LECTURENOTES

ON

THERMAL ENGINEERING

III B. Tech I semester

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UNIT- I
BASIC CONCEPTS OF RANKINE CYCLE

Vapor Power Cycles

We know that the Carnot cycle is most efficient cycle operating between two specified temperature limits. However; the Carnot cycle is not a suitable model for steam power cycle since:

The turbine has to handle steam with low quality which will cause erosion and wear in turbine blades.

It is impractical to design a compressor that handles two phase.

It is difficult to control the condensation process that precisely as to end up with the desired at point 4.

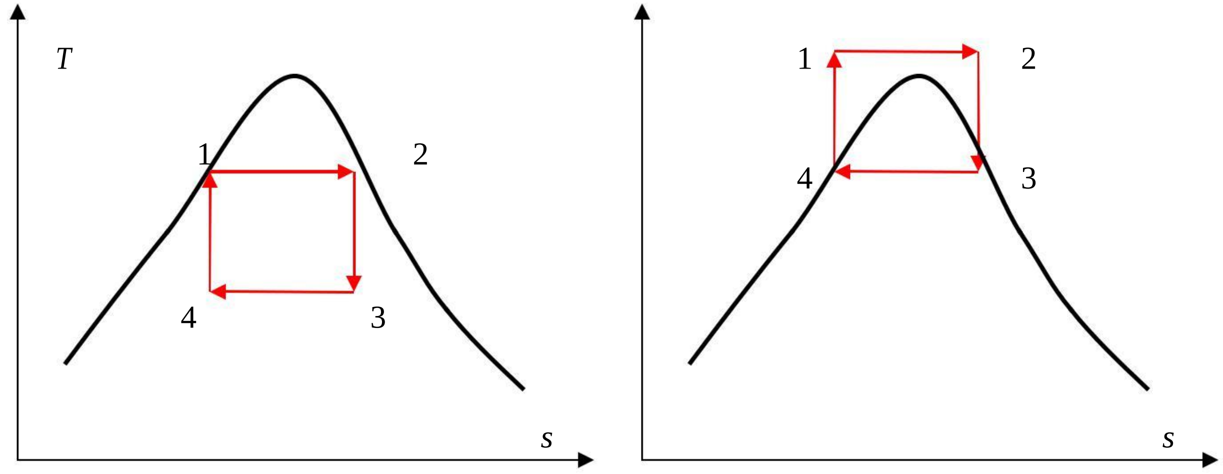


Fig. 1: *T-s* diagram for two Carnot vapor cycle.

Other issues include: isentropic compression to extremely high pressure and isothermal heat transfer at variable pressures. Thus, the Carnot cycle cannot be approximated in actual devices and is not a realistic model for vapor power cycles.

Ideal Rankine Cycle

The Rankine cycle is the ideal cycle for vapor power plants; it includes the following four reversible processes:

1-2:	Isentropic compression	Water enters the pump as state 1 as saturated liquid and is compressed isentropically to the operating pressure of the boiler.
2-3:	Const P heat addition	Saturated water enters the boiler and leaves it as superheated vapor at state 3
3-4:	Isentropic expansion	Superheated vapor expands isentropically in turbine and produces work.
4-1:	Const P heat rejection	High quality steam is condensed in the condenser

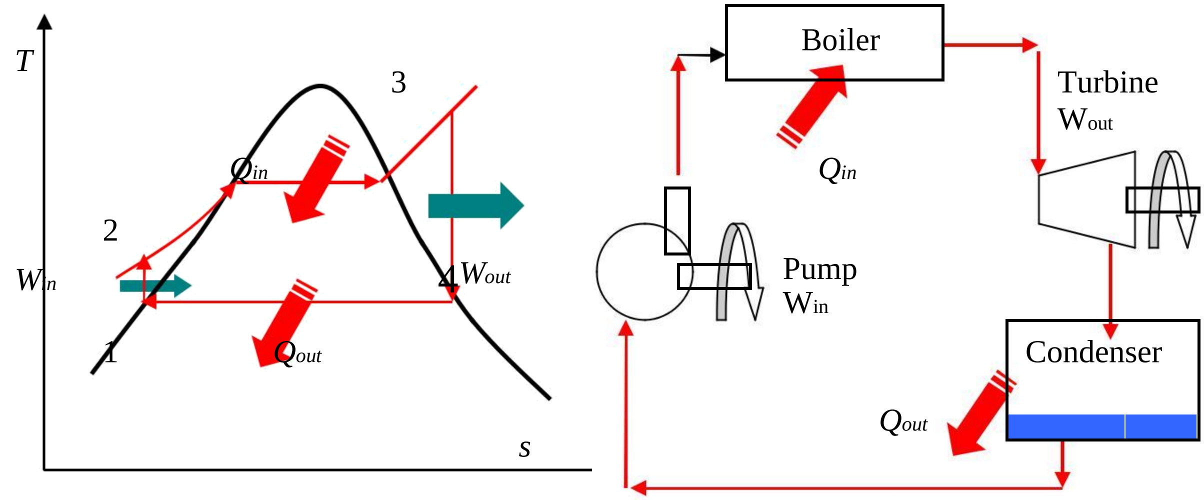


Fig. 2: The ideal Rankine cycle.

Energy Analysis for the Cycle

All four components of the Rankine cycle are steady-state steady-flow devices. The potential and kinetic energy effects can be neglected. The first law per unit mass of steam can be written as:

Pump	$q = 0$	$w_{pump,in} = h_2 - h_1$
Boiler	$w = 0$	$q_{in} = h_3 - h_2$
Turbine	$q = 0$	$w_{turbine,out} = h_3 - h_4$
Condenser	$w = 0$	$q_{out} = h_4 - h_1$

The thermal efficiency of the cycle is determined from:

$$\eta_{th} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$$

where

$$w_{net} = q_{in} - q_{out} = w_{turbine,out} - w_{pump,in}$$

If we consider the fluid to be incompressible, the work input to the pump will be:

$$(h_2 - h_1) = v(P_2 - P_1)$$

where $h_1 = h_{f@P1}$ & $v = v_1 = v_{f@P1}$

Deviation of Actual Vapor Power Cycle from Ideal Cycle

As a result of irreversibilities in various components such as fluid friction and heat loss to the surroundings, the actual cycle deviates from the ideal Rankine cycle. The deviations of actual pumps and turbines from the isentropic ones can be accounted for by utilizing isentropic efficiencies defined as:

$$_P \quad \frac{w_s}{w_a} \quad \frac{h_{2s} \quad h_1}{h_{2a} \quad h_1} \qquad _T \quad \frac{w_a}{w_s} \quad \frac{h_3 \quad h_{4a}}{h_3 \quad h_{4s}}$$

Increasing the Efficiency of Rankine Cycle

We know that the efficiency is proportional to: $_{th}1 \frac{T_L}{T_H}$

That is, to increase the efficiency one should increase the average temperature at which heat is transferred to the working fluid in the boiler, and/or decrease the average temperature at which heat is rejected from the working fluid in the condenser.

Decreasing the of Condenser Pressure (Lower T_L)

Lowering the condenser pressure will increase the area enclosed by the cycle on a *T*-*s* diagram which indicates that the net work will increase. Thus, the thermal efficiency of the cycle will be increased.

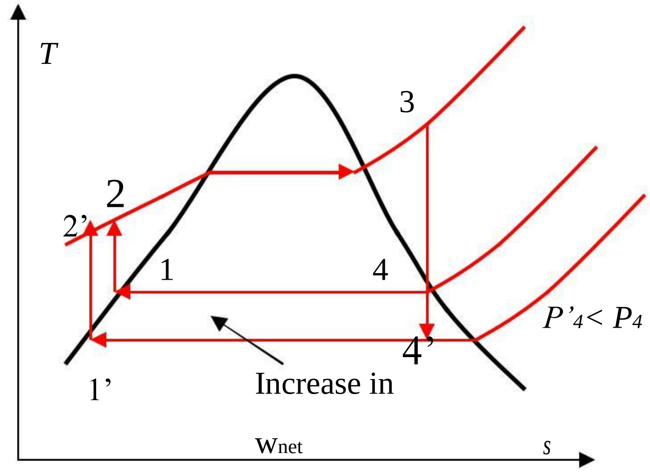


Fig. 4: Effect of lowering the condenser pressure on ideal Rankine cycle.

The condenser pressure cannot be lowered than the saturated pressure corresponding to the temperature of the cooling medium. We are generally limited by the thermal reservoir temperature such as lake, river, etc. Allow a temperature difference of 10°C for effective heat transfer in the condenser. For instance lake @ 15°C + ΔT (10°C) = 25°C. The steam saturation pressure (or the condenser pressure) then will be $\Rightarrow P_{sat} = 3.2\ kPa$.

Superheating the Steam to High Temperatures (Increase T_H)

Superheating the steam will increase the net work output and the efficiency of the cycle. It also decreases the moisture contents of the steam at the turbine exit. The temperature to which steam can be superheated is limited by metallurgical considerations (~ 620°C).

Increasing the Boiler Pressure (Increase T_H)

Increasing the operating pressure of the boiler leads to an increase in the temperature at which heat is transferred to the steam and thus raises the efficiency of the cycle.

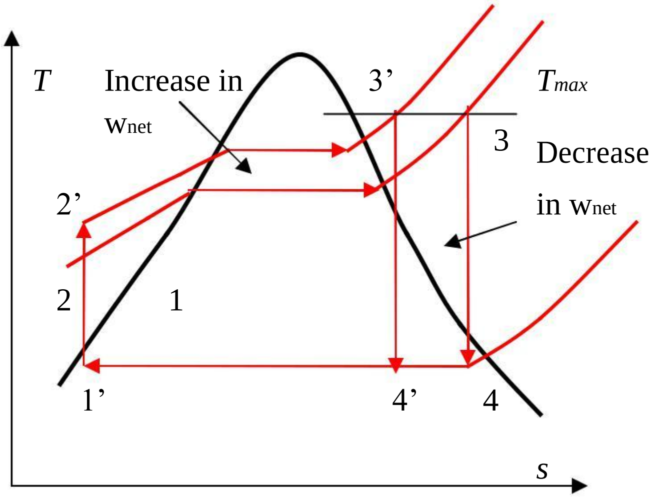


Fig.6: The effect of increasing the boiler pressure on the ideal cycle.

