance,
- To calculate the speed of IC engine, fuel consumption, air consumption, etc.,
- To evaluate the exhaust smoke and exhaust emission.

PERFORMANCE PARAMETERS

1. Power and Mechanical Efficiency
2. Fuel Air Ratio
3. Volumetric Efficiency
4. Specific Output and specific weight
5. Specific Fuel Consumption
6. Thermal Efficiency and Heat Balance
7. Exhaust Smoke and Emissions
8. Effective Pressure and Torque

The particular application of the engine decides the relative importance of these performance parameters.

For Example: For an aircraft engine specific weight is more important whereas for an industrial engine specific fuel consumption is more important.

Power and mechanical efficiency

- An IC engine is used to produce mechanical power by combustion of fuel. Power is referred to as the rate at which work is done. Power is expressed as the product of force and linear velocity or product of torque and angular velocity. In order to measure power one needs to measure torque or force and speed. The force or torque is measured by Dynamometer and speed by Tachometer.
- The power developed by an engine and measured at the output shaft is called the **brake power (bp)** and is given by,

$$bp = \frac{2\pi N\tau}{60}$$

where:

T is the torque, in Newton meter (N.m),
N is the rotational speed, in minutes,
bp is the brake power, in watt.

However while calculating the **Mechanical efficiency** another factor called **Indicated Power (ip)** is considered. It is defined as the power developed by combustion of fuel in the engine cylinder. It is always more than brake power and is given by,

$$ip = \frac{PVNK}{60}$$

where:

P is the mean pressure,
V is the displacement volume of the piston
N is the rotational speed, in minutes
K is the number of cylinders

Therefore, the difference between ip and bp indicates the power loss in the mechanical components of engine (due to friction).

So the mechanical efficiency is defined as ratio of brake power to the indicated power.

$$E = \frac{bp}{ip} \text{ or } E = \frac{bp}{bp + fp}$$

Measurement of brake power

- The torque and the angular speed measurement of engine are involved in measurement of brake power.
- Dynamometer is used for torque measurement. The rotor of the engine which is under state is connected to stator. Rotor moves through distance 2πr against force F. Hence work done,

$$W = 2\pi rF$$

They are of two types-

1. Absorption dynamometer
2. Transmission dynamometer

1. **Absorption dynamometer**

- It absorbs and measures output power of engine. This power is dissipated in the form of heat. e.g., prony brake, hydraulic dynamometer, rope dynamometer, eddy current dynamometer, swinging field d.c. dynamometer etc.
- Absorption dynamometers are ideally suited for testing petrol engines for mopeds and electrical F.H.P. motors. Their main advantage lies in the fact that they are self-air-cooled and hence water cooling or additional air cooling is not required.

2. **Transmission dynamometer**

- In this the power is transmitted to load connected to engine. Torque meter is alternative name of this dynamometer.
- It is usually consist of strain gauge which measures the torque by angular deformation of shaft.
- These dynamometers are accurate and widely used in automatic units.

Air–fuel ratio

- It is the ratio of mass of fuel to mass or volume of air in mixture. It affects the phenomenon of combustion and used for determining flame propagation velocity, the heat released in combustion chamber. For practice always relative air fuel ratio is defined. It is the ratio of actual air–fuel ratio to that of the stoichiometric air fuel ratio required for burning of fuel which is supplied.
- Relative ratio,

$$\lambda : (A/F)=\{\text{Actual air-fuel ratio/Stoichiometric air-fuel ratio}\}$$

Volumetric efficiency

- It is the ratio of the actual volume of the charge drawn in during the suction stroke to the swept volume of the piston.
- The amount of air taken inside the cylinder is dependent on the volumetric efficiency of an engine and hence puts a limit on the

amount of fuel which can be efficiently burned and the power output.

- The value of volumetric efficiency of a normal engine lies between 70 and 80 percent, but for engines with forced induction it may be more than 100 percent.

Specific output and specific weight

- Specific output of an engine is defined as the brake power (output) per unit of piston displacement and is given by,

$$\text{Specific output} = \frac{bp}{A \times L}$$

- Specific weight is defined as the weight of the engine in kilogram for each brake power developed and is an indication of the engine bulk. Specific weight plays an important role in applications such as power plants for aircrafts.

Thermal efficiency and heat balance

- Thermal efficiency of an engine is defined as the ratio of the output to that of the chemical energy input in the form of fuel supply.
- It may be based on brake or indicated output. It is the true indication of the efficiency with which the chemical energy of fuel (input) is converted into mechanical work.
- Thermal efficiency also accounts for combustion efficiency, i.e., for the fact that whole of the chemical energy of the fuel is not converted into heat energy during combustion.

$$\text{Brake thermal efficiency} = \frac{bp}{m_f \times C_v}$$

Where,

Cv = Calorific value of fuel, kJ/kg, and
m_f = Mass of fuel supplied, kg/sec.

- The energy input to the engine goes out in various forms – a part is in the form of brake output, a part into exhaust, and the rest is taken by cooling water and the lubricating oil.
- The break-up of the total energy input into these different parts is called the heat balance.
- The main components in a heat balance are brake output, coolant losses, heat going to exhaust, radiation and other losses.
- Preparation of heat balance sheet gives us an idea about the amount of energy wasted in various parts and allows us to think of methods to reduce the losses so incurred.

Brake specific fuel consumption (BSFC)

- It is defined as the amount of fuel consumed for each unit of brake power per hour; it indicates the efficiency with which the engine develops the power from fuel. It is used to compare performance of different engines.
- The amount of fuel which an engine consumes is rated by its brake specific fuel consumption (BSFC).
- For most internal combustion engines the BSFC will be in the range of 0.5 to 0.6.
- The fuel efficiency will tend to peak at higher engine speeds. The BSFC tends to be the same for similar engines.
- The estimate of brake specific fuel consumption for two-stroke engines ranges from 0.55 to as high as 0.8 pounds of fuel per horsepower per hour.

Exhaust smoke and other emission

- Smoke and other emission are undesirable for public environment.
- Because of global warming and emphasis on air pollution all possible things are tried to keep them low.
- Smoke is an indication of incomplete combustion. It limits the output of an engine if air pollution control is the consideration.
- Here are some tips of what you can adopt as air pollution solutions:
- Air conditioning systems and electrical gadgets within the vehicle (e.g. sound system, mobile tv systems) also take up energy. So if they are not in use, turn them off.
- Keep your car in efficient working condition.
- check the pressure of your car tires regularly.
- Get rid of excess load in your car.

Mean effective pressure and torque

Mean effective pressure is an important parameter for comparing the performance of different engines. It is defined as the average pressure acting over piston throughout a power stroke. It is given by the following relation;

$$p = \frac{ip60}{LARK}$$

where: P is the Mean Effective Pressure,
ip is Indicated Power
A is the Area of the Piston
R is the Rotational Speed
K is the Number of Cylinders,
L is stroke length

- If mean effective pressure is based on brake power(bp) then it is referred to as brake mean effective pressure(bmep). If it is based on indicated power(ip) it is called indicated mean effective pressure(imep).
- Mean effective pressure also has an effect on torque. Torque could be expressed by following relation also,

$$\tau = \frac{bmepARK}{2\pi}$$

- Mean effective pressure and torque both are affected by the size of engine. A large engine produces more Torque for the same mean effective pressure. For this reason engines mean effective pressure gives indication of its displacement utilization and not torque.
- Power of an engine is dependent on its size so it is not possible to compare different engines based on their power or torque. Therefore, mean effective pressure is the true indication of the relative performance of different engines.

CHAPTER-2

AIR COMPRESSOR

Intoduction

Compressors are work absorbing devices which are used for increasing pressure of fluid at the expense of work done on fluid. The compressors used for compressing air are called air compressors. Some of popular applications of compressor are, for driving pneumatic tools and air operated equipments, spray painting, compressed air engine, supercharging in internal combustion engines, material handling (for transfer of material), surface cleaning, refrigeration and air conditioning, chemical industry etc.

Classification of Compressors

(a) ***Based on principle of operation:*** Based on the principle of operation compressors can be classified as,
(i) Positive displacement compressors
(ii) Non-positive displacement compressors

In positive displacement compressors the compression is realized by displacement of solid boundary and preventing fluid by solid boundary from flowing back in the direction of pressure gradient. Positive displacement compressors can be further classified based on the type of mechanism used for compression.
(i) Reciprocating type positive displacement compressors
(ii) Rotary type positive displacement compressors

Reciprocating compressors generally, employ piston-cylinder arrangement where displacement of piston in cylinder causes rise in pressure. **Reciprocating compressors are capable of giving large pressure ratios but the mass handling capacity is limited or small**. Reciprocating compressors may also be single acting compressor (one delivery stroke per revolution) or double acting (two delivery strokes per revolution of crank) compressor.

Rotary compressors employing positive displacement have a rotary part whose boundary causes positive displacement of fluid and thereby compression. Rotary compressors of this type are available in the names as given below;
(i) Roots blower
(ii) Vaned type compressors
(iii) Screw compressor
(iv) Scroll compressor

Non-positive displacement compressors, also called as steady flow compressors use dynamic action of solid boundary for realizing pressure rise. Non-positive displacement compressor can be classified depending upon type of flow in compressor
(i) axial flow type
(ii) centrifugal type

(b) ***Based on number of stages:*** Compressors can be single stage or multistage.
(i) Single stage compressor, for delivery pressure up to 5 bar
(ii) Two stage compressor, for delivery pressure between 5 and 35 bar
(iii) Three stage compressor, for delivery pressure between 35 and 85 bar
(iv) Four stage compressor, for delivery pressure more than 85 bar

(c) ***Based on capacity (air delivered per unit time) of compressors:***
(i) Low capacity compressors, having air delivery capacity of 0.15 m3/s or less
(ii) Medium capacity compressors, having air delivery capacity between 0.15 and 5 m3/s.
(iii) High capacity compressors, having air delivery capacity more than 5 m3/s.

(d) ***Based on highest pressure developed:*** Typical values of maximum pressure developed for different compressors are as under;
(i) Low pressure compressor, having maximum pressure up to 1 bar
(ii) Medium pressure compressor, having maximum pressure from 1 to 8 bar
(iii) High pressure compressor, having maximum pressure from 8 to 10 bar
(iv) Super high pressure compressor, having maximum pressure more than 10 bar.

RECIPROCATING COMPRESSORS

Reciprocating compressor has piston cylinder arrangement as shown in Fig. (1)

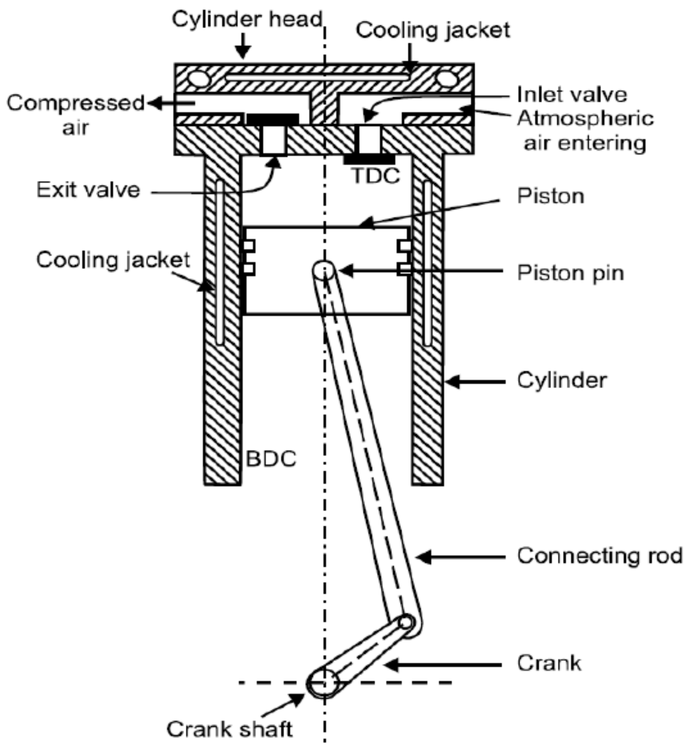


Fig. (1) Line diagram of reciprocating compressor

Construction: Reciprocating compressor has piston, cylinder, inlet valve, exit valve, connecting rod, crank, piston pin, crank pin and crank shaft. Inlet valve and exit valves may be of spring loaded type which get opened and closed due to pressure differential across them.

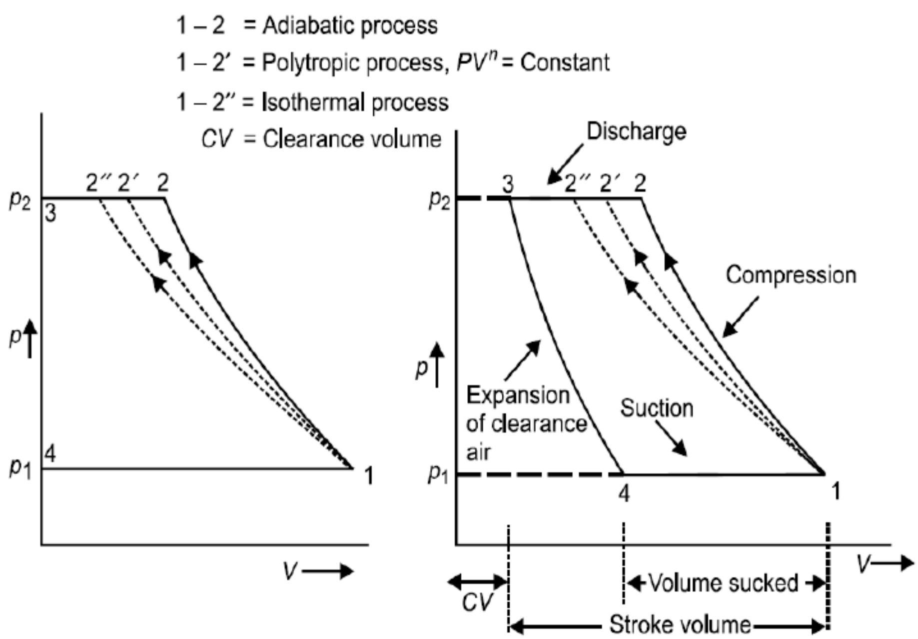
Working: Let us consider piston to be at top dead centre (TDC) and move towards bottom dead centre (BDC). Due to this piston movement from TDC to BDC suction pressure is created causing opening of inlet valve. With this opening of inlet valve and suction pressure, atmospheric air enters the cylinder. Air gets into cylinder during this stroke and is subsequently compressed in next stroke with both inlet valve and exit valve closed. After piston reaching BDC it reverses its motion and compresses the air inducted in previous stroke. Compression is continued till the pressure of air inside becomes sufficient to cause deflection in exit valve. At the moment when exit valve plate gets lifted the exhaust of compressed air takes place. This piston again reaches TDC from where downward piston movement is again accompanied by suction. This is how reciprocating compressor keeps on working as flow device.