Note that for a fixed turbine inlet temperature, the cycle shifts to the left and the moisture content of the steam at the turbine exit increases. This undesirable side effect can be corrected by *reheating* the steam.

The Ideal Reheat Rankine Cycle

To take advantage of the increased efficiencies at higher boiler pressure without facing the excessive moisture at the final stages of the turbine, reheating is used. In the ideal reheating cycle, the expansion process takes place in two stages, i.e., the high-pressure and low-pressure turbines.

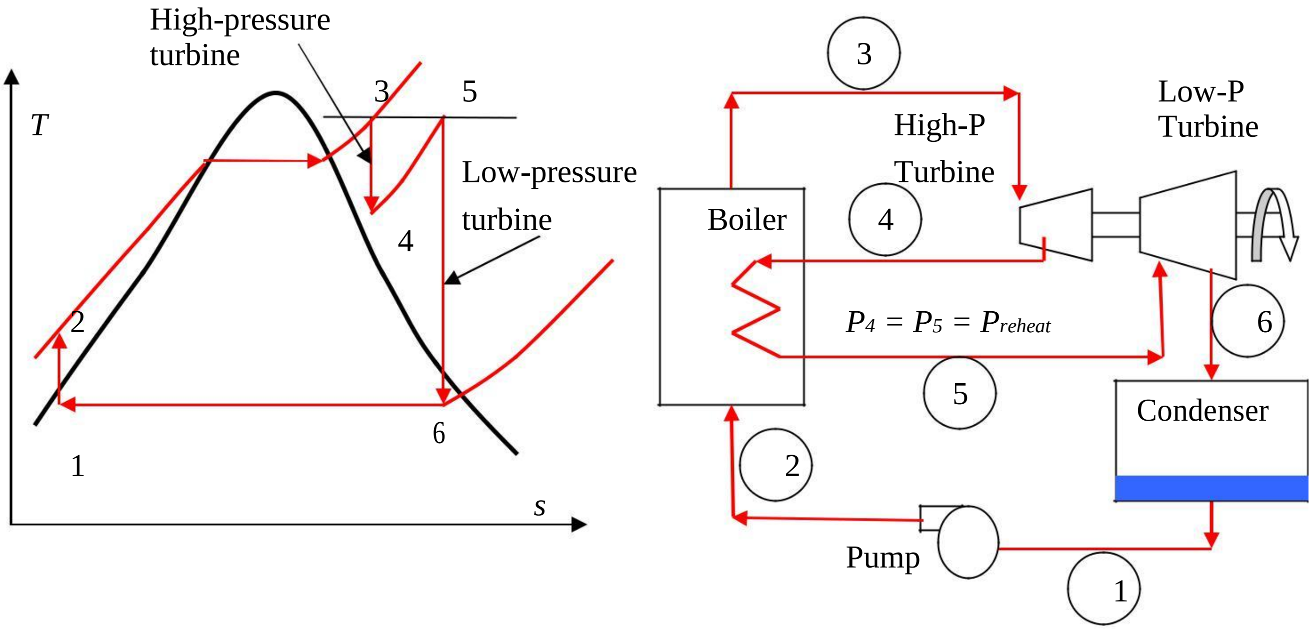


Fig. 7: The ideal reheat Rankine cycle.

The total heat input and total turbine work output for a reheat cycle become:

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

$$w_{turbine,out} = w_{H-P\ turbine} + w_{L-P\ turbine} = (h_3 - h_4) + (h_5 - h_6)$$

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

The Ideal Regenerative Rankine Cycle

The regeneration process in steam power plants is accomplished by extracting (or bleeding) steam from turbine at various stages and feed that steam in heat exchanger where the feedwater is heated. These heat exchangers are called regenerator or feedwater heater (FWH).

FWH also help removing the air that leaks in at the condenser (deaerating the feedwater).

There are two types of FWH's, open and closed.

Open (Direct-Contact) Feedwater Heaters

An open FWH is basically a mixing chamber where the steam extracted from the turbine mixes with the feedwater exiting the pump. Ideally, the mixture leaves the heater as a saturated liquid at the heater pressure.

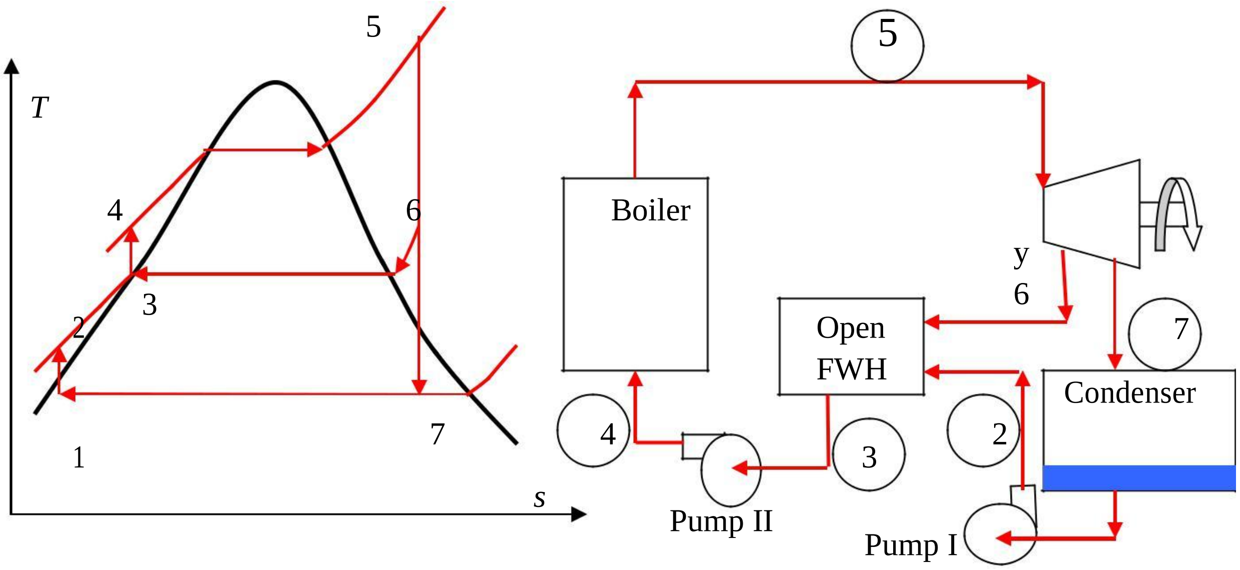


Fig. 8: The ideal regenerative Rankine cycle with an open FWH.

Using Fig. 8, the heat and work interactions of a regenerative Rankine cycle with one FWH can be expressed per unit mass of steam flowing through the boiler as:

$$q_{in} = h_5 - h_4$$
$$q_{out} = (1-y)(h_7 - h_1)$$
$$w_{turbine,out} = (h_5 - h_6) + (1-y)(h_6 - h_7)$$
$$w_{pump,in} = (1-y)w_{PumpI} + w_{PumpII}$$

where

$$y = \dot{m}_6 / \dot{m}_5$$
$$w_{PumpI} = v_1(P_2 - P_1) \qquad w_{PumpII} = v_3(P_4 - P_3)$$

Thermal efficiency of the Rankine cycle increases as a result of regeneration since FWH raises the average temperature of the water before it enters the boiler. Many large power plants have as many as 8 FWH's.

Closed Feedwater Heaters

In closed FWH, heat is transferred from the extracted steam to the feedwater without any mixing taking place. Thus; two streams can be at different pressures, since they don't mix.

In an ideal closed FWH, the feedwater is heated to the exit temperature of the extracted steam, which ideally leaves the heater as a saturated liquid at the extraction pressure.

Cogeneration

Many system and industries require energy input in the form of heat, called *process heat*. Some industries such as chemical, pulp and paper rely heavily on process heat. The process heat is typically supplied by steam at 5 to 7 atm and 150 to 200 C. These plants also require large amount of electric power. Therefore, it makes economical and engineering sense to use the already-existing work potential (in the steam entering the condenser) to use as process heat. This is called cogeneration.

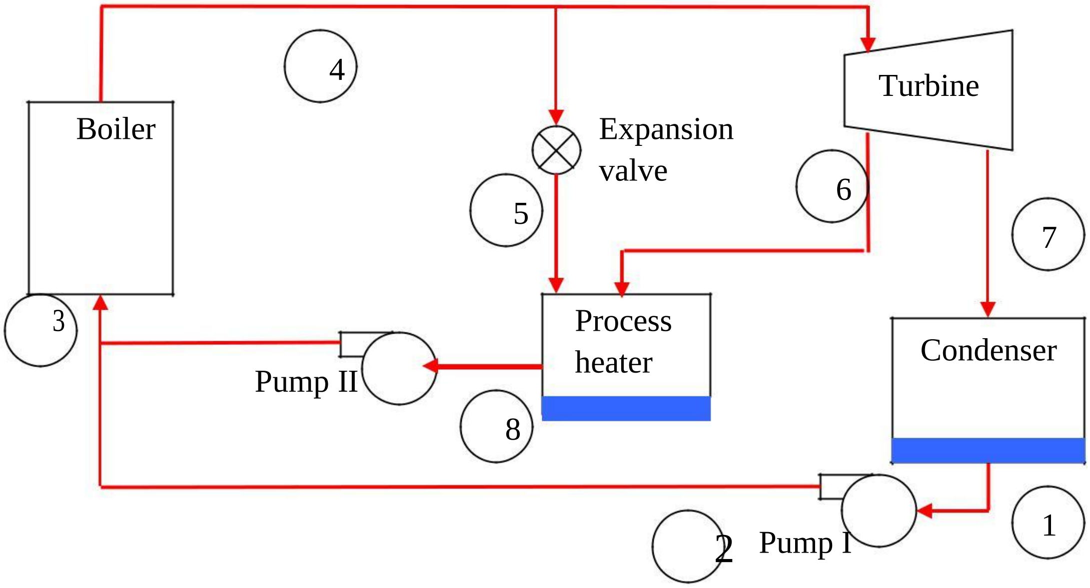


Fig. 10: A cogeneration plant with adjustable loads.

In the cogeneration cycle shown in the above figure, at times of high demands for process heat, all the steam is routed to the process heating unit and none to the condenser.