See the working of reciprocating compressor ⟹ https://www.youtube.com/watch?v=F5Tcv8VxuG4
⟹ https://www.youtube.com/watch?v=bJluUxA7aaY

Thermodynamic Analysis of Reciprocating Compressor

Compression of air in compressor may be carried out in three different ways of thermodynamic processes such as isothermal compression, polytropic compression or adiabatic compression. Figure (2) shows the thermodynamic cycle involved in compression. Clearance volume is provided in reciprocating compressor. Purpose of clearance volume in cylinder is twofold. One is to accommodate valve mechanism and another one is to prevent collision of piston with cylinder head.

On *p*-*V* diagram process 4–1 shows the suction process followed by compression during 1–2, discharge process 2–3 and expansion of clearane air 3-4 (if clearance volume is provided).



(a) (b)

Fig. (2) Compression cycle on *p*-*V* diagram (a) without clearance volume (b) with clearance volume

Air enters compressor at pressure p_1 and is compressed up to p_2. Compression work requirement can be estimated from the area bounded by the curves comprising the cycle. Area on *p*–*V* diagram shows that work requirement shall be minimum with isothermal process $1-2''$. Work requirement is maximum with process 1–2 i.e. adiabatic process. As an engineer one shall attempt to minimise the requirement of compression-work. Therefore, ideally compression should occur isothermally for minimum work input. In practice, it is not possible to realise isothermal compression. Reason is maintaining constant temperature during compression is very difficult. Generally, compressors run at substantially high speed while isothermal compression requires compressor to run at very slow speed so that heat produced during compression is dissipated out and temperature remains constant. High running speed of compressor lead compression process near to adiabatic or polytropic process. It is thus obvious that actual compression process should be compared with isothermal compression process. A mathematical parameter called isothermal efficiency is defined for quantifying the degree of deviation of actual compression process (adiabatic or polytropic process) from ideal compression process (isothermal compression process). Isothermal efficiency is defined as the ratio of isothermal work to actual indicated work in reciprocating compressor.

$$Isothermal\ Efficiency = \frac{Isothermal\ Work}{Actual\ Indicated\ Work}$$

Compression process following three different processes is also shown on *T-s* diagram in Fig. (3).

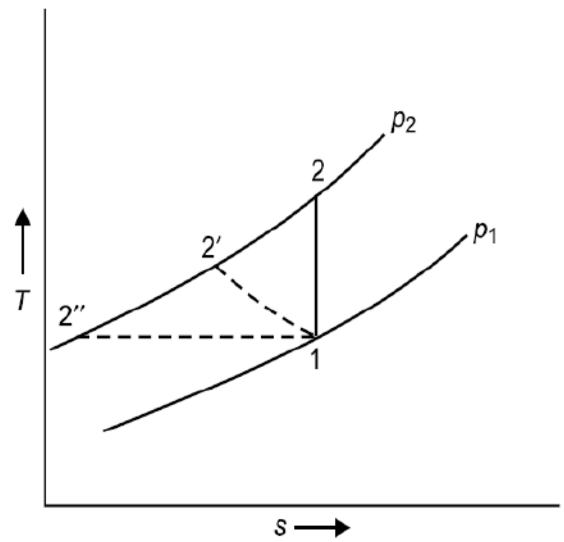


Fig. (3) Compression process on *T-S* diagram.

Compression Work, W_C (without clearance volume)- Assuming compression process follow polytropic process i.e. $pV^n = C$

$$W_c = \text{Area on } p\text{-}V \text{ diagram}$$

$$= \left[p_2V_2 + \left(\frac{p_2V_2 - p_1V_1}{n-1}\right)\right] - p_1V_1$$

$$= \left(\frac{n}{n-1}\right)[p_2V_2 - p_1V_1]$$

$$= \left(\frac{n}{n-1}\right)(p_1V_1)\left[\frac{p_2V_2}{p_1V_1} - 1\right]$$

$$W_c = \left(\frac{n}{n-1}\right)(p_1V_1)\left[\left(\frac{p_2}{p_1}\right)^{\frac{(n-1)}{n}} - 1\right]$$

$$\boxed{W_c = \left(\frac{n}{n-1}\right)(mRT_1)\left[\left(\frac{p_2}{p_1}\right)^{\frac{(n-1)}{n}} - 1\right]}$$

or, $$W_c = \left(\frac{n}{n-1}\right) mR\,(T_2 - T_1)$$

In case of compressor having isothermal compression process, *n=1* i.e. $p_1V_1 = p_2V_2$

$$W_{c,\ \text{iso}} = p_2V_2 + p_1V_1 \ln r - p_1V_1$$

$$W_{c,\ \text{iso}} = p_1V_1 \ln r, \text{ where } r = \frac{V_1}{V_2}$$

In case, compressor follow adiabatic compression process, $n = \gamma$

$$W_{c,\ \text{adiabatic}} = \left(\frac{\gamma}{\gamma-1}\right) mR\,(T_2 - T_1)$$

Or, $$W_{c,\ \text{adiabatic}} = mC_p\,(T_2 - T_1)$$

$$W_{c,\ \text{adiabatic}} = m\,(h_2 - h_1)$$

Hence isothermal efficiency

$$\eta_{\text{iso}} = \frac{p_1V_1 \ln r}{\left(\frac{n}{n-1}\right)(p_1V_1)\left[\left(\frac{p_2}{p_1}\right)^{\frac{(n-1)}{n}} - 1\right]}$$

As an engineer one should attempt to design a compressor which efficiency approaches 100%, thereby meaning that actual work of compression should approach isothermal work of compression. This can be achieved by adopting following method

I. Provide fins over the surface of cylinder. Fins facilitate quick heat transfer from air (which is being compressed) to atmosphere.
II. Water jacket may be provided around compressor cylinder so that heat can be picked by cooling water circulating through water jacket.
III. Water may also be injected at the end of compression process in order to cool the air being compressed.
IV. In case of multistage compression in different compressors operating serially, the air leaving one compressor may be cooled up to ambient state or somewhat high temperature before being injected into subsequent compressor.

All these methods restrict the temperature rise during compression. Hence actual compression process approaches to isothermal compression.

Compression Work, W_C (with clearance volume)- With clearance volume the cycle is represented on Fig. (2-b). The work done for compression of air polytropically can be given by the area enclosed in cycle 1–2–3–4.

$$W_{c,\text{ with CV}} = \text{Area}1234$$

$$= \left(\frac{n}{n-1}\right)(p_1V_1)\left[\left(\frac{p_2}{p_1}\right)^{\frac{(n-1)}{n}} - 1\right] - \left(\frac{n}{n-1}\right)(p_4V_4)\left[\left(\frac{p_3}{p_4}\right)^{\frac{(n-1)}{n}} - 1\right]$$

$$W_{c,\text{ with } CV} = \left(\frac{n}{n-1}\right)(p_1V_1)\left[\left(\frac{p_2}{p_1}\right)^{\frac{(n-1)}{n}} - 1\right] - \left(\frac{n}{n-1}\right)(p_1V_4)\cdot\left[\left(\frac{p_2}{p_1}\right)^{\frac{(n-1)}{n}} - 1\right]$$

$(\because\ p_1 = p_4 \ \&\ p_2 = p_3)$

$$W_{c,\text{ with } CV} = \left(\frac{n}{n-1}\right)p_1\cdot\left[\left(\frac{p_2}{p_1}\right)^{\frac{(n-1)}{n}} - 1\right]\cdot(V_1 - V_4)$$

This ($V_1 - V_4$), say V_d, is actually the volume of air inhaled in the cycle and delivered subsequently.

$$W_{c,\text{ with } CV} = \left(\frac{n}{n-1}\right)p_1V_d\left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} - 1\right]$$

Assuming air behaves as a perfect gas. Now temperature and pressure can be related as

$$\left(\frac{p_2}{p_1}\right)^{\frac{(n-1)}{n}} = \frac{T_2}{T_1} \qquad \text{And} \qquad \left(\frac{p_4}{p_3}\right)^{\frac{(n-1)}{n}} = \frac{T_4}{T_3} \Rightarrow \left(\frac{p_1}{p_2}\right)^{\frac{(n-1)}{n}} = \frac{T_4}{T_3}$$

Substituting,

$$W_{c,\text{ with } CV} = \left(\frac{n}{n-1}\right)(m_1RT_1 - m_2RT_4)\left[\frac{T_2}{T_1} - 1\right]$$

Ideally there shall be no change in temperature during suction and delivery i.e. $T_1 = T_4$ & $T_2 = T_3$. Above equation can be written as

$$W_{c,\text{ with } CV} = \left(\frac{n}{n-1}\right)(m_1RT_1 - m_2RT_1)\left[\frac{T_2 - T_1}{T_1}\right]$$

Or,

$$W_{c,\text{ with } CV} = \left(\frac{n}{n-1}\right)(m_1 - m_2)\,R(T_2 - T_1)$$

Where $(m_1 - m_2)$ indicates the mass of air sucked or delivered. For unit mass of air delivered the work done per kg of air can be given as,

$$W_{c,\text{ with } CV} = \left(\frac{n}{n-1}\right) R(T_2 - T_1), \text{ per kg of air}$$

Thus from above expressions it is obvious that the clearance volume reduces the effective swept volume i.e. the mass of air handled but the work done per kg of air delivered remains unaffected.

Power required to run the compressor

For single acting compressor,

$$\text{Power required} = \left[\left(\frac{n}{n-1}\right) p_1 (V_1 - V_4)\left\{\left(\frac{p_2}{p_1}\right)^{\frac{(n-1)}{n}} - 1\right\}\right] \times N$$

$$\text{for double acting compressor, power} = \left[\left(\frac{n}{n-1}\right) p_1 (V_1 - V_4)\left\{\left(\frac{p_2}{p_1}\right)^{\frac{(n-1)}{n}} - 1\right\}\right] \times 2N$$

Volumetric Efficiency

It is defined as the ratio of actual volume of air sucked into the cylinder during suction stroke to the piston displacement (PD) or swept volume (V_s) of the cylinder. Volumetric efficiency of compressor is often referred to at free air conditions, i.e., temperature and pressure of the environment, which may be taken as 15°C & 101.325 kPa, if not mentioned.

Consideration for free air is necessary as otherwise the different compressors can not be compared using volumetric efficiency because specific volume or density of air varies with altitude. This concept is used for giving the capacity of compressor in terms of 'free air delivery' (FAD). "Free air delivery is the volume of air delivered being reduced to free air conditions". In case of air the free air delivery can be obtained using perfect gas equation as,

$$\frac{p_a \cdot V_a}{T_a} = \frac{p_1 (V_1 - V_4)}{T_1} = \frac{p_2 (V_2 - V_3)}{T_2}$$

Volumetric efficiency referred to free air conditions,

$$\eta_{vol} = \frac{\text{Volumeof air sucked referred to free air conditions (FAD)}}{\text{Swept Volume}}$$

$$= \frac{V_1 - V_4}{V_1 - V_3}$$

$$= \frac{(V_s + V_c) - V_4}{V_s}$$

Here V_c is clearance volume, $V_c = V_3$ and $V_s = V_1 - V_3$.

CHAPTER-4

STEAM GENERATOR

Introduction

A steam generator or boiler, usually, a closed vessel made of steel. Its function is to transfer the heat produced by the combustion of fuel (solid, liquid or gaseous) to water, and ultimately to generate steam. The steam produced may be supplied :

1. To an external combustion engine, i.e. steam engines and turbines.

2. At low pressures for industrial process work in cotton mills, sugar factories, breweries, etc, and

3. For producing hot water, which can be used for heating installations at much lower pressures.

Classification of steam boilers.

Though there are many classification of steam boilers, yet the following are important from the subject point of view :

1. ***According to the contents in the tube***. The steam boilers, according to the contents in the tube may be classified as :

(a) Fire tube or smoke tube boiler and

(b) Water tube boiler.

In fire tube steam boilers, the flames and hot gases, produced by the combustion of fuel, pass through the tubes (called multi-tubes) which are surrounded by water. The heat is conducted through the walls of the tubes from the hot gases to the surrounding water. Examples of fire tube boilers are : Simple vertical boiler, Cochran boiler, Lancashire boiler, Cornish boiler, Scotch marine boiler, Locomotive boiler and Velcon boiler.

In water tube steam boilers, the water is contained inside the tubes (called water tubes) which are surrounded by flames and hot gases from outside. Examples of water tube boilers are : Babcock and Wilcox boiler, Stirling boiler, La-Mont boiler, Benson boiler, Yarrow boiler and Loeffler boiler.

2. ***According to the position of the furnace***. The steam boilers, according to the position of the furnace are classified as :

(a) Internally fired boilers, and

(b) Externally fired boilers

In internally fired steam boilers, the furnace is located inside the boiler shell. Most of the fire tube steam boilers are internally fired.

In externally fired steam boilers, the furnace is arranged underneath in a brick-work setting. Water tube steam boilers are always externally fired.

3. ***According to the axis of the shell***. The steam boilers, according to the axis of the shell, may be classified as :

(a) Vertical boilers and

(b) Horizontal boilers.

In vertical steam boilers, the axis of the shell is vertical. Simple vertical boiler and Cochran boiler are vertical boilers.

In horizontal steam boilers, the axis of the shell is horizontal. Lancashire boiler, Locomotive boiler and Babcock and Wilcox boiler are horizontal boilers.

4. ***According to the number of tubes***. The steam boilers, according to the number of tubes, may be classified as :

(a) Single tube boilers and

(b) Multi tubular boilers

In single tube steam boilers there is only one fire tube or water tube. Simple vertical boiler and Cornish boiler are single tube boilers.

In Multitubular steam boilers, there are two or more fire tubes or water tubes. Lancashire boiler, Locomotive boiler, Cochran boiler, Babcock and Wilcox boiler are multitubular boilers.

5. ***According to the method circulation of water and steam***. The steam boilers, according to the method of circulation of water and steam, may be classified as :

(a) Natural circulation boilers, and

(b) Forced circulation boilers.

In natural circulation steam boilers, the circulation of water is by natural convention currents, which are set up during the heating of water. In most of the steam boilers, there is a natural circulation of water.

In forced circulation steam boilers, there is a forced circulation of water by a centrifugal pump driven by some external power. Use of forced circulation is made in high pressure boilers such as La-Mont boiler, Benson boiler, Loeffler boiler and Velcon boiler.

6. ***According to the use.*** The steam boilers, according the their use, may be classified as

(a) Stationary boilers, and

(b) Mobile boilers

The stationary steam boilers are used in power plants, and in industrial process work. These are called stationary because they do not move from one place to another.

The mobile steam boilers are those which move from one place to another. These boilers are locomotive and marine boilers.

7. ***According to the source of the heat***. The steam boilers may also be classified according to the source of heat supplied for producing steam. The sources maybe the combustion of solid, liquid or gaseous fuel, hot waste gases as by-products of other chemical processes, electrical energy or nuclear energy etc.

Cochran Boiler or Vertical Multitubular Boiler

These are various designs of vertical multitubular boilers, A Cochran boiler is considered to be one of the most efficient type of such boilers. It is an improved type of simple vertical boiler.

This boiler consists of an external cylindrical shell and a fire box as shown in Fig. The shell and fire box are both hemispherical. The hemispherical crown of the boiler shell gives pressure of steam and strength to withstand the pressure of steam inside the boiler. The hemispherical crown of the fire box is also advantageous for resisting intense heat. The fire box and the combustion chamber is connected through a short pipe. The flue gases from the combustion chamber flow to the smoke box through a number of smoke tubes. Then tubes generally have 62.5 mm external diameter and are 165 in number. The gases from the smoke box pass to the atmosphere through a chimney. The combustion chamber is lined with fire bricks on the shell side. A manhole near the top of the crown on the shell is provided for cleaning.

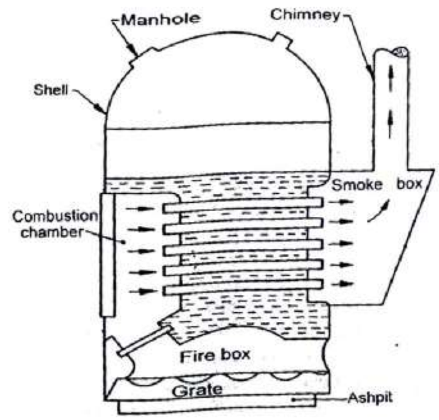


Fig. Cochran Boiler

At the bottom of the fire box, there is a grate (in case of coal firing) and the coal is fed through the fire hole. If the boiler is used for oil firing, no grate is provided, but the bottom of the fire box is lined with firebricks. The oil burner is fitted at the fire hole.

Babcock and Wilcox Boiler

It is a straight tube, stationary type water tube boiler, as show in Fig. It consist of a stem and water drum (1). It is connected by a short tube with uptake header or riser (2) at the back end.

The water tubes (5) (100mm diameter) are inclined to the horizontal and connects the uptake head to the down take header. Each row of the tubes is connected with two headers, and there are plenty of such rows. The headers are curved when viewed in the direction of tubes so that one tube is not in the space of other, and hot gases can pass properly after heating all the tubes. The headers are provided with hand holes in the front of the tubes and are covered with caps (18).

A mud box (6) is provided with each down take header and the mud, that settles down is removed. There is slow moving automatic chain grate on which the coal is fed from the hopper (21). A fire bricks baffle causes hot gases to move upwards and downwards and again upwards before entering shell by a chain (22) which passes over a pulley to the boiler is suspended on steel girders, and surrender on all the four sides by fire brick walls. The doors (4) are provided for a man

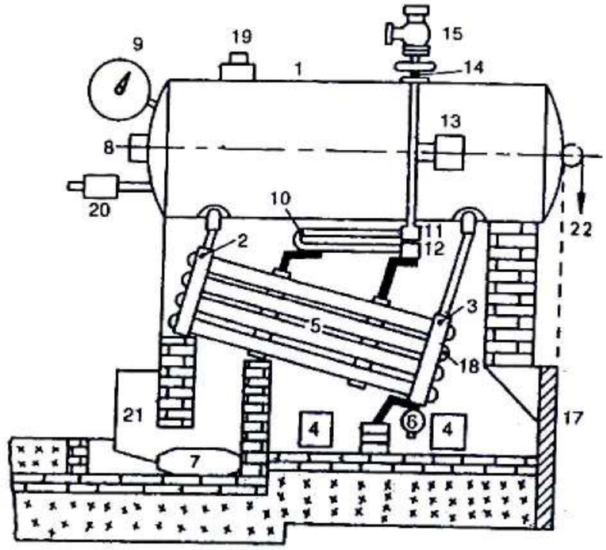


Fig. Babcock and Wilcox Boiler

to enter the boiler for repairing and cleaning. Water circulates from the drum (1) into the header (2) and through the tubes (5) to header (3) and again to the drum. Water continues to circulate like this till it is evaporated. A steam superheater consists of a large number of steel tubes (1) and contains two boxes; one is superheated steam box (11) and other is saturated steam box (12).

The steam generated above the water level in the drum flows in the dry pipe (13) and through the inlet tubes into the superheated steam box (11). It then passes through the tubes (10) into the becomes superheated. The steam, during the passage through tubes (10), gets further heated and through the outlet pipe (14) to the stop valve (15).

The boiler is fitted with usual mountings, such as safely vale (19), feed valve (20), water level indicator (8) and pressure gauge (9).

Comparison between Water and Fire Tube boilers

Following are the few points of comparison between a water tube and a fire tube boiler.

	Water tube boiler	Fire tube boiler
1.	The water circulates inside the tubes which are surrounded by hot gases from the furnace.	The hot gases from the furnance the furnace pass through the tubes which are surrounded by water.
2.	It generates steam at a higher pressure upto 165 bar.	It can generation of steam only up to 24.5 bar.
3.	The rate of generation of steam is high i.e. upto 450 tonnes per hour.	The rate of generation of steam is low, i.e. upto 9 tonnes per hour.
4.	For a given power, the floor area required for the generation of steam is less, i.e. about 5 m^2 per tone per hour of steam generation.	The floor area required is more, i.e. about 8m^2 per tonne per hour of steam generation.
5.	Overall efficiency with economizer is upto 90%.	Its overall efficiency is only 75%.
6.	It can be transported and erected easily as its various parts can be separted.	The transportation and erection is difficult.
7.	It is preferred for widely fluctuating loads.	It can also cope reasonably with sudden increase in load but for a shorter period.
8.	The direction of water circulation is well defined.	The water does not circulate is a definite direction.
9.	The operating cost is high.	The operating cost is less.
10.	The bursting chance are more.	The bursting chances are less.
11.	The bursting does not produce any destruction to the whole boiler.	The bursting produces greater risk to the damage of the property.
12.	It is used for large power plants.	It is not suitable for large plants.

Boiler Mountings and Accessories

Introduction

Boiler mountings and accessories are reuiqred for the proper and satisfactory functioning of the steam boilers. Now in this chapter, we shall discuss these fittings and appliances which are commonly used these days.

Boiler Mountings

These are the fittings, which are mounted on the boiler for its proper and safe functioning. Though there are many types of boiler mountings, yet the following are important from the subject point of view :

1. Water level indicator
2. Pressure gauge
3. Safety valves
4. Stop valve
5. Blow off cock
6. Feed check valve and
7. Fusible plug

1. Water level indicator

It is important fitting, which indicates the water level inside the boiler to an observer. It is a safety device upon which the correct working of the boiler depends. This fitting may be seen in front of the boiler, and are generally two in number.

A water level indicator, mostly employed in the steam boiler is shown in Fig. It consists of the cocks and a glass tube. Steam cock C_1 Keeps the glass tube in connection with the steam space. Water cook C_2 Puts the glass tube in connection with the water in the boiler. Drain cock C_3 is used at frequent intervals to ascertain that the steam and water cocks are clear.

In the working of a steam boiler and for the proper functioning of the water level indicator, the steam and water cocks are opened and the drain cock is closed. In this case, the handles are place in a vertical position as shown in Fig. The rectangular passage at the ends of the glass tube contains two balls.

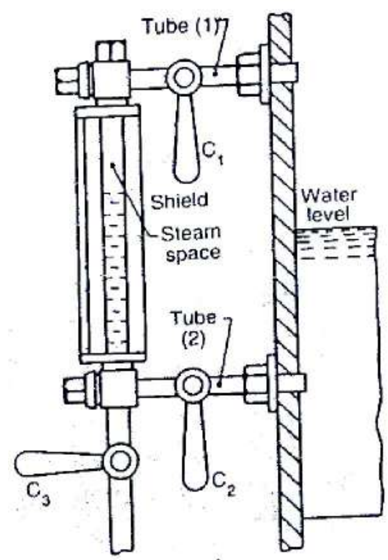


Fig. Water level indicator

In case the glass tube is broken, the two balls are carried along its passages to the ends of the glass tube. It is thus obvious, that water and steam will not escape out. The glass tube can be easily replaced by closing the steam and water cocks and opening the drain cock.

When the steam boiler is not working, the bolts may be removed for cleaning. The glass tube is kept free from leaking by means of conical ring and the gland nut.

2. Pressure gauge

A pressure gauge is used to measure the pressure of the steam inside the steam boiler. It is fixed in front of the steam boiler. The pressure gauges generally used are of bourden type.

A bourden pressure gauge, in its simplest form, consists of an elliptical elastic tube ABC bent into an arc of a circle, as shown in Fig. This bent up tube is called bourden's tube.

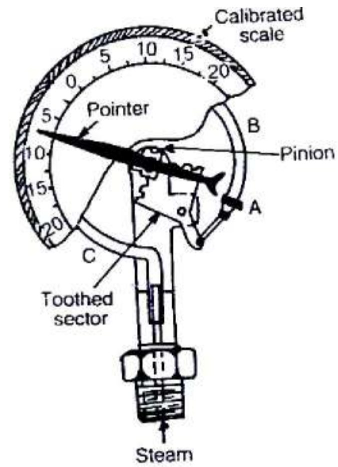


Fig. Water level indicator

One end of the tube gauge is fixed and connected to the steam space in the boiler. The other end is connected to a sector through a link. The steam, under pressure, flows into the tube. As a result of this increase pressure, the bourden's tube tends to straighten itself. Since the tube is encased in a circular curve, therefore it tends to become circular instead of straight. With the help of a simple pinion and sector arrangement, the elastic deformation of the bourdens tube rotates the pointer. This pointer moves over a calibrated scale, which directly gives the gauge pressure.

3. Safety valves

These are the devices to the steam chest for preventing explosions due to excessive internal pressure of steam. A steam boiler is, usually, provided with two safety valves. These are directly placed on the boiler. In brief, the function of a safety valve is to blow off the steam when the pressure of steam inside the boiler exceeds the working pressure. The following are the four types of safety valves :

(i) Lever safety valve,

(ii) Dead weight safety valve

(iii) High steam and low water safety valve

(iv) Spring loaded safety valve.

It may be noted that the first three types of the safety valves are usually employed with stationary boilers, but the fourth type is mainly used for locomotive and marine boilers.

(i) Lever safety valve

A lever safety valve used on steam boiler is shown Fig. It serves the purpose of maintaining constant safe pressure inside the steam boiler. If the pressure inside the boiler exceeds the designed limit, the valve lifts from its seat and blows off the steam pressure automatically.

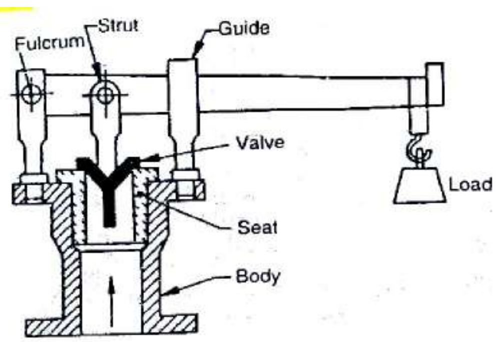


Fig. Lever safety valve

A lever safety valve consists of a valve body with a flange fixed to the steam boiler. The bronze valve seat is screwed to the body, and the valve is also made of bronze. It may be noted that by using the valve and seat of the same material, rusting is considerably reduced. The thrust on the valve is transmitted by the strut. The guide keeps the lever in a vertical plane. The load is properly adjusted at the other end of the lever.

(ii) Dead weight safety valve

A dead weight safely valve, used for stationary boilers, is shown in Fig. The valve is made of gun metal, and rests on its gun metal seat. It is fixed to the top of a steel pipe. This pipe is bolted to the mountings block, riveted to the top of the shell. Both the valve and the pipe are covered by a case which contains weights. These weights keep the valve on its seat under normal working pressure. The case hangs freely over the valve to which it is secured by means of a nut.

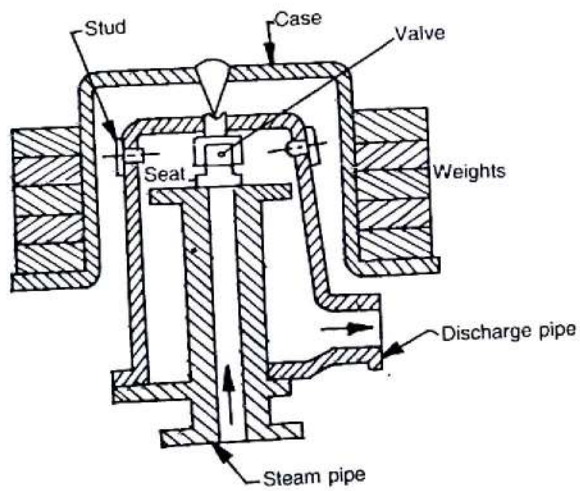


Fig. Dead weight safety valve

When the pressure of steam exceeds the normal pressure, the valve as well as the case (along with the weights) are lifted up from its seat. This enables the steam to escape through the discharge pipe, which carries the steam outside the boiler house.

The lift of the valve is controlled by the studs. The head of the studs projects into the interior of the casing. The centre of gravity of the dead weight safety valve is considerably below the valve which ensures that the load hangs vertically.

The dead weight safety valve has the advantage that it cannot be readily tempered because any added weight be equal to the total increases pressure of steam on the valve. The only disadvantage of these valves, is the heavy which these valves carry.

(iii) High steam and low water safety valve

These valves are placed at the top of Cornish and Lancashire boilers. It is combination of two valves, one of which is the lever safety valve which blows off steam when the working pressure of steam exceeds. The second valve operates blowing off the steam when the water level becomes too low.

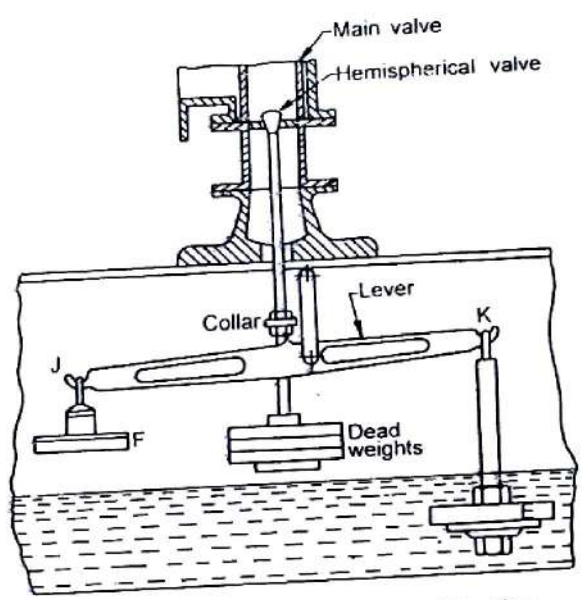


Fig. High steam and low water safety valve

A best known combination of high steam low water safety valve is shown in Fig. It consists of a main valve (known as lever safety valve) and rests on its seat. In the centre of the main valve, a seat for a hemispherical valve is formed for low water operation. This valve is loaded directly by the dead weights attached to the valve by a long rod. There is a lever J.K, which has its fulcrum at K. the lever has weight E suspended at the K. when it is fully immersed in water, it is balanced by a weight F at the other end J of the lever.

When the water level falls, the weight E comes out of water and the weight F will not be sufficient to balance weight E. Therefore weight E comes down. There are two projections on the lever to the left of the fulcrum which comes in contact with a collar attached to the rod. When weight E comes down, the hemispherical valve is lifted up and the steam escapes with a loud noise, which warns the operator. A drain pipe is provided to carry water, which is deposited in the valve casing.

(iv) Spring loaded safety valve.