INTRODUCTION:

Fuel is a combustible substance, containing carbon as main constituent, which on proper burning gives large amount of heat, which can be used economically for domestic and industrial purposes. Eg., Wood, Charcoal, Coal, Kerosene, Petrol, Producer gas, Oil gas, LPG etc.,

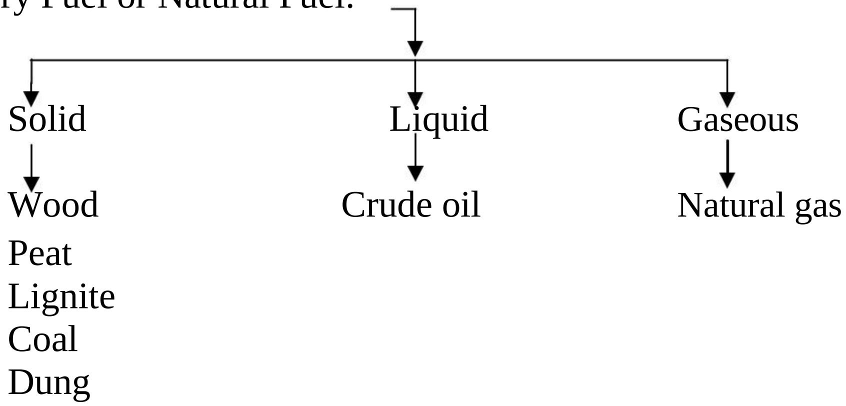
During the process of combustion of a fuel (like coal), the atoms of carbon, hydrogen, etc. combine with oxygen with the simultaneous liberation of heat at a rapid rate.

Fuel + Oxygen ---> Products + Heat

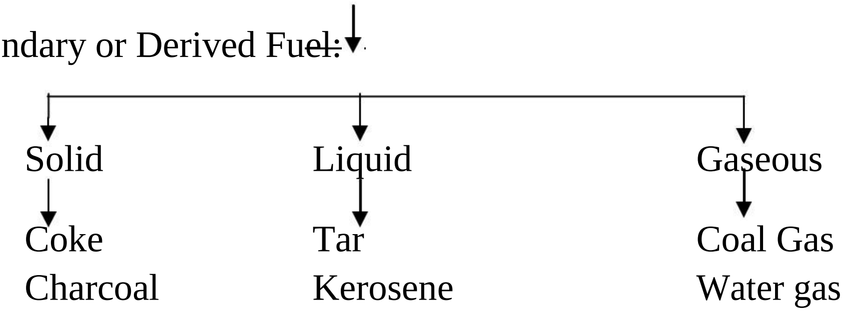
CLASSIFICATION OF FUELS:

Chemical Fuels: It is of two types viz., Primary or Natural Fuel and Secondary or Derived Fuel.

Primary Fuel or Natural Fuel:



Secondary or Derived Fuel:



Petroleum	Diesel	Oil gas
Coke	Petrol	Bio gas
Coal	Fuel oil	Blast furnace gas
Briquette	Synthetic Gasoline gas	Coke over gas

CALORIFIC VALUE

Calorific value of a fuel is "the total quantity of heat liberated, when a unit mass (or volume) of the fuel is burnt completely"

Units of Heat: (1) Calorie- is the amount of heat required to raise the temperature of one gram of water through one degree centigrade (15-16° C).

(2) Kilocalorie – is equal to 1,000 calories. This is the unit of metric system and may be defined as "the quantity of heat required to raise the temperature of one kilogram of water through one degree centigrade. Thus, 1 kcal = 1,000 calories.

(3) British Thermal Unit (BTU)- is defined as "the quantity of heat required to raise the temperature of one pound of water through one degree Fahrenheit (60-61° F). This is the English system unit.

1 BTU = 252 cal = 0.252 kcal and 1 kcal = 3.968 BTU

(4) Centigrade heat unit (CHU)-is "the quantity of heat required to raise the temperature of 1 pound of water through one degree centigrade". Thus,

1 kcal = 3.968 BTU = 2.2 CHU

HIGHER OR GROSS CALORIFIC VALUE:

It is the total amount of heat produced, when unit mass/volume of the fuel has been burnt completely and the products of combustion have been cooled to room temperature (15° C or 60° F).

It is explained that all fuels contain some hydrogen and when the calorific value of hydrogen containing fuel is determined experimentally, the hydrogen is converted into steam. If the products of combustion are condensed to the room temperature, the latent heat of condensation of steam also gets included in the measured heat which is then called GCV.

LOWER OR NET CALORIFIC VALUE:

It is the net heat produced, when unit mass/volume of the fuel is burnt completely and the products are permitted to escape.

In actual practice of any fuel, the water vapour and moisture, etc., are not condensed and escape as such along with hot combustion gases. Hence, a lesser amount of heat is available.

DETERMINATION OF CALORIFIC VALUE USING BOMB CALORIMETER

The calorific value of solid or liquid fuels can be determined with the help of bomb calorimeter.

Description:

Bomb Calorimeter consists of a strong stainless steel bomb where the fuel sample is burnt. The bomb has oxygen inlet valve and two stainless steel electrodes. A small ring is attached to one of the electrodes. In this ring, a nickel or stainless steel crucible is placed.

The bomb is placed in a copper calorimeter containing a known weight of water sample. The copper calorimeter is provided with a Beckmann's thermometer and stirrer for stirring water. The copper calorimeter is covered by an air jacket and water jacket.

Functioning:

A known weight of the fuel sample is taken into the crucible. The fine magnesium wire is touching the fuel sample and then stretched across the electrodes. The bomb lid is tightly closed with the help of screw. The bomb is filled with oxygen at 25 atmospheric pressure.

The bomb is now placed in a copper calorimeter which containing known weight of water. Initial temperature of the water in the calorimeter is noted (t1°C) after stirring. The electrodes are connected to a battery (6 v). The current is now supplied to the fuel sample which undergoes burning with the evolution of heat. The liberated heat increases the temperature of water in the calorimeter. The maximum temperature of the water during experiment is finally noted (t2°C). From the temperature difference, calorific value of the fuel can be calculated as follows:

Calculation:

Weight of the fuel sample taken in the crucible = x g
Weight of water taken in the calorimeter = W g
Weight of calorimeter and stirrer in terms of water Equivalent = A g
Initial temperature of water in the calorimeter = t1°C
Final temperature of water in the calorimeter = t2°C
Heat absorbed by the water = W (t2-t1) cal ----(1)
Heat absorbed the calorimeter = A (t2-t1) cal ----(2)
Total heat absorbed by the water = W(t2-t1) + A(t2-t1) cal
= (W+A) (t2-t1) cal ----(3)

The relationship between heat liberated by the fuel and HCV is as follows:
Heat liberated by the fuel = $x \times (\text{HCV})$ ----(4)

Therefore, heat liberated by the fuel = Heat absorbed by the water and calorimeter X Weight of fuel

Compare equation (3) and (4), we get

$$x \times (\text{HCV}) = (W+A)(t_2-t_1)$$

$$\textbf{HCV} = \frac{(W+A)(t_2-t_1)}{X}\ \textbf{cal/g}$$

Calculation of Lower Calorific Value (LCV):

The percentage of hydrogen in the fuel = H
Weight of water produced 1 g of the fuel = $\frac{9\,H}{100}$ g = 0.09 g

Therefore, heat liberated during the Condensation of steam = 0.09 H x 587 cal/g

Lower calorific value of the fuel = HCV – Latent heat of water liberated by the fuel

LCV = HCV – (0.09 H x 587) cal/g.

CHARACTERISTICS OF A GOOD FUEL:

High calorific value
Moderate ignition temperature
Low moisture content
Low non-combustible matter content
Moderate velocity of combustion
Products of combustion should not be harmful Low cost
Easy to transport
Combustion should be easily controllable
Should not undergo spontaneous combustion
Storage cost in bulk should be low
Should burn in air with efficiency without much smoke
In case of solid fuel, the size should be uniform so that combustion is regular.

COAL:

Coal is a highly carbonaceous matter that has been formed as a result of alteration of vegetable matter (eg., plants) under certain favourable conditions. It is chiefly composed of C, H, N and O besides non-combustible inorganic matter.

The successive stages in the transformation of vegetable matter into coal are – wood, peat, lignite, bituminous coal, steam coal and anthracite. Anthracite is probably the purest form of coal and contains 95 % carbon.

ANALYSIS OF COAL:

The composition of coal varies widely and hence it is necessary to analyse and interpret the results from the points of view of commercial classification, price fixation and proper industrial utilization. The quality of a coal is ascertained by the following two types of analysis.

Proximate Analysis and Ultimate Analysis

ULTIMATE ANALYSIS

Ultimate analysis refers the determination of weight percentage of carbon, hydrogen, nitrogen, oxygen and sulphur of pure, dry coal.

This analysis gives the elementary, ultimate constituents of coal.

This analysis is essential for calculating heat balances in any process for which coal is employed as a fuel.

It is useful to the designing of coal burning equipments and auxillaries.

a) Determination of carbon and hydrogen in coal:

A known amount of coal is burnt in presence of oxygen thereby converting carbon and hydrogen of coal into-

(i) CO_2 ($C + O_2 \longrightarrow CO_2$) and (ii) H_2O ($H_2 + ½ O_2 \longrightarrow H_2O$) respectively. The products of combustion CO_2 and H_2O are passing over weighed tubes of anhydrous $CaCl_2$ and KOH which absorb H_2O and CO_2 respectively.

The increase in the weight of $CaCl_2$ tube represents the weight of water formed while the increase in the weight of KOH tube represents the weight of CO_2 formed.

The percentage of carbon and hydrogen in coal can be calculated in the following way-

The weight of coal sample taken = x g

The increase in the weight of KOH tube = y g

The increase in the weight of $CaCl_2$ tube = z g

Consider the following reaction

$$C\ (12) + O_2 \longrightarrow CO_2\ (44)$$

44 g of CO_2 contains 12 g of carbon

Therefore y g of CO_2 contains = $\frac{y}{44}$ x 12 g of carbon.

X g of coal contains = $\frac{12\ y}{44}$ g carbon

% of carbon in coal = $\frac{12\ y}{44x}$ x 100

Significance of Total Carbon: It is the sum total of fixed carbon and the carbon present in the volatile matters like CO, CO_2, hydrocarbons. Thus, total carbon is always more than fixed carbon in any coal. High total carbon containing coal will have higher calorific value.