A spring loaded safety valve is mainly used for locomotives and marine boilers. It is loaded with spring instead of weights. The spring is made of round or square spring steel rod in helical form. The spring may be in tension or compression, as the steam pressure acts along the axis of the spring. In actual practice, the spring is placed in compression.

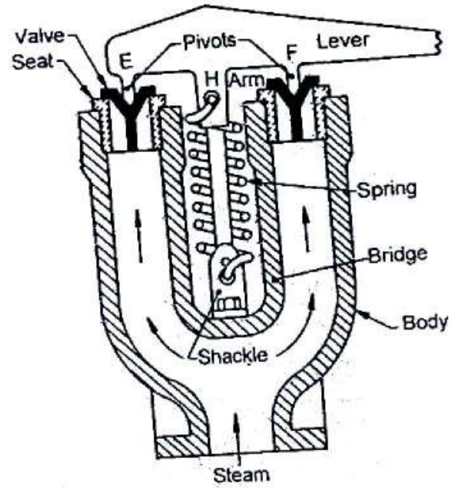


Fig. Spring loaded safety valve

A Ramsbottom spring loaded safety valve is shown in Fig.   It I, usually, fitted to locomotives. It consists of a cast iron body connected to the top of a boiler. It has two separate valves of the same size. These valves have their seating's in the upper ends of two hallow valve chests. These valve chests are united by a bridge and a base. The base is bolted to a mounting block on the top of a boiler over the fire box.

The valves are held down by means of a spring and a lever. The lever has two pivots E and F. the pivot E is joined by a pin to the lever, while the pivot F is forged on the lever. These pivots rest on the centre's of the valves. The upper end of the spring is hooked to the arm H, while the lower end of the shackle, which is secured to the bridge by a nut. The spring has two safety links, one behind the other, or one either side of the lever connected by pins at the ends. The lower pin passes through the shackle while the upper one passes through slot in arm H of the lever. The lever has an extension, which projects into the driver's cabin. By pulling or raising the lever, the driver can release the pressure from either valve separately.

4. Steam Stop valve

It is the largest valve on the steam boiler. It is, usually, fitted to the highest part of the shell by means of a flange as shown in Fig.   The principal functions of a stop valve are :

1. To control the flow of steam from the boiler to the main stream pipe.

2. To shut off the steam completely when required.

The body of the stop valve is made of cast iron or cast steel. The valve, valve seat and the nut through which the valve spindle works, are made of brass or gun metal.

The spindle passes through a gland and stuffing box. The spindle is rotated by means of a hand wheel. The upper

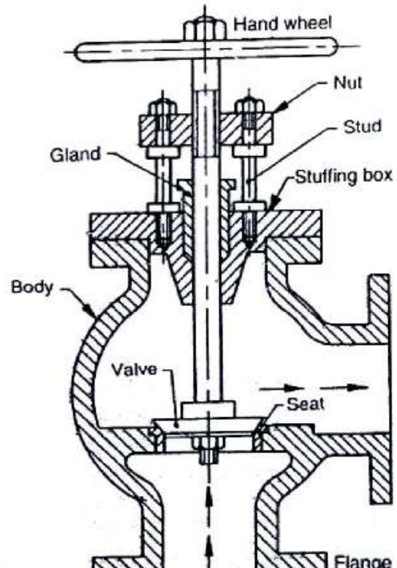


Fig. Steam Stop valve

portion of the spindle is screwed and made to pass through a nut in across head carried by two pillars. The pillars are screwed in the cover of the body as shown in the figure. The boiler pressure acts under the valve, so that the valve must be closed against the pressure. The valve is, gen¬erally, fastened to the spindle which lifts it up.

A non-return valve is, sometimes, fitted near the stop valve to prevent the acciden¬tal admission of steam from other boilers. This happens when a number of boilers are con¬nected to the same pipe, and when one is empty and under repair.

5. Blow off cock

The principal functions of a blow-off cock are :

3. To empty the boiler whenever requited.

4. To discharge the mud, scale or sediments which are accumulated at the bottom of the boiler.

The blow-off cock, as shown in Fig. , is fitted to the bottom of a boiler drum and consists of a conical plug fitted to the body or casing. The casing is packed, with asbestos packing, in grooves round the top and bottom of the plug. The asbestos packing is made tight and plug bears on the packing. It may be noted that the cocks packed in this way keep the grip better under high pressure and easily operated than unpacked.

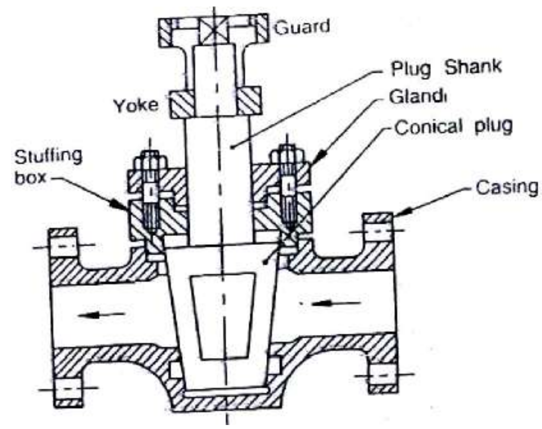


Fig. Blow off cock

The shank of plug passes through a gland and stuffing box in the cover. The plug is held down by a yoke and two stud bolts (not shown in the figure). The yoke forms a guard on it. There are two vertical slots on the inside of a guard for the box spanner to be used for operating the cock.

6. Feed check valve

It is a non-return valve, fitted to a screwed spindle to regulate the lift. Its function is to regulate the supply of water, which is pumped into the boiler, by the feed pump. This valve must have its spindle lifted before the pump is started. It is fitted to the shell slightly below the normal water level of the boiler.

A feed check valve for marine boilers is shown in Fig. . It consists of a valve whose lift is controlled by a spindle and hand wheel. The body of the valve is made of brass casting and except spindle, its every part is made of brass. The spindle is made of muntz metal. A flange is bolted to the end of boiler at a point from which perforated pipe leads the feed water. This pipe distributes the water in the boiler uniformly.

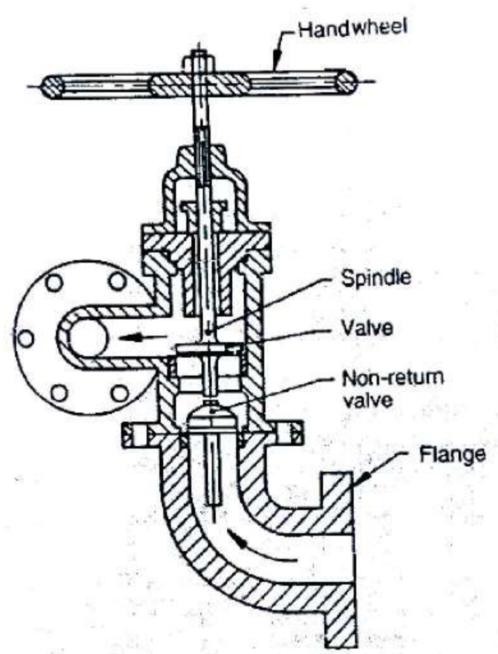


Fig. Feed check valve and

7. Fusible plug

It is fitted to the crown plate of the furnace or the fire box. Its object is to put off the fire in the furnace of the boiler when the level of water in the boiler falls to an unsafe limit, and thus avoids the explosion which may take place due to overheating of the furnace plate.

A fusible plug consists of a hollow gun metal plug P, as shown in Fig. It is screwed to the furnace crown. A second hollow gun metal plug P2 is screwed to the first plug. There is also a third hollow gun metal plug P3 separated from P, by a ring of fusible metal. The inner surface of P2 and outer surface of P3 are grooved so that when the fusible metal is poured into the plug, P2 and P3 are locked together. A hexagonal flange is provided on plug P, to take a spanner for fixing or removing the plug Pr There is a hexagonal flange on plug P2 for fixing or removing it. The fusible metal is protected from fire by the flange on the lower end of plug P2. There is also a contact at the top between P2 and P3 so that the fusible metal is completely enclosed.

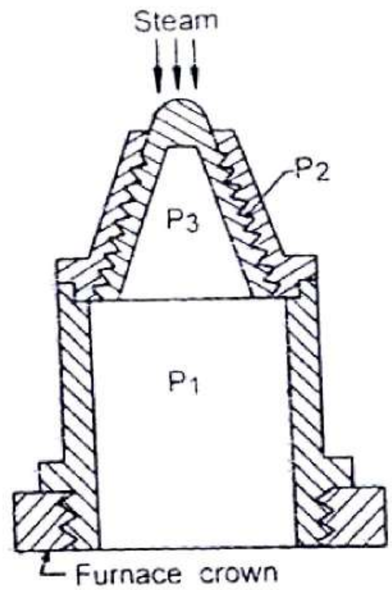


Fig. Fusible plug

The fusible plugs must be kept in a good condition and replaced annually. A fusible plug must not be refilled with anything except fusible metal.

Boiler Accessories

These are the devices which are used as integral parts of a boiler, and help in running efficiently. Though there are many types of boiler accessories, yet the following are important from the subject point of view :

1. Feed pump
2. Superheater
3. Economiser and
4. Air Preheater

Fig. shows the schematic diagram of a boiler plant with the above mentioned accessories.

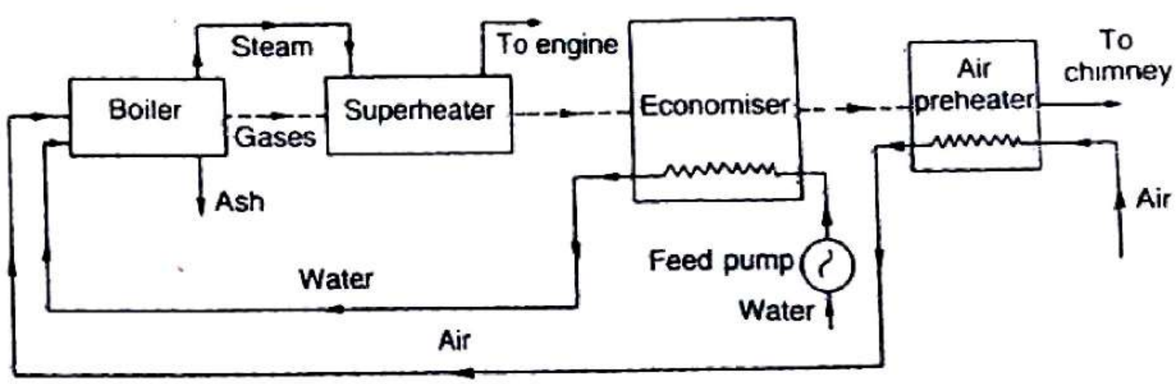


Fig. schematic diagram of a boiler plant

1. Feed Pump

We know that water, in a boiler, is continuously converted into steam, which is used by the engine. Thus we need a feed pump to deliver water to the boiler.

The pressure of steam inside a boiler is high. So the pressure of feed water has to be increased proportionately before it is made to enter the boiler. Generally, the pressure of feed water is 20% more than that in the boiler.

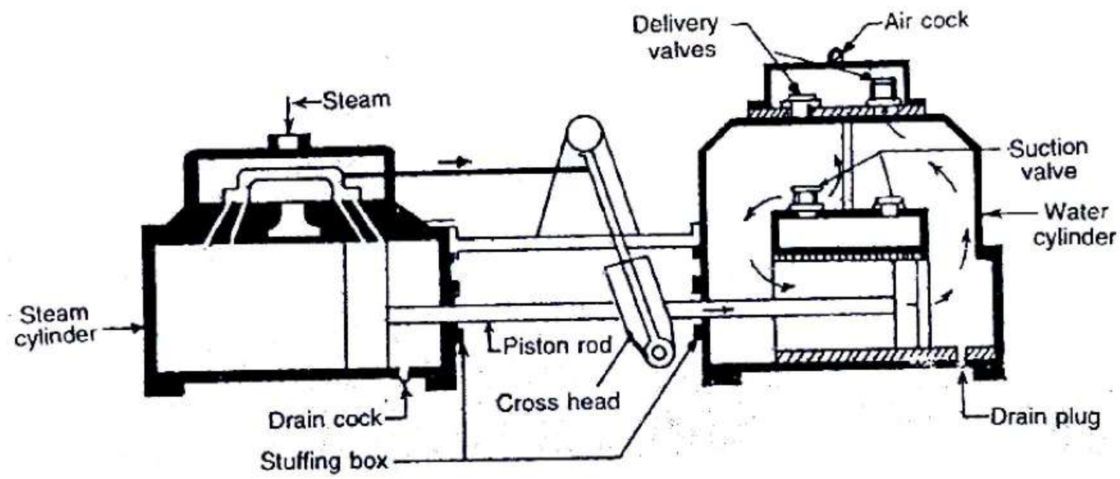


Fig. Duplex feed Pump

A feed pump may be of centrifugal type or reciprocating type. But a double acting reciprocat¬ing pump is commonly used as a feed pump these days. The reciprocating pumps are run by the steam from the same boiler in which water is to be fed. These pumps may be classified as simplex, duplex and triplex pumps according to the number of pump cylinders. The common type of pump used is a duplex feed pump, as shown in Fig. This pump has two sets of suction and delivery valves for forward and backward stroke. The two pumps work alternately so as to ensure continuous supply of feed water.

2. Superheater

A superheater is an important device of a steam generating unit. Its purpose is to increase the temperature of saturated steam without raising its pressure. It is generally an integral part of a boiler, and is placed in the path of hot flue gases from the furnace. The heat, given up by these flue gases, is used in superheating the steam. Such superheaters, which are installed within the boiler, are known as integral superheaters.

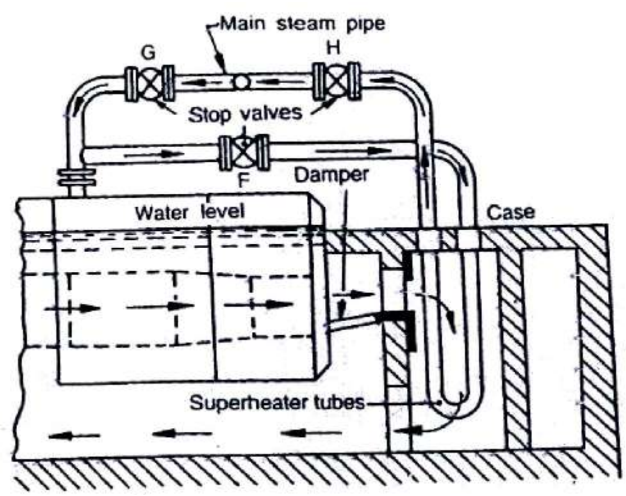


Fig. Superheater

A Sudgen's superheater commonly employed with Lancashire boilers is shown in Fig. It consists of two mild steel boxes or heaters from which hangs a group of solid drawn tubes bent to U-form. The ends of these tubes are expanded into the headers. The tubes are arranged in groups of four and one pair of headers generally carries ten of these groups or forty tubes in all. The outside of the tubes can be cleaned through the space between the headers. This space is closed by covers.

The steam enters at one end of the rear header and leaves at the opposite end of the front header. The overheating of superheater tubes is prevented by the use of a balanced damper which is operated by the handle. The superheater is in action when the damper is in a position as shown in the figure. If the damper is in vertical position, the gases pass directly into the bottom flue without passing over the superheater tubes. In this way, the superheater is out of action. By placing the damper in intermediate position, some of the gases will pass over the superheater tubes and the remainder will pass directly to the bottom flue. It is thus obvious, that required degree of heat for superheating may be obtained by altering the position of the damper.

It may be noted that when the superheater is in action, the stop valves G and H are opened and F is closed. When the steam is taken directly from the boiler, the valves G and H are closed and F is open.

3. Economiser

An economiser is a device used to heat teed water by utilising the heat in the exhaust Hue gases before leaving through the chimney. As the name indicates, the economiser improves the economy of the steam boiler.

A well known type of economiser is Greens economiser. It is extensively used for stationary boilers, especially those of Lancashire type. It consists of a large number of vertical pipes or tubes placed in an enlargement of the flue gases between the boiler and chimney as shown in Fig. These tubes are 2.75 meters long, 114 mm in external diameter and 11.5 mm thick and are made of cast iron.

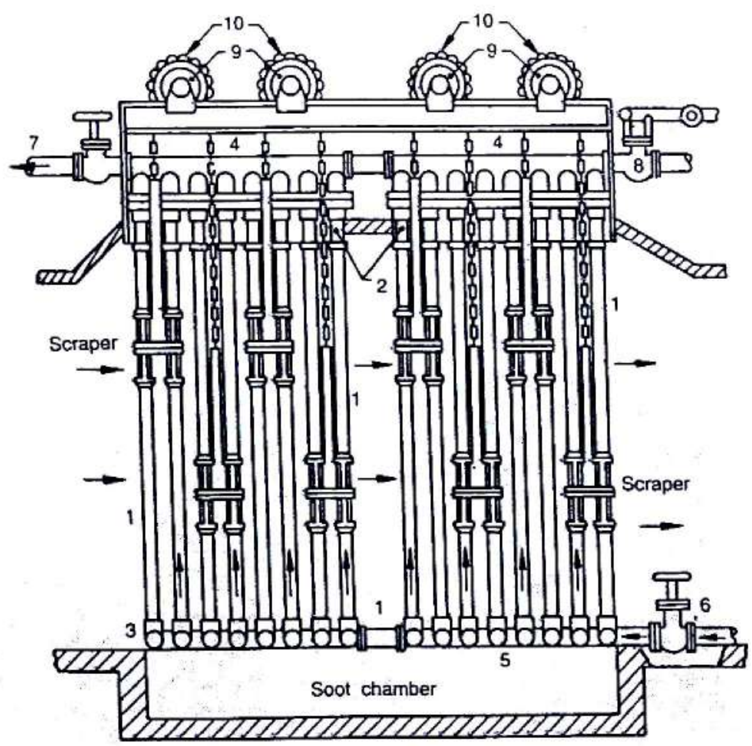


Fig. Economiser

The economiser is built-up of transverse section. Each section consists of generally six or eight vertical tubes (1). These tubes are joined to horizontal pipes or boxes (2) and (3) at the top and bottom respectively. The top boxes (2) of the different sections are connected to the pipe (4), while the bottom boxes are connected to pipe (5). The pipes (4) and (5) are on opposite sides, which are outside the brickwork enclosing the economiser.

The feed water is pumped into the economiser at (6) and enters the pipe (5). It then passes into the bottom boxes (3) and then into the top boxes (2) through the tubes (1). It is now led by the pipe (4) to the pipe (7) and then to the boiler. There is a blow-off cock at the end.of the pipe (5) opposite to the feed inlet (6). The purpose of this valve is to remove mud or sediment deposited in the bottom boxes. At the end of pipe (4) (opposite to the feed outlet) there is a safety valve.

It is essential that the vertical tubes may be kept free from deposits of soot, which greatly affect efficiencies of the economiser. Each tube is provided with scraper for this purpose. The scrapers of two adjoining sections of tubes are grouped together, and coupled by rods and chains to the adjacent group of scrapers. The chain passes over a pulley (9) so that one group of scrapers balance the adjacent group. The pulley (9) of each chain is connected to a worm wheel (10) which is driven by a worm on a longitudinal shaft (not shown in the figure). The scrapers automatically reverse when they reach the top or bottom end of the tubes. These are kept in motion continuously when the economiser is in use. The speed of scraper is about 46 m/h.

It may be noted that the temperature of feed should not be less than about 35° C, otherwise there is a danger of corrosion due to the moisture in the flue gases being deposited in cold tubes. Following are the advantages of using an economiser

4. There is about 15 to 20% of coal saving.

5. It increases the steam raising capacity of a boiler because it shortens the time required to convert water into steam.

6. It prevents formation of scale in boiler water tubes, because the scale tormed in the economiser tubes, can be cleaned easily.

7. Since the feed water entering the boiler is hot, therefore strains due to unequal expansion are minimised.

4. Air Preheater

An air preheater is used to recover heat from the exhaust flue gases. It is installed between the economiser and the chimney. The air required for the purpose of combustion is drawn through the air preheater where its temperature is raised. It is then passed through ducts to the furnace. The air is passed through the tubes of the heater internally while the hot flue gases are passed over the outside of the tubes.

The following advantages are obtained by using an air preheater:

1. The preheated air gives higher furnace temperature which results in more heat transfer to the water and thus increases the evaporative capacity per kg of fuel.

2. There is an increase of about 2% in the boiler efficiency for each 35-40° C rise in temperature of air.

3. It results in better combustion with less soot, smoke and ash.

It enables a low grade fuel to be burnt with less excess air.

CHAPTER-5

STEAM POWER CYCLE

STEAM POWER PLANT CYCLE:

Water is the working fluid here. It undergoes a change of phase in the course of cycle. Energy is released by the continuous burning of the fuel in the combustion chamber of a steam generation plant that includes a boiler and superheater. The working fluid is charged to the boiler via a BFW feed pump. Heat is transferred to the water in the boiler whereupon a high pressure and high temp saturated steam is generated in the boiler. The dry saturated HP steam is converted into a HP superheated steam in the super heater.

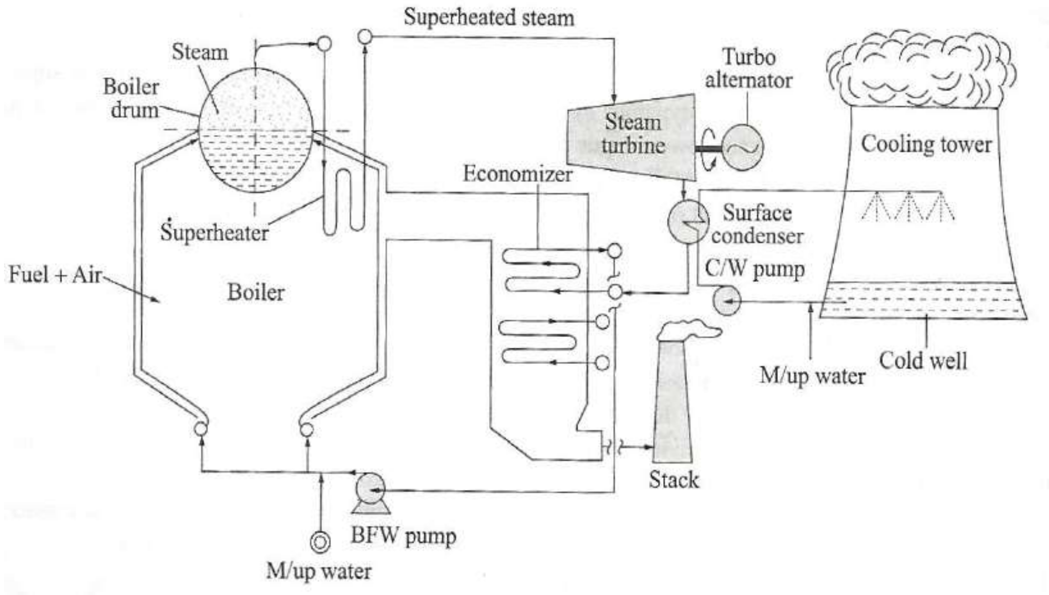
The high pressure and high temperature superheated steam is then allowed to expand through the steam turbine. As the steam passes over the blades of the turbine, it sheds its enthalpy which is converted into shaft work of the turbine which then generates power from the turbo alternator coupled to the turbine.

The steam after expansion in the ST is exhausted into a total condenser which is essentially a water steam heat exchanger wherein the exhaust steam is condensed into a condensate only to be recycled to the boiler via the boiler feed pump.

So a simple steam power cycle comprises a boiler + turbine + condenser + BFW pump where water is acting as the working fluid.`

Sometimes a vapour power cycle is referred to as a pressure limited cycle indicating the power plant operates between two pressure limits:

- The higher pressure limit is the boiler pressure
- The lower pressure limit is the condenser pressure.



As the case of first approximation, the steam power plant cycle is idealized as a quasi- static process approximating an ideal heat engine cycle:

$$\sum_{cycle} Qnet = \sum_{cycle} Wnet$$

Or $Q_1 - Q_2 = W_T - W_P$

Where Q_1= the heat input to water in the SGP(BFW preheater +boiler + superheater) in $kj\,.kg^{-1}$

Q_2 = the heat rejected from the working fluid (in the surface condenser) $kj\,.kg^{-1}$

W_T = the work output(the shaft work of the steam turbine) $kj\,.kg^{-1}$

W_P = the mechanical work input(the BFW pump work) $kj\ .kg^{-1}$

The efficiency of the ideal vapour power cycle,η_{cycle} = $\frac{\sum Wnet}{Q1}$

Thermal efficiency (η) :

Thermal efficiency is an important index of performance of a heat engine or steam power plant cycle. It is obtained from the first law: η = $\frac{w}{Qinput}$

CARNOTS CYCLE:

An ideal vapour power cycle would follow a carnot vapour cycle that comprises two iso-thermal and two adiabatic processes. In the vapour cycle ,the working substances changes phases .these are attainable by two internally reversible isothermal processes in the form of boiling of the liquid and condensation of the vapour. But, the heat transfer from a high temp. reservoir as well as from the condensing vapour to a low temp. reservoir will remain externally irreversible.

Process 4-1:

Isothermal heat addition to the water. The water is converted into a dry saturated steam

Heat added = Qadd

Process1-2:

Isentropic expansion of the steam in the steam turbine i.e; the steam is expanding adiabatically.

Heat interaction is nil, positive work output=W

Process2-3:

Isothermal heat rejection. Heat is extracted from the waste steam exhausted by the steam turbine to the condenser,

Heat rejected = Qrej

Process 3-4:

The steam water mixture is pumped to the boiler.

Input work = pump work = Wp

Net work output Wnet = Woutput - Wp

Therefore, efficiency, $\eta = \frac{Wnet}{Qadd} = \frac{Qadd-Qrej}{Qadd}$

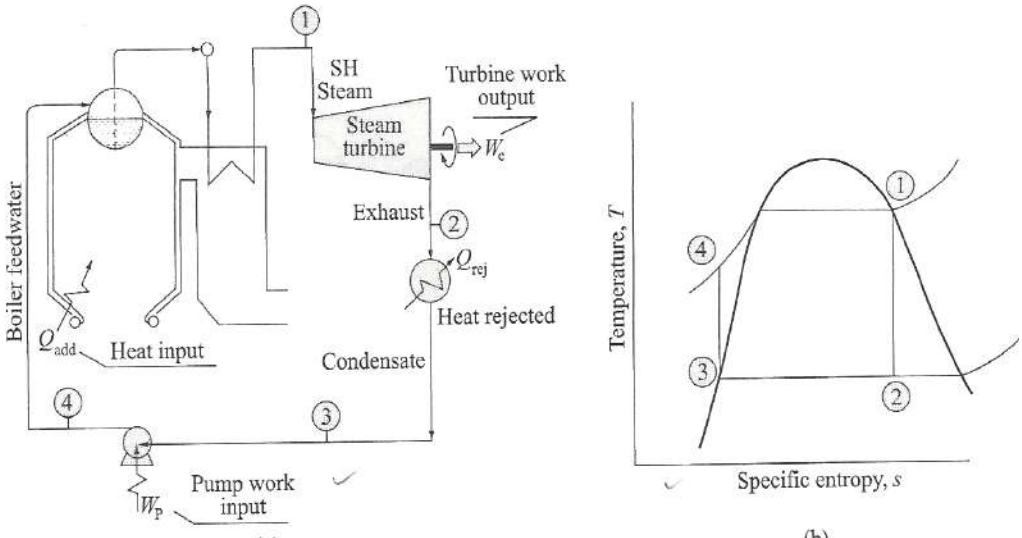
$$=1-\frac{Qrej}{Qadd}$$

$$=1-\frac{m(h2-h3)}{m(h1-h4)}$$

Also, $\eta = 1-\frac{T2}{T1}$

RANKINE CYCLE:

A rankine vapour cycle is based on a modified carnot cycle to overcome its limitations. It consists of four steady flow processes as in figure



(a) (b)

Process 4-1:

Heat is added in the boiler to the BFW, which is a constant pressure process generating a dry, saturated steam at saturation temp. corresponding to the boiler operating pressure,

$$Qadd = m(h1 - h4)$$

Process 1-2:

The steam is reversibly and adiabatically expanded in the turbine. So, turbine work input = We = m(h1 - h2)

Process 2-3:

Constant pressure heat rejection in the condenser. The cooling water extracts the latent heat of condensation from the exit steam exhausted to the condenser.the condensation is complete. The entire vapour is converted into a condensate.

Therefore heat rejection = m(h2 - h3)

Process 3-4:

Pump work. This work must be apportioned from the turbine output.

Wp = m(h4 - h3)

Net work output,Wnet = We - Wp

Therefore, efficiency,

$$\eta = \frac{Wnet}{Qadd}$$

$$= \frac{We - Wp}{Qadd}$$

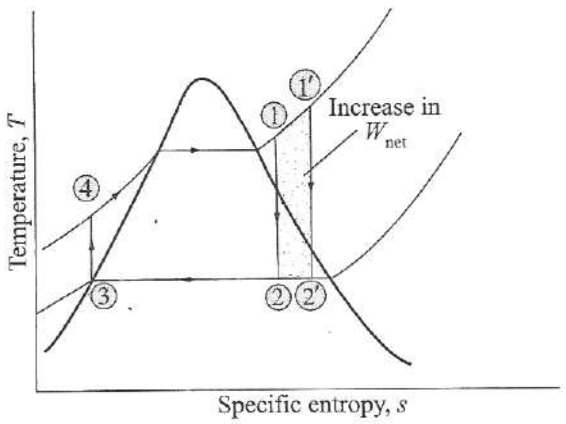
$$= \frac{m(h1-h2)-m(h4-h3)}{m(h1-h4)}$$

RANKINE CYCLE WITH SUPERHEATED STEAM:

If the heating of the working fluid(BFW) is continued beyond the dry saturation point, i.e; well into superheat regime before feeding it to the turbine,i.e; state$1'$ instead of state 1 , the amount of heat added increase bringing about an incipient increase in the work output

$(\Delta. Woutput = area\ 1 - 1' - 2' - 2)$

So, superheating begets a higher cycle efficiency.