Determination of hydrogen:
Consider the following
reaction.

$$H_2\ (2) + ½\ O_2 \longrightarrow H_2O(18)$$

18 g of water contains 2 g of hydrogen.

Z g of water contains = $\frac{2}{18}$ z of hydrogen

X g of coal contains = $\frac{2}{18}$ z g of hydrogen

% of hydrogen in coal = $\frac{2\ z}{18\ x}$ x 100

Significance of Hydrogen: It increases the calorific value of the coal. It is associatedwith the volatile matter of the coal. When the coal containing more of hydrogen is heated, it combines with nitrogen present in coal forming ammonia. Ammonia is usually recovered as $(NH_4)_2SO_4$, a valuable fertilizer.

(c) Determination of nitrogen:

This is done by Kjeldhal's method.

A known amount of powdered coal is heated with concentrated sulphuric acid in the presence of K_2SO_4 and $CuSO_4$ in a long necked Kjeldhal'sfask. This converts nitrogen of coal to ammonium sulphate. When the clear solution is obtained (ie., the whole of nitrogen is converted into ammonium sulphate), it is heated with 50 % NaOH solution and the following reaction occurs:

$$(NH_4)_2SO_4 + 2\ NaOH \longrightarrow Na_2SO_4 + 2\ NH_3 + H_2O$$

The ammonia thus formed is distilled over and is absorbed in a known quantity of standard 0.1 N H_2SO_4 solution. The volume of unused 0.1 N H_2SO_4 is then determined by titrating against standard NaOH solution. Thus, the amount of acid neutralized by liberated ammonia from coal is determined using the formula.

$$\% \text{ Nitrogen in coal} = \frac{14 \text{ x volume of acid used x normality}}{1000 \text{ x}} \text{ x } 100$$

Or

$$= \frac{1.4 \text{ x voume of acid used x normality}}{X}$$

Significance: Presence of nitrogen decreases the calorific value of the coal. However,when coal is carbonized, its N_2 and H_2 combine and form NH_3. Ammonia is recovered as $(NH_4)_2SO_4$, a valuable fertilizer.

(d) Determination of sulphur in coal:

A known amount of coal is burnt completely in Bomb calorimeter in presence of oxygen.

Ash thus obtained contains sulphur of coal as sulphate which is extracted with dil. HCl.

The acid extract is then treated with BaCl2 solution to precipitate sulphate as $BaSO_4$. The precipitate is filtered, washed, dried and weighed. From the weight of $BaSO_4$, the percentage of sulphur in coal is calculated in the following way.

The weight of coal sample taken = x g

The weight of BaSO4 precipitate = y g

Consider the following equations

$$S\ (32) + 2O_2 \longrightarrow \quad BaCl_2$$

$$SO_4 \longrightarrow BaSO_4\ (233)$$

233 g of $BaSO_4$ contains 32 g of sulphur.

Therefore, y g of $BaSO_4$ contains $= \frac{32}{233}\ y$ g sulphur.

Therefore x g of coal contains $= \frac{32\ y}{233}$ gsulphur.

% of sulphur in the coal $= \frac{32\ y}{233}$ x 100.

Significance:

It increases the calorific value of the coal, yet it has the following undesirable effect-The oxidation products of sulphur (SO_2, SO_3)

especially in presence of moisture formssulphuric acid which corrodes the equipment and pollutes the atmosphere.

e) Determination of oxygen in coal:

It is calculated indirectly in the following way-

% of oxygen in coal = 100 - % (C + H + N + S + ash).

Significance:

The less the oxygen content, the better is the coal. As the oxygen content increases, its moisture holding capacity also increases.

FLUE GAS ANALYSIS – ORSAT’S APPARATUS

The mixture of gases like SO_2, CO_2, O_2, CO etc. coming out from the combustion chamber is called flue gas.

Importance of Flue Gas Analysis:

(i) The analysis gives the idea of whether a combustion process is complete or not.

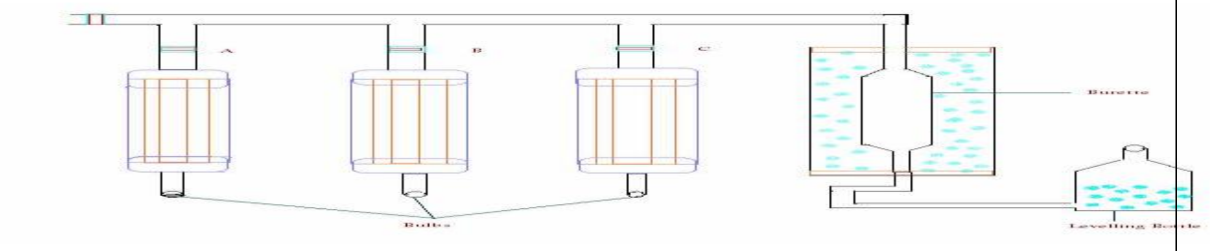
(ii) The C and H present in a fuel undergo combustion forming CO_2 and H_2O respectively. Any N present is not at all involved in the combustion. ie., the products of combustion are CO_2, H_2O and N_2.

(iii) If analysis of a flue gas indicates the presence of CO; it is suggestive of incomplete combustion. (wastage of heat is inferred)

(iv) If there is considerable amount of oxygen, it shows that there is excess supply of O_2 although combustion would have been complete.

Analysis:

The flue gas analysis is carried out by using Orsat’s apparatus. The analysis of flue gas generally deals with the determination of CO_2, O_2 and CO by absorbing them in the respective solution of KOH, alkaline pyrogallol and ammonium cuprous chloride.



Description of Orsat’s apparatus:

Orsat’s apparatus consists of a horizontal tube having 3 way stopcock at one end and a water jacketed measuring burette at the other end. The horizontal tube is connected to three different absorption bulbs for the absorption of CO_2, O_2 and CO respectively. The lower end of the burette is connected to the leveling bottle by means of rubber tube.

The level of water in the leveling bottle (water reservoir) can be raised or lowered by raising or lowering the water reservoir. By changing the level of water, the flue gas can be moved into various parts of the apparatus during analysis.

It is essential to follow the order of absorbing the gases- CO_2 first; O_2 second and CO last.

This is because the absorbent used for O_2 (ie., alkaline pyrogallol) can also absorb some amount of CO_2 and the percentage of CO_2 left would be less.

a) Absorption of CO_2

Flue gas is passed into the bulb A via its stopcock by raising the water reservoir. CO2 present in the flue gas is absorbed by KOH (usually 250 g KOH in 500 mL distilled water). The gas is again sent to the burette and then again sent to bulb A. This process is repeated several times, by raising or lowering of water reservoir so as to ensure complete absorption of CO_2 in KOH. Now, the stopcock of bulb A is closed. The volume of residual gases in the burette is taken by equalizing the water level both in the burette and in the water reservoir. The difference between original volume and the volume of the gases after CO_2 absorption gives the volume of CO_2 absorbed.

b) Absorption of O_2

Stopcock of bulb A is closed and bulb B is opened. Oxygen present in the flue gas is absorbed by alkaline pyrogallol (25 g pyrogallol +200 g KOH in 500 mL distilled water). The absorption process is same as in bulb A.

c) Absorption of CO

Now the stopcock of bulb B is closed and stopcock of bulb C is opened. Carbon monoxide present in the flue gas is absorbed by ammoniacal cuprous chloride (100 g Cu_2Cl_2 + 125 mL liquid NH_3 + 375 mL water). Here also absorption process is same as in bulb A.

Since the total volume of the gas taken for analysis is 100 mL, the volume of the constituents are their percentage.

The residual gas after the above three determinations is taken as nitrogen.

Further, as the content of CO in the flue gas would be very low, it should be measured quite carefully.

Theoretical Air for Combustion:

Combustion is a process of rapid oxidation in which a fuel burns with the evolution of heat and light. The rate of combustion depends onature of the fuel

(i) Temperature
(ii) Concentration of the fuel and air or oxygen

Thus the combustion rate is increased by

(i) Preheating the fuel and air
(ii) Increasing the surface area of the fuel, and
(iii) Increasing the pressure of air or oxygen used for combustion

The aim of combustion is to get the maximum amount of heat from a fuel in the shortest time and utilize the heat for various purposes. During the combustion, a fuel may undergo thermal decomposition to give simple products such as CO_2, H_2O etc. For efficient combustion, it is essential that the fuel must be mixed with sufficient quantity of air. The combustible constituents present in a fuel are C, H, S and O. But, non-combustible constituents N_2, CO_2 and ash present in the fuel do not take any oxygen during combustion.

UNIT- II
BOILERS AND STEAM NOZZLES

Introduction

A steam generator or a boiler is defined as a closed vessel in which water is converted into steam by burning of fuel in presence of air at desired temperature, pressure and at desired mass flow rate.

According to American society of Mechanical Engineers (A.S.M.E.), a steam generator or a boiler is defined as "a combination of apparatus for producing, finishing or recovering heat together with the apparatus for transferring the heat so made available to the fluid being heated and vaporized.

Boiler or a steam generator is example of heat exchanger. (Heat exchangers are defined as a mechanical device for exchanging heat between hot fluid and cold fluid with maximum rate, with minimum investment and with minimum running cost).

Principle:

In case of boiler, any type of fuel burn in presence of air and form flue gaseswhich are at very high temperature (hot fluid). The feed water at atmospheric pressure and temperature enters the system from other side (cold fluid). Because of exchange of heat between hot and cold fluid, the cold fluid (water) temperature raises and it form steam. The flue gases (hot fluid) temperature decreases and at lower temperature hot fluid is thrown into the atmosphere via stack/chimney.

The function of boiler is to facilitate the generation of steam by providing the necessary heat transfer surfaces, space for storage of water and steam, furnace for burning the fuel and necessary equipments for control of safe operation The large variety of available boilers have cylindrical drum or shell and tubes except for the once through boilers in which drum is not used.

Function of a boiler

- The steam generated is employed for the following purposes
- Used in steam turbines to develop electrical energy
- Used to run steam engines
- In the textile industries, sugar mills or in chemical industries as a cogeneration plant
- Heating the buildings in cold weather
- Producing hot water for hot water supply

IBR and non-IBR boilers

Boilers generating steam at working pressure below 10 bar and having water storage capacity less than 22.75 litres are called non-lBR boilers (Indian Boiler Regulations).