RANKINE CYCLE WITH SUPERHEATED STEAM:-

EFFECT OF INCREASING PRESSURE WHILE BEING TEMPERATURE CONSTANT:

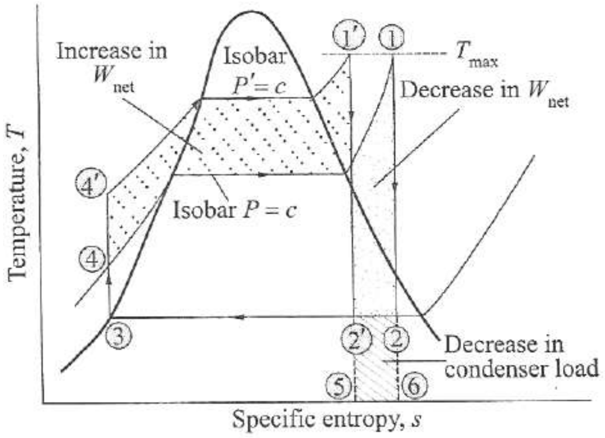
The steam pressure at the SHP exit is increased from p to p' while maintaining a constant superheated steam temperature,i.e; $T_1 = T1'$.

The operating conditions of the condenser remain unchanged. The work output remains nearly the same,i.e; there is no drastic gain in the work output;

$$\Delta.Woutput,p = area\ 1-2-3-4-1$$

$$\Delta.Woutput,p' = area\ 1'-2'-3-4'-1'$$

$$\Delta.Woutput,p \approx \Delta\ .Woutput,p'$$



However, the heat rejection area is reduced due to the higher pressure steam utilization(area 2- 2′-5-6).

This increases the efficiency of the cycle.

Efficiency,

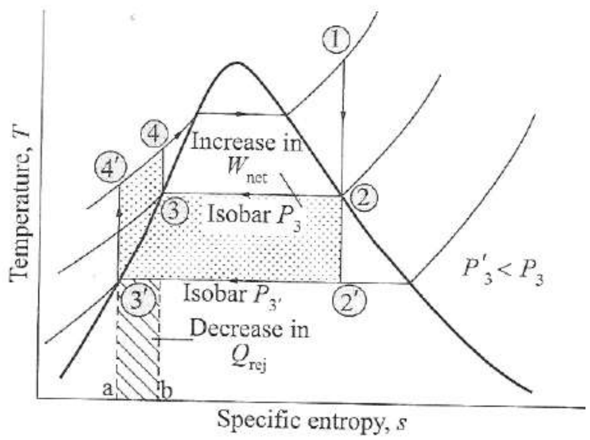
$$\eta = \frac{Qadd - Qrej}{Qadd}$$

$$= 1 - \frac{Qrej}{Qadd}$$

RANKINE CYCLE WITH SUPERHEATED STEAM:

EFFECT OF REDUCING CONSTANT PRESSURE:

If the condenser pressure is reduced ,the net work is increased by area 2-$2 - 2' - 3' - 4' - 4 - 3 - 2$..



When the operating pressure of the condenser is decreased ,the heat added area automatically increases and at the same time Qrej also decreases with the net effect;the cycle efficiency increases..

QUALITIES OF IDEAL WORKING FLUID FOR VAPOUR POWER CYCLES:

The desirable characteristics of the working fluid in a vapour power cycle to ensure the best thermal efficiency of the cycle are :

1. The maximum permissible limits of operating pressure and temp. is set by the metallurgy boiler and super heater tubes ,pipes lines, and headers. The working fluid should better have a high critical temp. so that its saturation pressure at the maximum permissible working temp. is relatively low. It should have a large enthalpy of evaporation at that pressure
2. To draw vaccum in the condenser is another costly setup that calls for adequate maintenance as less than the desired vaccum level will tell on the overall cycle efficiency. So it is better that the saturation pressure at the temp. of heat rejection should lie above the atmospheric pressure.
3. The specific heat of liquid should be low so as to boil it out with a relatively little heat transfer. However ,low specific heat means a low enthalpy content-not a desirable criterion for a high cycle efficiency.

4. The saturated vapour line in the T-s diagram should be steep rather than flat. This will safeguard the last stages of the turbine blades from an excessive level of condensation of the working fluid as it expands through the successive stages of the turbine.
5. The freezing point of the working fluid should be below the ambient temp. to avert pipeline chocking due to freezing.
6. Obviously the working fluid should be chemically stable and non-reactive with the materials of construction of the operating system at the maximum working temp
7. The working fluid must be abundantly available to buy economy.
8. It must be non-toxic,non-corossive, and not excessively viscous.

BINARY VAPOUR POWER CYCLES:

A binary cycle comprises two different cycles working in tanderm with two different fluids so that the sink of one becomes the source of the other.

The highest achievable efficiency is that of carnots

$$\eta_{thermal} = \frac{T1-T2}{T1}$$

$$= 1 - \frac{T2}{T1}$$

Which necessitates heat absorption at a constant temp. T1 and heat rejection at a constant temp. T2. Now, the efficiency is fixed byT1 asT2 is fixed by the natural sink. This makes it imperative that T1 should be as large as possible,consistent with the vapour being saturated.

When water is used as the working fluid its critical temp. is 374.15℃ and the critical pressure is 225 bar. Operating with a critical or supercritical steam entails design complicacy and enhances cost, operational and maintenance problems, and controlling difficulties . in order to obviate these difficulties ,it would be better to harness some fluid other than steam, which is having more desirable thermodynamic properties than water. The most fitting fluid for this purpose should have a very high critical temp. yet at a low pressure. Mercury, biphenyl oxide and similar other compounds, aluminium bromide, and zinc aluminium chloride are the fluids which posseses the requisite properties in varying degrees. Mercury, among them

,is the best candidate. It has a high critical temp. of 588.4℃ yet at low critical pressure. Mercury alone can not be used as its saturation temp. at the atmospheric pressure is high(355℃). Hence ,a binary vapour cycle is used to increase the overall efficiency of the plant.

The most important binary vapour cycle is the mercury steam cycle, which comprises two cycles—mercury cycle and steam cycle.

MERCURY CYCLE:

The mercury cycle is super imposed on the steam cycle. Liquid mercury is circulated through the evaporator tubes in the boiler whereupon the liquid mercury is converted into vapour which is then charged to the mercury turbine where the Hg – vapour expands to generate electric power. The turbine is then exhausted to the mercury condenser boiler where the vapour mercury condenses and then pumped back to the boiler.

STEAM CYCLE:

The heat rejected by the vapour mercury in the mercury condenser boiler is absorbed by the BFW to generate steam at a desired pressure. This steam is then superheated and then charged to the steam turbine to produce an additional power output.

Fuel is burned in the mercury boiler furnace. The liberated heat goes to vaporize the mercury, superheat the steam , and preheat the combustion air and the boiler feedwater.

The heat rejected during the condensation of mercury is transferred to boil water to saturated steam(stage 5-6). The saturated steam is then superheated to state 1 by an external heat source(stage 6-1).

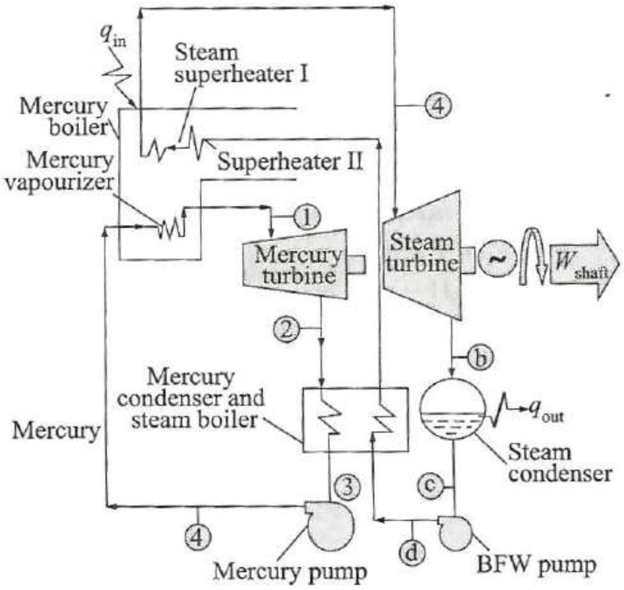
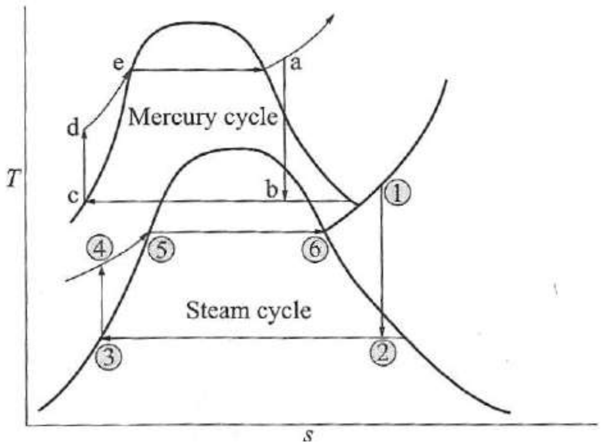


Fig. Schematic diagram of a mercury–steam binary cycle.



This superheated steam is then allowed to expand in the steam turbine(stage 1-2) and the waste steam is then exhausted to the surface condenser where the condensation is completed(stage 2-3). The condensate is then pumped back (by the BFW group) to the boiler(stage 3-4) . This is then heated in the economizer to the saturated liquid(stage 4-5) and then goes to the mercury condenser steam boiler, where the latent heat is absorbed.

Heat supplied = Q1= Qm = m(ha-hd) + (h1 - h6) + (h5 - h4)

Heat rejected= Q2=Qout=(h2-h3)

Turbine work= Wshaft = m(ha-hb)+(h1-h2)

Pump work= Wpump=m(hd-hc)+(h4-h3)

The thermal efficiency of the mercury-steam cycle

= ηthermal,mer-wat = $\frac{Wnet}{Qin}$

$= \frac{Wshaft- \ W\,pump}{Qin}$

Steam rate = $\frac{3600}{Wshaft-W\,pump}\,(kg\ kwh^{-1})$

Energy balance= m(h_b-h_c) =h6-h5

∴ m=$\frac{h6-h5}{hb-hc}$

ADVANTAGES OF MERCURY-STEAM CYCLE:

1. High overall plant efficiency
2. High degree of availability (-85%)
3. Simplicity in operation
4. Reasonable plant maintenance
5. No operational trouble (cf. mercury is toxic)

CHAPTER-6

HEAT TRANSFER

MODES OF HEAT TRANSFER:

CONDUCTION:-

A physical law for heat transfer by conduction is given by fourier according to which the rate of heat conduction is proportional to the area measured normal to the direction of heat flow, and to the temp. gradient in that direction.

$$Q = - kA\frac{\partial T}{\partial n}$$

$$\text{or } q = - k.\frac{\partial T}{\partial n}$$

The constant of proportionality is called the coefficient of thermal conductivity, which is a physical property of the substance and is defined as the ability of a substance to conduct heat,.

The quantity of heat transferred per unit time per unit area of isothermal surface is defined as the heat flux is determined by the relation

$$Q = - n_{i.}\, k\frac{\partial T}{\partial n}$$

The heat flux q, is normal to the isothermal surface, and is positive in the direction of decreasing temp. because according to the second law of thermodynamics, heat always flow from a hotter point to a colder one. Hence .the vectors grad T and q are both normal to isotherms but run in opposite directions. This also explains the existence of the minus sign in equation.

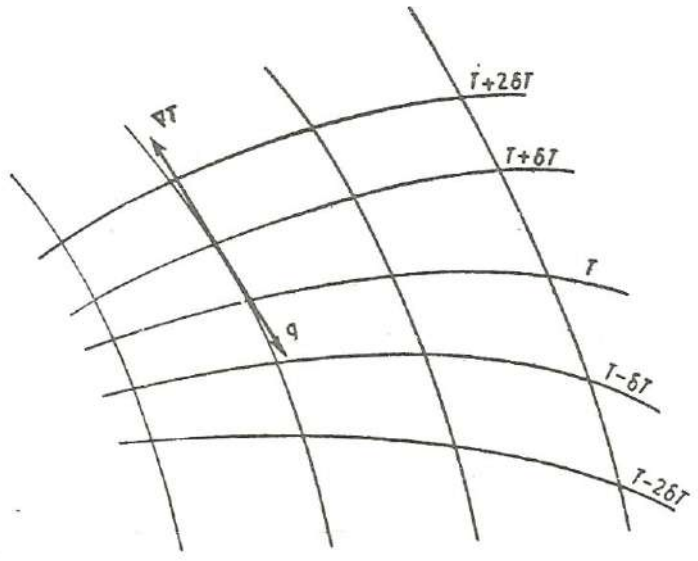


Fig. Lines of Heat Flow and Isotherms

The greatest rate of heat flow will be along the lines normal to the isothermal surfaces. Then, in accordance with equation we have

$$Q_X = - K_x.A\frac{\partial T}{\partial X} \quad \text{or } q_x = \frac{QX}{A} = - K_X \,.\frac{\partial T}{\partial X}$$

$$Q_Y = - K_{Y.}A\frac{\partial T}{\partial Y} \quad \text{or } q_y = \frac{QY}{A} = - K_Y.\frac{\partial T}{\partial Y}$$

$$Q_Z = - K_Z.A\frac{\partial T}{\partial Z} \quad \text{or } q_z = \frac{Qz}{A} = - k_z.\frac{\partial T}{\partial Z}$$

A material having $K_X = K_Y = K_Z = K$ is called an isotropic material. For an isotropic material, the heat transfer equation reduces to $Q_X = -K_A.\frac{\partial T}{\partial X}$

The heat flow vector q can be written as; $q = i.q_x + j\, q_y + k\, q_z$

For a plane wall of thickness L with temp. T_O and T_L on its two sides integration of equation yields:

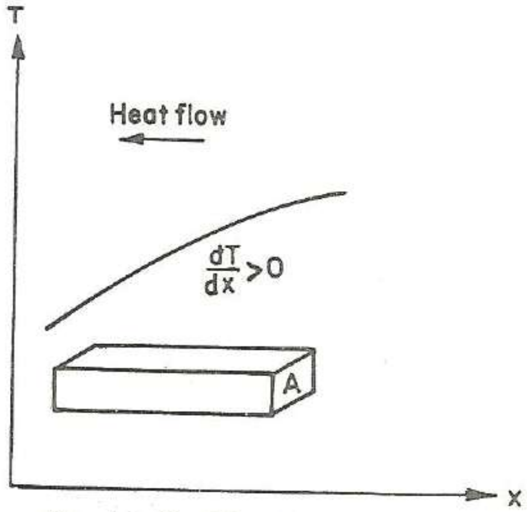


Fig. One-Dimensional Conduction

$Q_X \int_0^L dx = -kA \int_{T0}^{TL} dT$

$Q_X = \frac{kA}{L}(T0 - TL)$

The unit of thermal conductivity k, is $W/_{m°C}$ or $W/_{m.k}$

Since conduction is a molecular phenomenon , fourier law is similar to newtons viscosity law for laminar flow: $\tau = \mu.\frac{dv}{dy}$

Thermal conductivity is a physical property of a substance and like viscocity , it is primarily a function of temp. and/ or position , nature of the substance. It varies significantly with pressure only in the case of gases subjected to high pressure. However for many enginnering problems , materials are often considered to process a constant thermal conductivity .