Boilers outside these limits are covered by the IBR and have to observe certain specified conditions before being operated.

The different ways to classify the boilers are as follows

- **According to location of boiler shell axis**

    - Horizontal
    - vertical
    - Inclined boilers.

When the axis of the boiler shell is horizontal the boiler is called horizontal boiler. If the axis is vertical, the boiler is called vertical boiler and if the axis of the boiler is inclined it is known as inclined boiler.

- Horizontal boiler: Lancashire boiler, Locomotive boiler, Babcock and Wilcox boiler etc.
- Vertical boiler: Cochran boiler, vertical boiler etc.

According to the flow medium inside the tubes

- Fire tube
- Water tube boilers.

The boiler in which hot flue gases are inside the tubes and water is surrounding the tubes is called fire tube boiler. When water is inside the tubes and the hot gases are outside, the boiler is called water tube boiler.

Examples

Fire tube boilers: Lancashire, locomotive. Cochran and Cornish boiler

Water tube boiler: Simple vertical boiler, Babcock and Wilcox boiler.

According to Boiler Pressure

According to pressure of the steam raised the boilers are classified as follows

- Low pressure (3.5 - 10 bar)
- Medium pressure (10-25 bar)
- High pressure boilers(> 25 bar)

Examples

Low pressure: Cochran and Cornish boiler

Medium pressure: Lancashire and Locomotive boiler

High pressure: Babcock and Wilcox boiler.

According to the draft used

- Natural draft
- Artificial draft boilers

Boilers need supply of air for combustion of fuel. If the circulation of air is provided withthe help of a chimney, the boiler is known as natural draft boiler. When either a forced draft fan or an induced draft fan or both are used to provide the flow of air the boiler is called artificial draft boiler.

Natural draft boiler: Simple vertical boiler, Lancashire boiler.

Artificial draft boiler: Babcock and Wilcox boiler, Locomotive boiler.

According to Method of water circulation

- Natural circulation
- Forced circulation

If the circulation of water takes place due to difference in density caused by temperature of water, the boiler is called natural circulation boiler. When the circulation is done with the help of a pump the boiler is known as forced circulation boiler.

- Natural circulation: Babcock & Wilcox boiler, Lancashire boiler
- Forced circulation: Velox boiler, Lamont boiler, Loffler boiler

According to Furnace position

- Internally fired
- Externally fired boilers

When the furnace of the boiler is inside its drum or shell, the boiler is called internally fired boiler. If the furnace is outside the drum the boiler is called externally fire boiler.

- Internally fired boiler: Simple vertical boiler Lancashire boiler, Cochran boiler
- Externally fired boiler: Babcock and Wilcox boiler

According to type of fuel used

- Solid
- Liquid
- Gaseous
- Electrical
- Nuclear energy fuel boilers

The boiler in which heat energy is obtained by the combustion of solid fuel like coal or lignite is known as solid fuel boiler. A boiler using liquid or gaseous fuel for burning is known as liquid or gaseous fuel boiler. Boilers in which electrical or nuclear energy is used for generation of heat are respectively called as electrical energy headed boilers and nuclear energy heated boiler.

According to number of Tubes

- Single-tube
- Multi-tube boiler

A boiler having only one fire tube or water tube is called a single, tube boiler. The boiler having two or more, fire or water tubes is called multi tube boiler.

Examples

- Single tube boiler: Cornish boiler, Vertical boiler.
- Multi-tube boiler: Lancashire boiler, Locomotive boiler, Babcock and Wilcox boiler.

According to Boiler Mobility

- Stationary
- Portable
- Marine boilers

When the boiler is fixed at one location and cannot be transported easily it is known as stationary boiler. If the boiler can be moved from one location to another it is known as stationary boiler. If the boiler can be moved from one location to another it is known as a portable boiler. The boilers which can work on the surface of water are called marine boilers.

Examples

- Stationary: Lancashire, Babcock and Wilcox boiler, vertical boiler
- Portable: Locomotove boiler.
- Marine: Marine boilers

Factors affecting the selection of a boiler

One has to send the technical details to the manufacturer to purchase a boiler.The technical details that are used to give information about a particular boiler include the following things

- Size of drum (Diameter and length)
- Rate of steam generation(kg/hr)
- Heating surface (Square meters)
- Working pressure (bar)
- No. of tubes / drum
- Type of boiler
- Manufacturer of boiler
- Initial cost
- Quality of steam
- Repair and inspection facility

Detailed specifications of each boiler can be obtained from manufacturer's catalogue.

Comparison between water-tube and fire tube boilers

Water Tube boiler	Fire Tube boiler
Water is inside the tube and flue gases surrounded to it.	Flue gases inside the tube and water surrounded to it.
Operating pressure is up to 170-180 bar (high pressure boilers).	Operating pressure is up to 25 bar (low and medium pressure boilers).
Steam generation rate is very high (more than 3000 kg/hr)	Less steam generation rate.
Suitable for power plants.	Suitable for small industries.
Chance of explosion is more due to high steam pressure.	Chance of explosion is less due to low steam pressure.
Provide steam in power plants to develop electrical energy.	Provide steam in chemical and pharmaceutical industries.
Small chance of scale formation due to flue gases are in shell	More chance of scale formation
Example: Bobcock and Wilcox boiler	Example: Vertical boiler, locomotive boiler, Lancashire boiler.

Simple Vertical Boiler

Classification of boiler

Vertical, natural circulation, natural draft, single turbular, stationary, medium pressure, solid fuel fired, fired tube boiler with internally located furnace.

Construction and working:

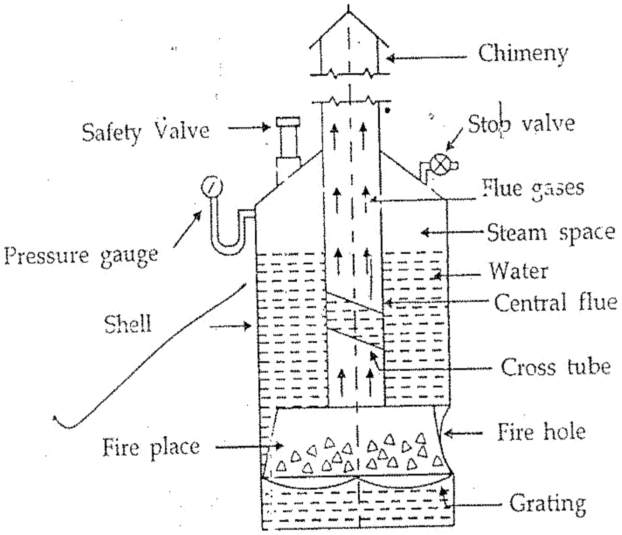


Figure: Simple Vertical boiler

Figure depicts a typical water tube boiler of early period. It has a cylindrical fire box surrounded by a cylindrical water shell connected by one inclined cross tube for improved water circulation. It is provided with standard safety control and inspection mountings.

Boiler drum is filled with water, the flue gas from the furnace rise in the tube. The exchange of heat takes place between water and flue gases. The water temperature raises and it converts into steam. The flue gases temperature drops and low temperature flue gases enters into environment via chimney. Due to provision of cross tube, the total heat transfer area increases and more amount of steam is available with the same amount of flue gases. They can built for small capacity and occupy small space. The boiler is fitted with all the mountings as per IBR.

Cochran Boiler

Classification of boiler

Vertical drum axis, natural circulation, natural draft, multi tubular, low pressure, solid fuel fired fire tube boiler with internally located furnace.

Construction and working of boiler

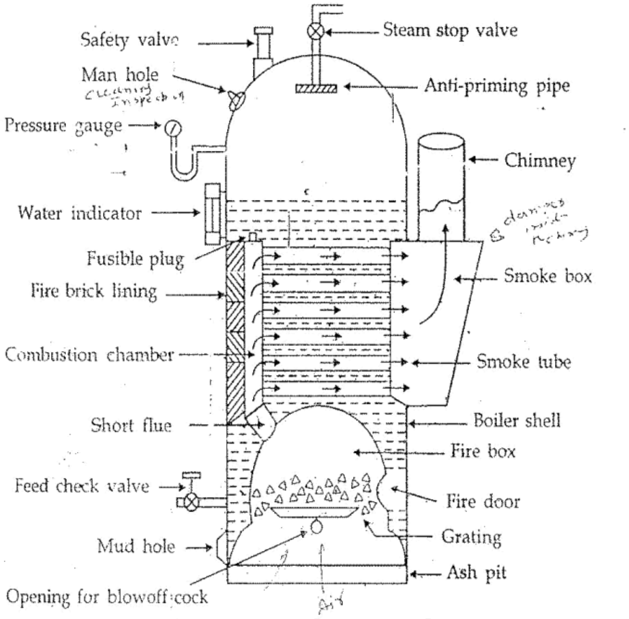


Figure: Cochran Boiler:

Figure depicts a Cochran boiler. It is a modified form of simple vertical boiler. It has a hemispherical crown to given maximum space for steam and very high strength to withstand high steam pressure.

Generated flue gas from the furnace pass through large number of smaller diameter tubes located horizontally in the boiler drum. The large heat transfer area is available for exchange of heat between water and flue gases. The water is converted into steam from the steam space it is supplied to the plant where the steam is required. Low temperature flue gases enter the environment via chimney. All the necessary mountings as per IBR is attached with above boiler.

The advantages of this boiler are its low chimney height, portability, high beaming rate and burning of clay kind of solid as well as liquid fuel. But it has poor efficiency for smaller unit, high head space, difficult to inspect and uneconomical in operation.

Locomotive boiler

Classification of boiler

Horizontal drum axis, natural circulation, artificial draft, multi-tubular, medium pressure, mobile, solid fuel fired, fired tube boiler with furnace located in tubes.

Construction and working

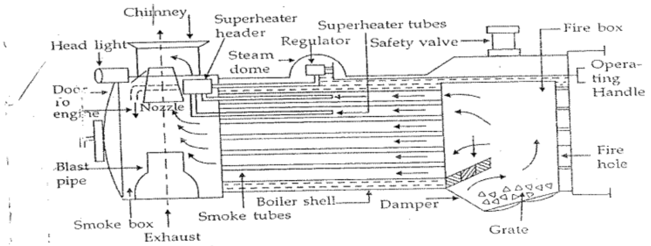


Figure: Locomotive boiler

It is multi-tubular boiler used in railway engines. It is a mobile boiler and steam generation rate is higher.

The boiler consists of large number of smaller diameter tubes located in a cylindrical shell along with a rectangular fire box at one end and a smoke box at the other end. Fuel burn on the inclined grate and flue gases enter into the tubes because of fire bridge arch.

The flue gases pass through number of tubes. Water is surrounded to the tubes. There is an exchange of heat between water and flue gases. The water convert into steam and the flue gases at lower temperature enter into chimney. The steam enters the super heater and the superheated steam is supplied to the steam engine via steam stop valve. The draft created in above case is of artificial type.

The chimney of this boiler is very short. As such enough draft cannot be created by chimney. The draft is obtained by passing the steam exhausted from the engine through a blast -pipe located in the smoke box. The steam passing through the nozzle above the blast pipe creates enough suction to draw in the air through the tubes. A circular door is provided at the end of smoke box for inspection and cleaning.

The rate of steam generation accelerated due to vibrations caused by the movement of the boiler. The boiler has a very low efficiency and cannot carry high overloads without suffering heavy damage due to overheating.

Babcock and Wilcox boiler

Classification of boiler

Horizontal drum axis, natural circulation, natural draft, multitubular, high pressure, stationary, solid fuel fired, water tube boiler with furnace located externally.

Construction and working

Figure depicts Babcock and Wilcox boiler. This is high pressure boiler used in power plants. It consists horizontal boiler drum connected by uptake header and down take header which in turn are connected by number of inclined tubes of water. The flue gases are exchange the heat with the water. The position of baffles cause the gas to move in zigzag way and more heat transfer is possible. A counter flow heating is used. The draft is regulated by dampers. The water enters the tube through down take header. Due to inclined tubes, the entire tube is not filled with the water. Due to exchange of heat, the steam is separated from the water and through uptake header, it enter the steam space inside the boiler drum. Anti-priming pipe is provided to ensure that only the dry saturated steam enter the super heater via steam stop valve.

It can be built for any width and height because of sectional construction, good circulation, rapid steaming,, safe and free from explosion, fast response to overloads, ease of repair, maintenance and cleaning. It is costlier and fluctuation in water level.

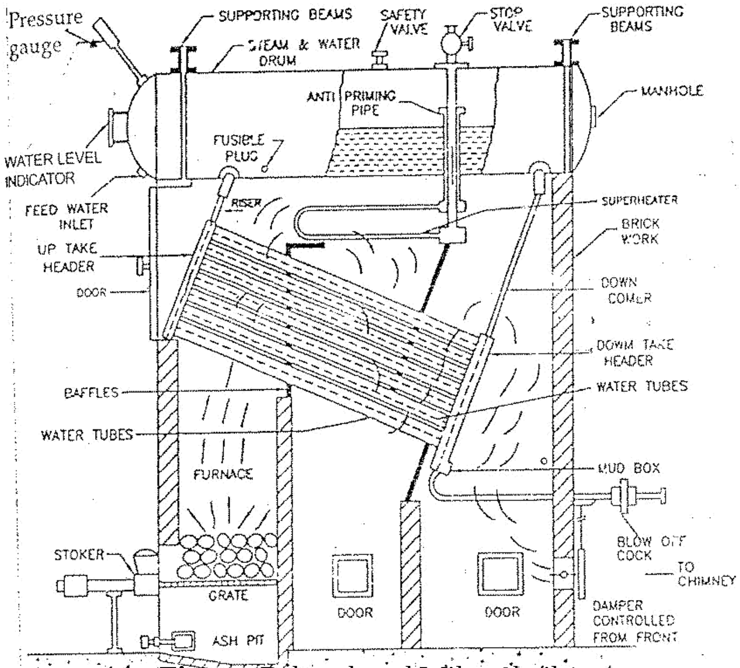


Figure: Babcock and Wilcox boiler

Lancashire Boiler

Classification of boiler

Horizontal drum axis, natural circulation, natural draft, two-tubular, medium pressure, stationary, fire tube boiler with furnace located internally.

Construction and working

Figure shows the constructional details of Lancashire boiler along with different boiler mountings, brick work, path of flue gases, furnace etc. Fuel is burnt on the grate and the flue gases can flow from one furnace end to other end of tubes (i.e. from front side to back side of furnace). This is first pass of flue gas through the boiler tubes. The water is surrounded to the tube. The heat between the water in the boiler drum and the flue gases inside the tube. So the steam is formed. Flue gases available at the backside of the furnace can be diverted in the downward direction due to presence of brick work. (Brick is a very poor conductor of heat energy and can works as insulating material for a given system). So the flue gases can flow from the bottom part of the boiler drum and exchange the heat with water. This is second pass of flue gases outside the tube. So the flue gases are available at front side. From front, because of brick work, they are divided into two side flues and once again flow backward from the sides of boiler drum and finally are expelled out to stack chimney through main flue. Dampers are provided at the end of side flues to regulate the flow of flue gases.

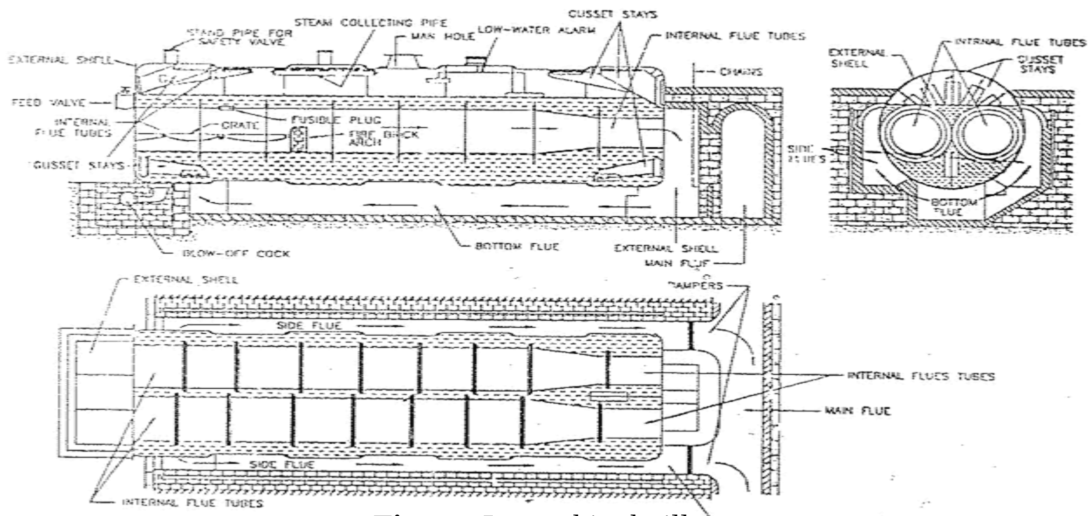


Figure: Lancashire boiller

The disadvantages of the boiler include more floor space, leakage problems through brick-settings, more steaming time, sluggish water circulation, limitation of high pressure of steam and limited space for grate area of furnace.

The advantage of Lancashire boiler are large steam space, load fluctuations can easily be met, easy to clean and inspect, reliable, easy to operate and maintain.

Steam boiler mountings

In accordance with the Indian boiler regulations the following mountings should be fitted to boilers.

Safety valves: The function of the valve is to blow off the steam when the pressure of thesteam in the boiler exceeds the working pressure

Water level Indicator: Its function is to indicate level of water, its upper and open in steamspace and lower and opens to water space

Pressure gauge: It is for indicating the pressure of steam in a boiler

Steam stop valve: It stops or allows the flow of steam from the boiler to the steam pipe.

Feed check valve: It allows or stops the supply of water to the boiler

Blow off cock: It is for removal of sediment periodically collected at the bottom of theboiler

Man hole: It is provided in opening from which a man can enter in a boiler for cleaning

Fusible plug: Its function is to extinguish fire in the furnace of a boiler when the water levelin the boiler fails to an unsafe extent thereby preventing the explosion which may takes place furnace plate

Boiler accessories

- Economizers
- Air pre-heaters
- Super heaters
- Feed pump
- Injectors

Economizers

Using economizer some of the heat recovered and sent back to the boilers in the feed water if an economizer is placed between the boiler and chimany.

The waste fire gases flow outside the economizer tubes and heat is transferred to the fuel water which flows upward inside the tubes. The external surfaces of the tubes are kept free from soft by scrapers which travels slowly and continuously up and down the tubes.

Advantages

- Fuel economy
- Long life of the boiler

Air pre-heaters

Air pre-heaters is installed between the economizer and the chimney and it abstracts heat from the five gases and transfers to air a portion of the heat that otherwise could pass up the chimney to waste.

Super heaters

Steam consumption is reduced with the use of superheated super heater heats the steam produced also production in condensation losses takes place.

Feed pumps

It is used to pump the water from storage to boiler.

Injectors

It is also used to pump the water with for to the boiler.

STEAM NOZZLES

Types of Nozzles:

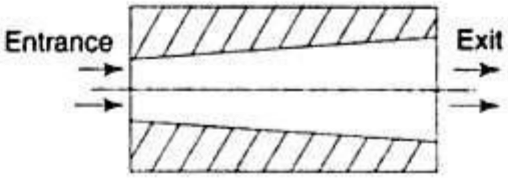
- Convergent Nozzle
- Divergent Nozzle
- Convergent-Divergent Nozzle

Convergent Nozzle:

A typical convergent nozzle is shown in fig. in a convergent nozzle, the cross sectionalarea decreases continuously from its entrance to exit. It is used in a case where the back pressure is equal to or greater than the critical pressure ratio.

Divergent Nozzle:

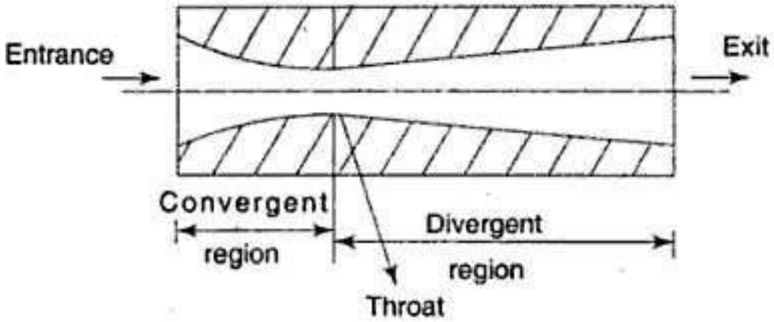
The cross sectional area of divergent nozzle increases continuously from its entrance to exit. It is used in a case, where the back pressure is less than the critical pressure ratio.