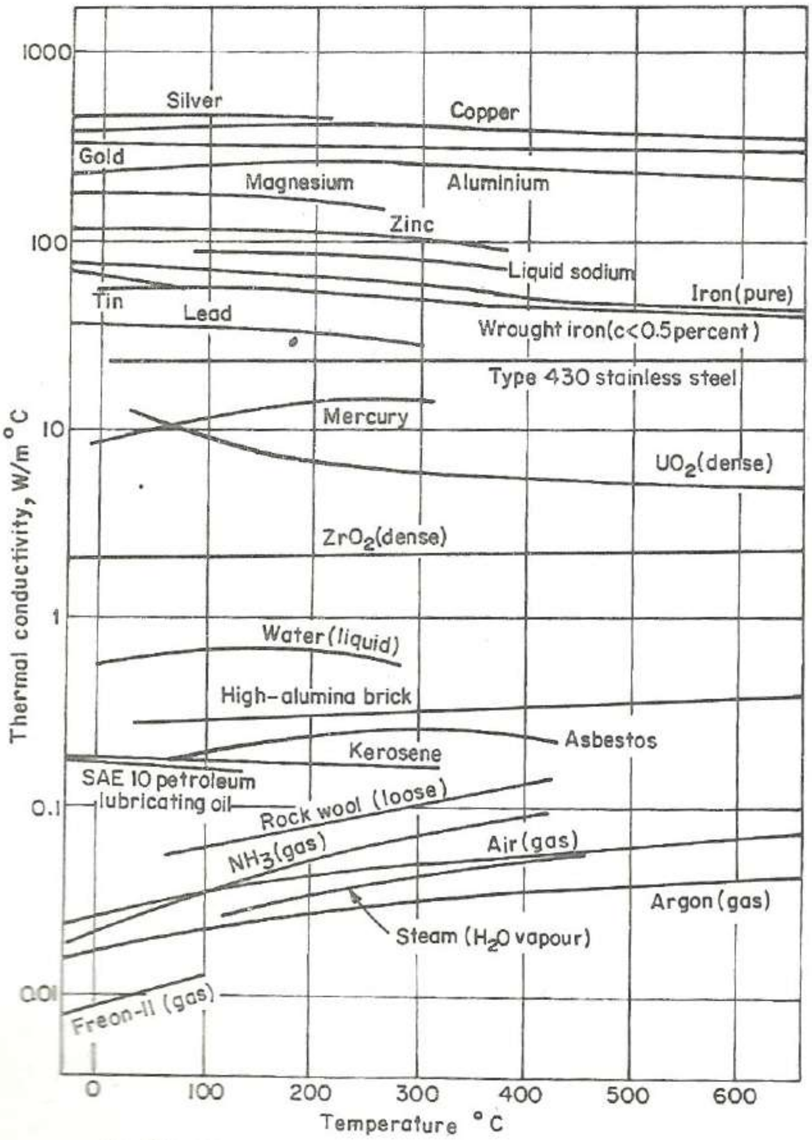


Fig. Thermal Conductivity of Some Engineering Materials.

The thermal conductivity for most materials can be determined experimentally by measuring the rate of heat flow and temp. gradient of the substance most commonly used.

From table ,We see that pure metals have the highest value of thermal conductivities while gases and vapours have the lowest; insulating materials and inorganic liquids have thermal conductivities that lie in between those of metals and gases.

Table Thermal Conductivities of Common Substances at 20 °C

Substance	$k(W/mK)$
Silver, pure	407.0
Copper pure	386.0
Aluminium, pure	175.6
Mild Steel	37.2
Lead	29.8
Stainless Steel	19.3
Wood	0.15
Asbestos, fibre	0.095
Water	0.51
Air	0.022

Thermal conductivity is also a function of temperature. For most pure metals it decreases with increasing temp, whereas for gases and insulating materials it increases with rise in temp. . Appendix A gives the thermal conductivity and other physical properties of some the most commonly used substances.

EXAMPLE 1

A stainless steel plate 2 cm thick is maintained at a temperature of 550°C at one face and 50°C on the other. The thermal conductivity of stainless steel at 300°C is 19.1 W/m·K. Compute the heat transferred through the material per unit area.

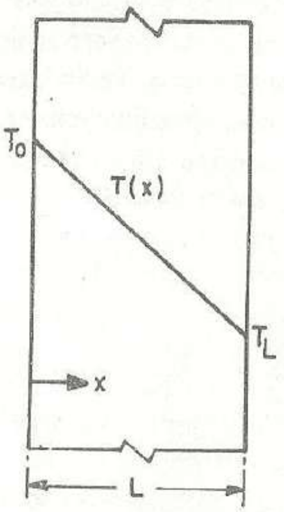


Fig. Ex. 1.1 Example 1.1

Solution This is the case of a plane wall as shown in Fig. Ex. 1.1. Using Eq. (1.12),

$$Q_x = \frac{kA}{L}(T_0 - T_L)$$

or $$\frac{Q_x}{A} = q_x = \frac{k}{L}(T_0 - T_L) = \frac{(19.1)(550 - 50)}{2 \times 10^{-2}} = 477.5 \text{ kW/m}^2$$

CONVECTION:

For a fluid flowing at a mean temp. T∞ over a surface at a temp. T_S , newton proposed the following heat convection equation; q = $\frac{Q}{A} = h(Ts - T\infty)$ = hΔT

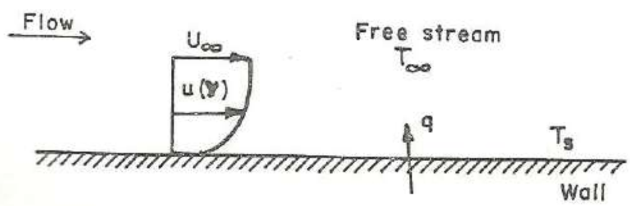


Fig. Convection from a Heated Plate

Where q is the heat flux at the wall. This equ. is called newton law of cooling. The heat transfer coefficient h has units $W/_{m2°C}$ or $W/_{m2\ k}$ when the heat flux q is given in the units of $\frac{W}{M2}$ and the temp. in °C.

In fig. it is seen that the viscosity of fluid layer at the wall is zero so the heat must be transferred only by conduction over there. Thus we may use to compute heat transfer at the wall. Then question arises , why consider convection at all when we can easily compute q by conduction. The answer is simple; the temp. gradient is dependent upon the rate at which the fluids carries the heat away, which in turn depends upon viscosity and other thermal properties of the fluid. Comparing these equations at the wall, h = - $\frac{k}{Ts-T\infty}\frac{\partial T}{\partial Y}\ |y = 0$.

Equation relates h with thermal conductivity and the temp. gradient at wall ,and is used in the determination of h experimentally.

It has been found that the heat transfer coefficient h varies significantly with the type of fluid and temperature . table gives the approximation ranges of convective heat transfer coefficient for forced and free convection encountered in typical engineering application.

EXAMPLE 1

A flat plate of length 1 m and width 0.5 m is placed in air stream at 30°C blowing parallel to it. The convective heat transfer coefficient is 30 W/m²K. Calculate the heat transfer if the plate is maintained at a temperature of 300°C.

Solution

$$Q = hA\,(T_s - T_\infty)$$
$$= (30)\,(1.0)\,(0.5)\,(300-30)$$
$$= 4.05\ \text{kW}.$$

THERMAL RADIATION:

According to the Stefan-boltzmann law , the radiation energy emitted by a body is proportional to the fourth power of its absolute temperature. Q = $\sigma A T_1^4$.

Where σ is called Stefan-boltzmann constant with the value of 5.6697*10^{-8} $\frac{W}{m2\ .k4}$, and T_1 is the surface temp. in degree Kelvin.

Consider a black body of surface area A and at an absolute temp. T_1 exchanging radiation with another black body at a temp. T_2. The net heat exchange is proportional to the difference in T^4.

Q = $\sigma A(T_1^4 - T_2^4)$

The real surface , like a polished metal plate, do not radiate as much as energy as a black body. The gray nature of real surfaces can be accounted for by introducing a factor $\in$ is called emissivity which relates radiation between gray and black bodies. $Q=\sigma A\in(T_1^4-T_2^4)$

To account for geometry and orientation of two black surfaces exchanging radiation is modified to $Q=\sigma AF(T_1^4-T_2^4)$

When the factor F, is called view vector, is dependent upon geometry of the two surfaces exchanging radiation.

EXAMPLE 1

A 'radiator' in a domestic heating system operates at a surface temperature of 55°C. Determine the rate at which it emits radiant heat per unit area if it behaves as a black body.

Solution

$$\frac{Q}{A} = q = \sigma T^4 = 5.6697 \times 10^{-8} (273 + 55)^4 = 0.66 \text{ kW/m}^2$$

FOURIER LAW OF HEAT CONDUCTION:-

$Q \propto A.\frac{dT}{dX} = k.\ A.\frac{dT}{dX}$

Where Q= amount of heat flow through the body in a unit time

A= surface area of heat flow

dT= temperature difference on the two faces of body

dX= thickness of the body through which the heat flows. It is taken along the direction of heat flow

k= constant of proportionality known as thermal conductivity of the body

THERMAL CONDUCTIVITY:-

$.\ Q = \frac{k.A.(T_1-T_2).t}{x}$

The thermal conductivity of a material is numerically equal to the quantity of heat which flows in one second through a slab of material of area 1 m^2 and thickness 1 m when its faces differ in temperature by 1 k.

Example 1. *The glass windows of a room have a total area of 10 m^2 and the glass is 4 mm thick. Calculate the quantity of heat that escapes from the room by conduction per second when the inside surfaces of windows are at 25° C and the outside surfaces at 10° C. The value of k is 0.84 W/m K.*

Solution. Given : $A = 10\ m^2$; $x = 4\ mm = 0.004\ m$; $T_1 = 25°\ C = 298\ K$; $T_2 = 10°\ C = 283\ K$; $k = 0.84\ W/m\ K$

We know that the quantity of heat that escapes from the room per second,

$$Q = \frac{k\,A\,(T_1 - T_2)}{x} = \frac{0.84 \times 10\,(298 - 283)}{0.004} = 31\,500\ J$$

$$= 31.5\ kJ\ \textbf{Ans.}$$

HEAT CONDUCTION THROUGH PLANE WALLS:-

Consider a plane wall of materials of uniform thermal conductivity k, which is assumed to be extending to infinity in y and z directions. For this problems, the temp. is only a function of x . the walls of a room may be considered as a plane if energy lost through the edges is negligible. Starting the general conduction equation $\frac{\partial 2T}{\partial x2}+\frac{\partial 2T}{\partial Y2}+\frac{\partial 2T}{\partial z2}+\frac{q}{k} =\frac{1}{\alpha}\frac{\partial T}{\partial t}$

For this case $\frac{\partial T}{\partial t}$ =0(steady state)

$\frac{\partial 2T}{\partial Y2} = \frac{\partial 2T}{\partial z2}$ =0(one-dimensional) ,$\frac{q}{k}$ =0(no heat generation)

The conduction equation simplifies to $\frac{\partial 2T}{\partial x2}$ =0 or $\frac{d2T}{dx2}$ = 0------------------------(1)

Above equation is a second order differential equation requiring two boundary conditions for its solution.

These are $T = T_1$ at $x = 0$

$T = T_2$ at $x = L$

Integrating this above equation twice , we get $T = C_1x + C_2$

Where C1 and C2 can be determined from the boundary conditions

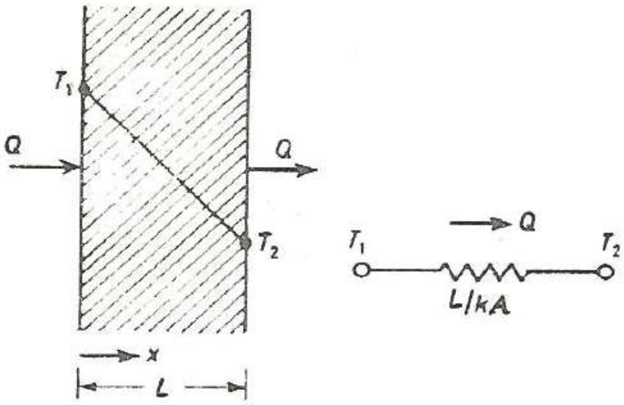


Fig. Steady State Conduction Through a Plane Wall

At $x = 0$, $T = T_1$,so that $C_2 = T_1$

At $x = L$, $T = T_2$, so that $T_2 = C_1L + T_1$

Or $C_1 = \frac{T2-T1}{L}$

So the equation for temp. distribution becomes $T = \frac{T2-T1}{L} x + T_1$

Or $\frac{dT}{dx} = \frac{T2-T1}{L}$ $\therefore Q = -K.A\frac{dT}{dx} = \frac{-kA(T2-T1)}{L} = \frac{kA(T1-T2)}{L}$ -----------------(2)

This quantity of heat Q, must be supplied to the low face of the wall to maintain a temp. difference

$(T1 - T2)$ across it. The thermal resistance is defined for a plane wall is $Rth = \frac{L}{KA}$

Equation -2 can also be obtained by fourier equation ,$Q = -KA\frac{dT}{dx}$------------------(3)

Integrating this equation between the boundaries of the plane wall,

we get $\int_0^L Qdx = -kA\int_{T1}^{T2} dT$

$$QL = -KA(T2 - T1)$$

$$\text{Or} \quad Q = \frac{-kA(T2-T1)}{L}$$

$$= \frac{kA(T1-T2)}{L}$$

The temp. at any point x along the wall can be obtained by integrating equation-3 between 0 and x

$$Q.x = -KA(T - T_1)$$

and comparing with equation-2 , $T = \frac{(T2-T1).x}{L} + T_1$

HEAT CONDUCTION THROUGH HOLLOW CYLINDER:-

`Consider a long cylinder of inside radius r_i , outside radius r_0, and length L. we consider the cylinder to be long so that the end losses are negligible. The inside and outside surfaces are kept at constant temperature Ti and To respectively. A steam pipe in a room can be taken as an example of a long hollow cylinder. The general heat conduction equation in cylindrical coordinates is

$$\frac{\partial 2T}{\partial r2} + \frac{1}{r}\left(\frac{\partial T}{\partial r}\right) + \frac{1}{r2}\frac{\partial 2T}{\partial \emptyset 2} + \frac{\partial 2T}{\partial z2} + \frac{q}{k} = \frac{1}{\alpha}\frac{\partial T}{\partial t}$$

Assuming the heat flows only a radial directions, the above equation under steady state takes the form:

$$\frac{\partial 2T}{\partial r2} + \frac{1}{r}\left(\frac{\partial T}{\partial r}\right) = 0$$

$$\text{or} \quad \frac{d}{dr}\left(r\frac{dT}{dr}\right) = 0$$

Subject to the boundary conditions, $T = T_1$ at $r = r_1$

$T = T_0$ at $r = r_0$

Integrating twice we get , $T = C_1 \ln r + C_2$ -----------------(1)