Divergent Nozzle:

Convergent-Divergent Nozzle:

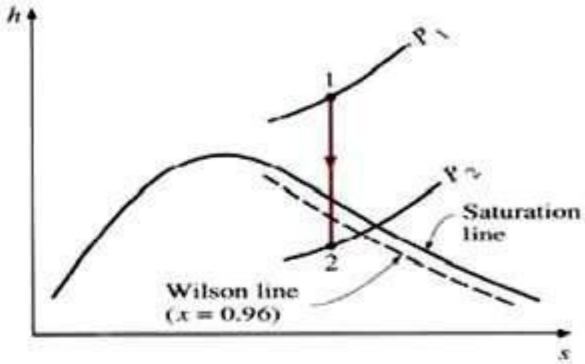
In this case, the cross sectional area first decreases from its entrance to throat, and then increases from throat to exit.it is widely used in many type of steam turbines.



Convergent-Divergent Nozzle

S**upersaturated flow or Meta stable flow in Nozzles:** As steam expands in the nozzle, its pressure and temperature drop, and it is expected that the steam start

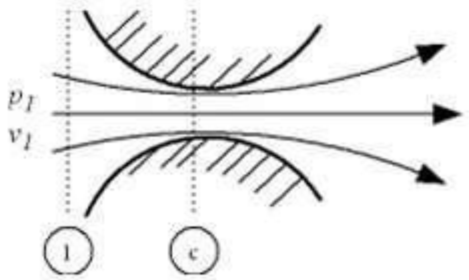
condensing when it strikes the saturation line. But this is not always the case. Owing to the high velocities, the residence time of the steam in the nozzle is small, and there may not sufficient time for the necessary heat transfer and the formation of liquid droplets. Consequently, the condensation of steam is delayed for a little while. This phenomenon is known as super saturation, and the steam that exists in the wet region without containing any liquid is known as supersaturated steam The locus of points where condensation will take place regardless of the initial temperature and pressure at the nozzle entrance is called the Wilson line. The Wilson line lies between 4 and 5 percent moisture curves in the saturation region on the h-s diagram for steam, and is often approximated by the 4 percent moisture line. The super saturation phenomenon is shown on the h-s chart below:



The h-s diagram for the isentropic expansion of steam in a nozzle.

Critical Pressure Ratio: The critical pressure ratio is the pressure ratio which will accelerate theflow to a velocity equal to the local velocity of sound in the fluid.

Critical flow nozzles are also called **sonic chokes**. By establishing a shock wave the sonic chokeestablish a fixed flow rate unaffected by the differential pressure, any fluctuations or changes in downstream pressure. A sonic choke may provide a simple way to regulate a gas flow.



Critical flow nozzles

The ratio between the critical pressure and the initial pressure for a nozzle can

expressed as

Pc / p1 = (2 / (n + 1)) Where, p_c = critical pressure (Pa) p_1 = inlet pressure (Pa)
n = index of isentropic expansion or compression or polytrophic constant

For a perfect gas undergoing an adiabatic process the index – n – is the ratio of specific heats k = cp / cv. There is no unique value for – n. Values for some common gases are

- Steam where most of the process occurs in the wet region: n = 1.135
- Steam super-heated: n = 1.30
- Air: n = 1.4
- Methane: n = 1.31
- Helium: n = 1.667

Effect of Friction on Nozzles:

- Entropy is increased.
- Available energy is decreased.
- Velocity of flow at throat is decreased.
- Volume of flowing steam is decreased.
- Throat area necessary to discharge a given mass of steam is increased.

Most of the friction occurs in the diverging part of a convergent-divergent nozzle as the length of the converging part is very small. The effect of friction is to reduce the available enthalpy drop by about 10 to 15%. The velocity of steam will be then

$V_2 = 44.72\sqrt{K(H_1 - H_2)}$

Where, k is the co-efficient which allows for friction loss. It is also known as nozzle efficiency.

Velocity of Steam at Nozzle Exit:

$$V_2^2 = 2000(H_1 - H_2) + V_1^2 \quad \therefore \quad V_2 = \sqrt{2000(H_1 - H_2) + V_1^2}$$

As the velocity of steam entering the nozzle is very small, V_1 can be neglected.

$$\therefore \qquad V_2 = \sqrt{2000(H_1 - H_2)} = 44.72\sqrt{(H_1 - H_2)} \text{ m/s}$$

If frictional losses are taken into account then

$$V_2 = 44.72\sqrt{(H_1 - H_2)\eta_n} \text{ m/s}$$

3.5 Mass of steam discharged through nozzle:

$$m = A\sqrt{2000\frac{n}{n-1} \times \frac{P_1}{v_1}\left[\left(\frac{P_2}{P_1}\right)^{\frac{2}{n}} - \left(\frac{P_2}{P_1}\right)^{\frac{n+1}{n}}\right]}$$

Condition for maximum discharge through nozzle: The nozzle is always designed for maximumdischarge**Values for maximum discharge:**

Where P1 is the initial pressure of the steam in kpa and v1 is the specific volume of the steam in m3/kg at the initial pressure.

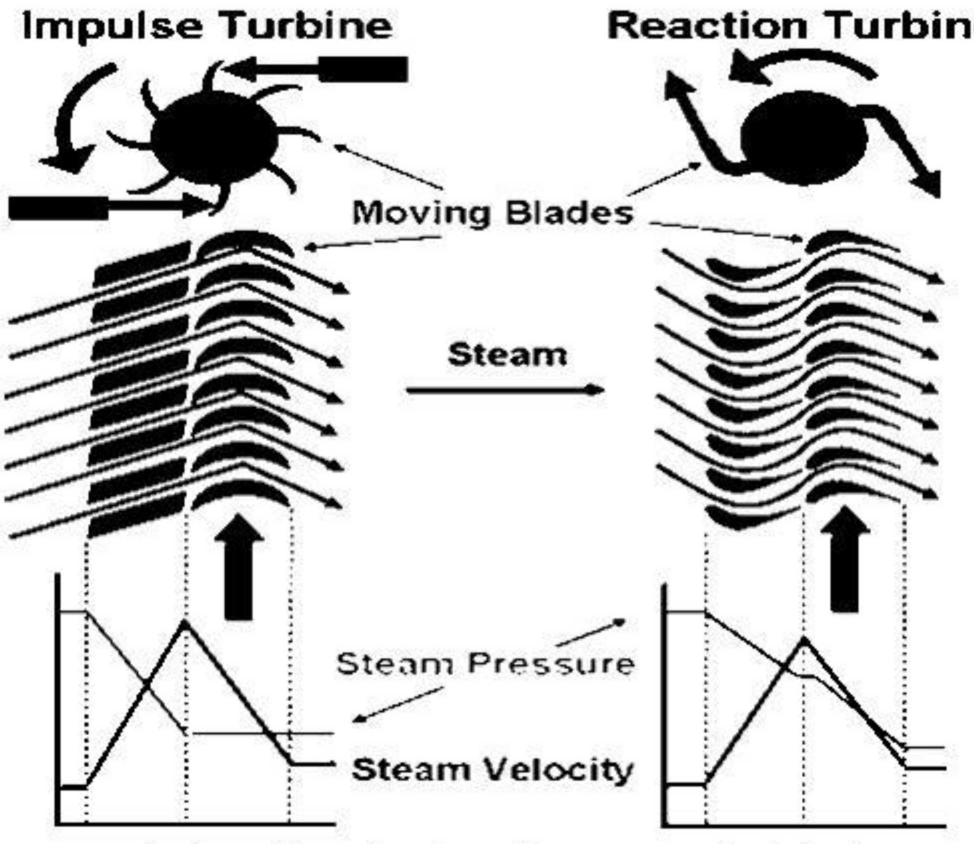
UNIT- III
STEAM TURBINE AND CONDENSERS

STEAM TURBINES: Normally the turbines are classified into types,

i) Impulse Turbine

ii) Reaction Turbine

Impulse and Reaction Turbines:



impulse turbine and reaction turbine pressure and velocity diagram

Impulse Turbines:

The steam jets are directed at the turbines bucket shaped rotor blades where the pressure exerted by the jets causes the rotor to rotate and the velocity of the steam to reduce as it imparts its kinetic energy to the blades. The blades in turn change the direction of flow of the steam however its pressure remains constant as it passes through the rotor blades since the cross section of the chamber between the blades is

constant. Impulse turbines are therefore also known as constant pressure turbines. The next series of fixed blades reverses the direction of the steam before it passes to the second row of moving blades

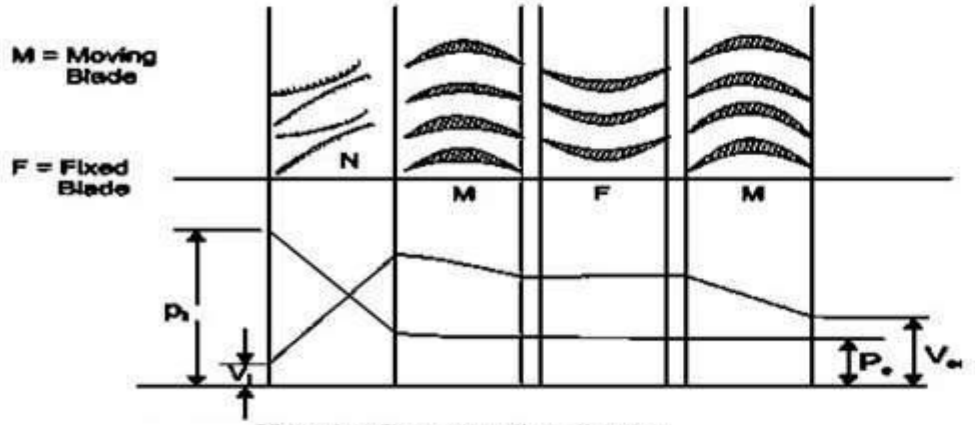
Reaction Turbines

The rotor blades of the reaction turbine are shaped more like aero foils, arranged such that the cross section of the chambers formed between the fixed blades diminishes from the inlet side towards the exhaust side of the blades. The chambers between the rotor blades essentially form nozzles so that as the steam progresses through the chambers its velocity increases while at the same time its pressure decreases, just as in the nozzles formed by the fixed blades. Thus the pressure decreases in both the fixed and moving blades. As the steam emerges in a jet from between the rotor blades, it creates a reactive force on the blades which in turn creates the turning moment on the turbine rotor, just as in Hero’s steam engine. (Newton’s Third Law – For every action there is an equal and opposite reaction).