Using the boundary conditions , at $r = r_1$,$T = T_1$; $T_1 = C_1 \ln r_1 + C_2$

at $r = r_0$,$T = T_0$;$T_0 = C_1 \ln r_0 + C_2$

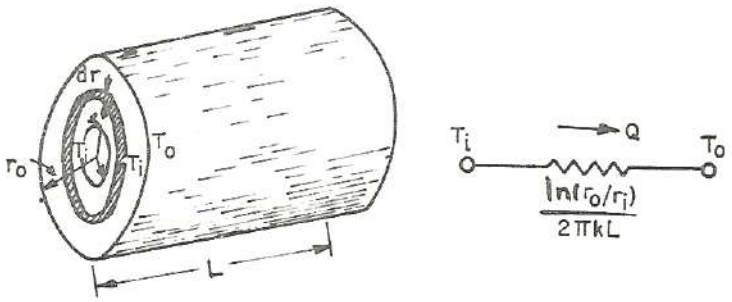


Fig. Steady State Conduction through a Hollow Cylinder i

$$C_1 = \frac{T1-T0}{\ln\frac{r0}{r1}} \ln r_1$$

$$= \frac{T0 - T1}{\ln\frac{r1}{r0}}$$

$$C_2 = T_1 - \frac{T0-T1}{\ln\frac{r0}{r1}} \ln r_1$$

$$= \frac{T1 \, ln \, r0 - T0 \, ln \, r1}{\ln\frac{r0}{r1}}$$

Substituting the values of C_1 and C_2 in equation -1 ,

$$T = \frac{T0 - T1}{\ln\frac{r1}{r0}} \ln r + \frac{T1 \, ln \, r0 - T0 \, ln \, r1}{\ln\frac{r0}{r1}}$$

$$Q = -KA_r \frac{dT}{dr} \, |r = ri$$

$$= -K.2\pi r_1 L.\frac{C1`}{R1} \;\; = -K.2\pi r_1 L(T_0 - T_i) \, .\frac{1}{ri \ln\frac{r0}{r1}}$$

$$= \frac{2\pi KL(T1 - T0)}{\ln\frac{r0}{r1}} \text{--------------(2)}$$

Equation-2 can alternatively be derived as follows:

$Q = - KA\frac{dT}{dr}$, where $A = 2\pi rL$

Or $\quad Q \,.\frac{dr}{r} = -2\pi KL dT$

Integration of this equation gives

$$Q.\int_{r1}^{r0} \frac{dr}{r} = -2\pi KL \;\int_{T1}^{T0} dT$$

$$Q. (\ln \frac{r0}{r1}) = -2\pi KL \;\; (T_0 - T_1)$$

$$Q = \frac{2\pi KL(T1 - T0)}{\ln\frac{r0}{r1}}$$

The thermal resistance for the hollow cylinder would be, $Rth = \frac{ln\left(\frac{r0}{r1}\right)}{2\pi KL}$

HEAT CONDUCTION THROUGH HOLLOW SPHERE:

Consider a hollow sphere whose inside and outside surfaces are held at constant temperature T_1 and T_0 respectively . if the temperation is only in the radial direction , then for steady state conditions with no heat generation , the heat conduction equation simplifies to

$$\frac{\partial 2T}{\partial r2} + \frac{2}{r}\left(\frac{\partial T}{\partial r}\right) = 0$$

Multiplying throught by r^2 , we get $r^2 . \frac{\partial 2T}{\partial r2} + 2\ r . \frac{\partial T}{\partial r} = 0$

Or $\frac{d}{dr}\left(r^2 \frac{dT}{dr}\right) = 0$----------------------------- (1)

Integration of equation-1 gives $dT = C_1 \frac{dr}{r^2}$

Integrating again, we get $T = \frac{-C_1}{r} + C_2$

Applying the boundary conditions ,

$T = T_1$ at $r = r_1$; $T_1 = \frac{-C_1}{r_1} + C_2$

$T = T_0$ at $r = r_0$; $T_0 = \frac{-C_1}{r_0} + C_2$

Solving for C_1 and C_2

$C_1 = \frac{T_1 - T_0}{\left[\frac{1}{r_0} - \frac{1}{r_1}\right]}$, $C_2 = T_1 + \frac{1}{r_1} \frac{T_1 - T_0}{\left[\frac{1}{r_0} - \frac{1}{r_1}\right]}$

$\therefore\ T = T_1 - \frac{T_1 - T_0}{\left[\frac{1}{r_0} - \frac{1}{r_1}\right]}\left[\frac{1}{r} - \frac{1}{r_1}\right]$

$= \frac{r_0}{r}\left[\frac{r - r_1}{r_0 - r_1}\right][T_0 - T_1] + T_1$

Knowing that $Q = -KA_r \frac{dT}{dr} |r = r_1$,

where $A_r = 4\pi r^2$

We can know that ,

$Q = \frac{4\pi r_1 r_0 . K(T_1 - T_0)}{(R_0 - R_1)}$ --------------------------(2)

Equation-2 can also be obtained by integration of fourier equation as follows:

$Q = -KA\frac{dT}{dr} = -4\pi K r^2 \frac{dT}{dr}$

$Q \int_{r_1}^{r_0} \frac{dr}{r^2} = -4\pi K \int_{T_1}^{T_0} dT$

$-Q\left[\frac{1}{r_0} - \frac{1}{r_1}\right] = -4\pi K[T_0 - T_1]$

Or , $-Q(\frac{r_1 - r_0}{r_0 r_1}) = -4\pi K[T_0 - T_1]$

And , $Q = \frac{4\pi r_1 r_0 . K(T_1 - T_0)}{(R_0 - R_1)}$----------------------(3)

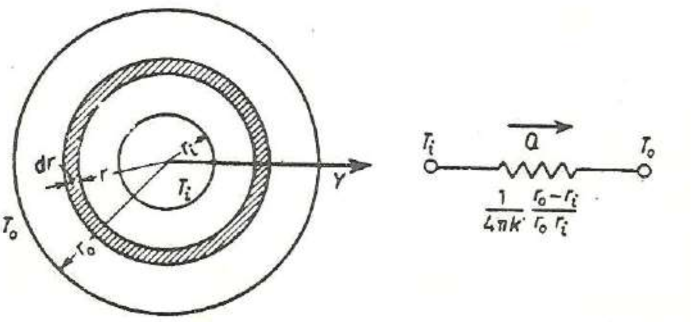


Fig. Steady State Conduction Through a Hollow Sphere

Equation-3 can also be put as , $Q = \frac{(T_1 - T_0)}{\frac{1}{4\pi K}\frac{[(r_0 - r_1)]}{r_0 r_1}}$

$$= \frac{T_1 - T_0}{R_{sph}}$$

Where the thermal resistance of a sphere is defined as $R_{sph} = \frac{1}{4\pi K}\frac{[(r_0 - r_1)]}{r_0 r_1}$

Geometric mean area: R_{sph} can be rearranged as

$R_{sph} = \frac{1}{4\pi K}\frac{[(r_0 - r_1)]}{r_0 r_1}$

$= \frac{r_0 - r_1}{K.\sqrt{(4\pi r_0{}^2)(4\pi r_1{}^2)}}$

$= \frac{L_{sph}}{K .\sqrt{A_0 A_1}}$

$= \frac{L_{sph}}{A_g . K}$-----------------------(4)

Where A_1 and A_0 are the areas of the inner and outer surfaces of the sphere.

L_{sph} = $(R_0 - R_1)$ = thickness of sphere

A_g = $\sqrt{A_0 A_1}$ is called the geometric mean area of the sphere.

The thermal resistance of a sphere given by equation-4 is similar to that of a plane wall except that the area is replaced by the geometric mean area.

NEWTON LAW OF COOLING:-

It states that, " heat transfer from a hot body to a cold body is directly proportional to the surface area and difference of temperature between the bodies.

It is a general law, for the heat transfer which can not be applied to all sets of conbdition. But it paved the way for other laws dealing in the heat loss.

ABSORPTION, REFLECTION, AND TRANSMISSION:-

When incident radiation is called irradiation impinges on a surface, three things happen; a part is reflected back, a part is transmitted through and the remainder is absorbed, depending upon the characteristics of the body.

By conservation of energy particle, Ga + Gr + Gt = G

Dividing both sides by G, we get , $\frac{Ga}{G} + \frac{Gr}{G} + \frac{Gt}{G} = \frac{G}{G}$

So, $\propto + \rho + \tau = 1$

Black body:- For perfectly absorbing body, $\propto = 1$, $\rho = 0$, τ=0. Such a body is called black body.it is one which neither reflect nor transmit any part of the incident radiation but absorb all of it.

White body:- If all the incident radiation falling on a body are reflected, it is called white body. Gases such as hydrogen, oxygen, nitrogen have a transmittivity of practically unity.

Gray body:- If the radiative properties of a body are assumed to be uniform over the entire wavelength spectrum, then such a body is called gray body. It is also defined as one whose absorpivity of a surface does not vary with temperature and wavelength of the incident radiation.

CONCEPT OF BLACK BODY:- A black body is an object that absorbs all the radiant energy reaching its surface. No actual body is perfectly black; a black body has following properties:

1. It absorbs all the incident radiation falling on it and does not transmit or reflect regardless of wavelength and direction
2. It emits maximum amount of heat radiation at all wavelength at any specified temperature.
3. It is a diffuse emitter .

KIRCHHOFF'S LAW:-

The law states that any temp.the ratio of total emissive power E to the total absorpivity $\propto$ is a constant for all substances which are in thermal equilibrium with their environment.

Let us consider a large radiating body of surface area A which encloses a small body of surface area A_1 . let the energy fall on the unit surface of the body at a rate E_b.by considering generality of bodies, we obtain, $E_b = \frac{E_1}{\propto_1} = \frac{E_2}{\propto_2} = \frac{E}{\propto}$

Also , as per the definition of emissivityε , $we\ have\ \varepsilon = \frac{E}{E_b}$. By comparing ,we obtain , $\varepsilon = \propto$

PLANCK;S LAW :-

In 1900 Max Planck showed by quantum arguments that the spectral distribution of the radiation intensity of a black body is given by

$$(E_\lambda)_b = \frac{2\pi c^2 h \lambda^{-5}}{\exp\left(\frac{ch}{\lambda kT}\right) - 1} \quad \text{... (Planck's law)} \quad ...(11.14)$$

where, $(E_\lambda)_b$ = Monochromatic (single wavelength) emissive power of a black body,

c = Velocity of light in vacuum, $2.998 \times 10^8 \simeq 3 \times 10^8$ m/s

h = Planck's constant = 6.625×10^{-34} j.s

λ = Wavelength, μm

k = Boltzmann constant = 1.3805×10^{-23} J/K, and

T = Absolute temperature, K

Hence the unit of $(E_\lambda)_b$ is W/m^2. μm.

Quite often the Planck's law is written as

$$(E_\lambda)_b = \frac{C_1 \lambda^{-5}}{\exp\left(\frac{C_2}{\lambda T}\right) - 1} \quad ...(11.15)$$

where, $C_1 = 2\pi c^2 h = 3.742 \times 10^8$ W.μm^4/m^2;

$C_2 = \frac{ch}{k} = 1.4388 \times 10^4$ μmK

Equation (11.14) is of great importance as it provides quantitative results for the radiation from a black body.

MAXWELL EQUATION:-

Now let us derive the Maxwell's equation.

We know that for a system undergoing an infinitesimal reversible process from one equilibrium state to another :

1. Internal energy, $dU = \delta Q - \delta W$ ... (General gas energy equation)

$$= T\,dS - p\,dv \quad \ldots (\because \delta Q = T\,dS \text{ and } \delta W = p\,dv) \quad \ldots (i)$$

The above equation (*i*) is of the form

$$dz = M\,dx + N\,dy$$

where $M = T,\ N = -p,\ x = S$ and $y = v$

$$\therefore \quad \left(\frac{\partial T}{\partial v}\right)_S = -\left(\frac{\partial p}{\partial S}\right)_v \quad \ldots (ii)$$

2. Enthalpy,

$$dH = dU + d\,(pv)$$

$$= dU + p\,dv + v\,dp$$

$$= (T\,dS - p\,dv) + p\,dv + v\,dp \quad \ldots (\because dU = T\,dS - p\,dv)$$

$$= T\,ds + v\,dp \quad \ldots (iii)$$

The above equation (*iii*) is of the form

$$dz = M\,dx + N\,dy$$

where $M = T,\ N = v,\ x = S$ and $y = p$

$$\therefore \quad \left(\frac{\partial T}{\partial p}\right)_S = \left(\frac{\partial v}{\partial S}\right)_p \quad \ldots (iv)$$

3. Helmholtz function (*A*),

$$dA = dU - d\,(TS)$$

$$= dU - T\,dS - S\,dT$$

$$= (T\,dS - p\,dv) - T\,dS - S\,dT \quad \ldots (\because dU = T\,dS - p\,dv)$$

$$= -p\,dv - S\,dT \quad \ldots (v)$$

The above equation (*v*) is of the form

$$dz = M\,dx + N\,dy$$

where $M = -p, N = -S, x = v, y = T$

$$\therefore \quad -\left(\frac{\partial p}{\partial T}\right)_v = -\left(\frac{\partial S}{\partial v}\right)_T$$

or

$$\left(\frac{\partial p}{\partial T}\right)_v = \left(\frac{\partial S}{\partial v}\right)_T \quad \ldots (vi)$$

4. Gibbs function (*G*), $dG = dH - d\,(TS)$

$$= dH - T\,dS - S\,dT$$

$$= (T\,dS + v\,dp) - T\,dS - S\,dT \quad \ldots (\because dH = T\,dS + v\,dp)$$

$$= v\,dp - S\,dT \quad \ldots (vii)$$

The above equation (*vii*) is of the form

$$dz = M\,dx + N\,dy$$

where $M = v, N = -S,\ x = p, y = T$

$$\therefore \quad \left(\frac{\partial v}{\partial T}\right)_p = -\left(\frac{\partial S}{\partial p}\right)_T \quad \ldots (viii)$$

The equations (*ii*), (*iv*), (*vi*) and (*viii*) are known as *Maxwell's equations* in thermodynamics.

HEAT EXCHANGER:-

It may be defined as an equipment which transfer the energy from a hot fluid to a cold fluid, with maximum rate and minimum investment and running cost.

In heat exchanger the temperature of each fluid changes it passes through the exchangers, and hence the temperature of the dividing wall between the fluids also changes along the length of the exchanger.

CLASSIFICATION OF HEAT EXCHANGER:-

1. NATURE OF HEAT EXCHANGER PROCESS:-
   - (i) Direct contact heat exchanger
   - (ii) Indirect contact heat exchanger
     - (a) Regenerators
     - (b) Recuperators
2. RELATIVE DIRECTION OF FLUID MOTION:-
   - (i) Parallel flow
   - (ii) Counter flow
   - (iii) Cross flow
3. DESIGN AND CONSTRUCTIONAL FEATURES:-
   - (i) Concentric tube
   - (ii) Shell and tube
   - (iii) Multiple shell and tube passes
   - (iv) Compact heat exchanger
4. PHYSICAL STATE OF FLUIDS:-
   - (i) Condenser
   - (ii) Evaporator