Compounding of impulse turbine:

This is done to reduce the rotational speed of the impulse turbine to practical limits. (A rotor speed of 30,000 rpm is possible, which is pretty high for practical uses.) - Compounding is achieved by using more than one set of nozzles, blades, rotors, in a series, keyed to a common shaft; so that either the steam pressure or the jet velocity is absorbed by the turbine in stages. - Three main types of compounded impulse turbines are: a) Pressure compounded, b) velocity compounded and c) pressure and velocity compounded impulse turbines.

Velocity Compounding:



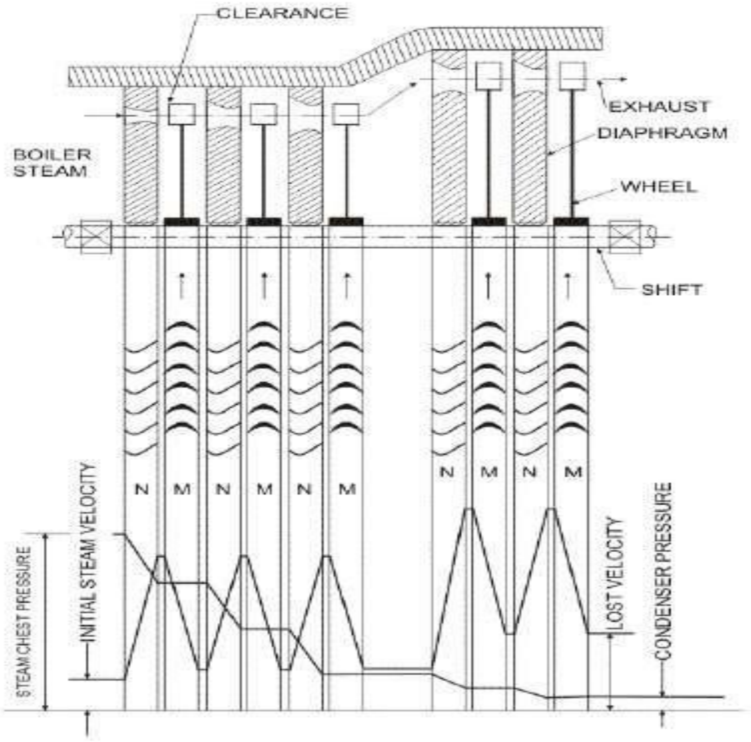
Velocity Compounding diagram

Pi = Inlet Pressure, Pe= Exit Pressure, Vi =Inlet Velocity, Ve=Exit Velocity.

The velocity-compounded impulse turbine was first proposed by C.G. Curtis to solve the problems of a single-stage impulse turbine for use with high pressure and temperature steam. The Curtis stage turbine, as it came to be called, is composed of one stage of nozzles as the single-stage turbine, followed by two rows of moving blades instead of one. These two rows are separated by one row of fixed blades attached to the turbine stator, which has the function of redirecting the steam leaving the first row of moving blades to the second row of moving blades. A Curtis stage impulse turbine is shown in Fig. with schematic pressure and absolute steam-velocity changes through the stage. In the Curtis stage, the total enthalpy drop and hence pressure drop occur in the nozzles so that the pressure remains constant in all three rows of blades.

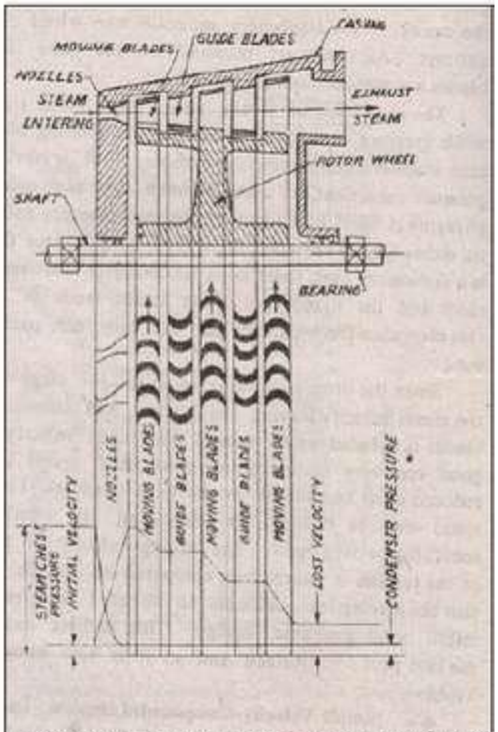
Pressure Compounding:

This involves splitting up of the whole pressure drop from the steam chest pressure to the condenser pressure into a series of smaller pressure drops across several stages of impulse turbine. -The nozzles are fitted into a diaphragm locked in the casing. This diaphragm separates one wheel chamber from another. All rotors are mounted on the same shaft and the blades are attached on the rotor.



Pressure-Velocity Compounding

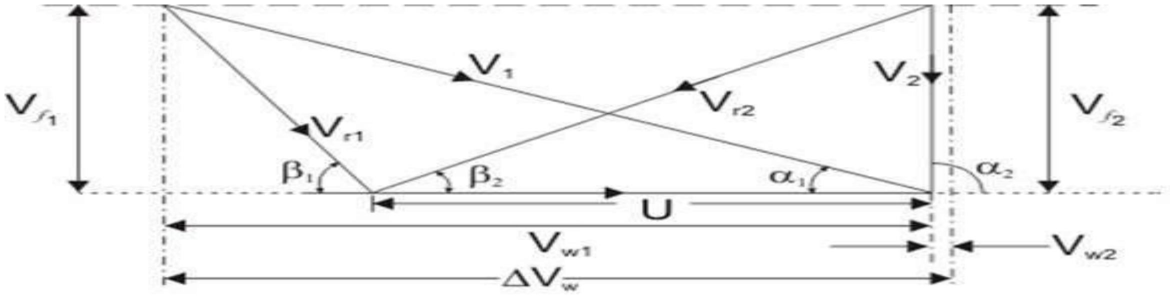
This is a combination of pressure and velocity compounding. A two-row velocity compounded turbine is found to be more efficient than the three-row type. In a two-step pressure velocity compounded turbine, the first pressure drop occurs in the first set of nozzles, the resulting gain in the kinetic energy is absorbed successively in two rows of moving blades before the second pressure drop occurs in the second set of nozzles. Since the kinetic energy gained in each step is absorbed completely before the next pressure drop, the turbine is pressure compounded and as well as velocity compounded. The kinetic energy gained due to the second pressure drop in the second set of nozzles is absorbed successively in the two rows of moving blades.



Diagrammatic arrangement of Velocity Compounded Impulse Turbine.

The pressure velocity compounded steam turbine is comparatively simple in construction and is much more compact than the pressure compounded turbine.

Velocity diagram of an impulse turbine:



Velocity diagram of an impulse turbine

Power developed = $\dot{m} U \Delta V_w$

Blade efficiency or Diagram efficiency or Utilization factor is given by

$$\eta_b = \frac{\dot{m} \cdot U \cdot \Delta V_w}{m(V_1^2/2)} = \frac{Workdone}{K.E \quad supplied}$$

Or,

$$\eta_b = \frac{2U\Delta V_w}{V_1^2}$$

stage efficiency $= \eta_s = \dfrac{\text{Work done by the rotor}}{\text{Isentropic enthalpy drop}}$

$$\eta_s = \frac{\dot{m}U\Delta V_w}{\dot{m}(\Delta H)_{isen}} = \frac{\dot{m}U\Delta V_w}{\dot{m}\left(\dfrac{V_1^2}{2}\right)} \cdot \frac{\dot{m}(V_1^2/2)}{\dot{m}(\Delta H)_{isen}}$$

or,

or, $\eta_s = \eta_b \times \eta_n \qquad [\eta_n = \text{Nozzle efficiency}]$

Optimum blade speed of a single stage turbine

$$\Delta V_w = V_{r1}\cos\beta_1 + V_{r2}\cos\beta_2$$

$$= V_{r1}\cos\beta_1 + \left(1 + \frac{V_{r2}}{V_{r1}} \cdot \frac{\cos\beta_2}{\cos\beta_1}\right)$$

$$= (V_1 \cos\alpha_1 - U) + (1 + kc)$$

where, $k = (V_{r2}/V_{r1})$ = friction coefficient

$$c = (\cos\beta_2 / \cos\beta_1)$$

$$\eta_b = \frac{2U\Delta V_w}{V_1^2} = 2\frac{U}{V_1}\left(\cos\alpha_1 - \frac{U}{V_1}\right)(1 + kc)$$

$$\rho = \frac{U}{V_1} = \frac{\text{Blade speed}}{\text{Fluid velocity at the blade inlet}} = \text{Blade speed ratio}$$

η_b is maximum when $\frac{d\eta_b}{d\rho} = 0$ also $\frac{d^2\eta_b}{d\rho} = -4(1+kc)$

$$\text{or,} \quad \frac{d}{d\rho}\{2(\rho\cos\alpha_1 - \rho^2)(1+kc)\} = 0$$

$$\text{or,} \quad \rho = \frac{\cos\alpha_1}{2}$$

α_1 is of the order of 18^0 to 22^0

Now, $(\rho)_{opt} = \left(\frac{U}{V_1}\right)_{opt} = \frac{\cos\alpha_1}{2}$ (For single stage impulse turbine)

∴ The maximum value of blade efficiency

$$(\eta_b)_{\max} = 2(\rho\cos\alpha_1 - \rho^2)(1+kc)$$

$$= \frac{\cos^2\alpha_1}{2}(1+kc)$$

For equiangular blades,

$$(\eta_b)_{\max} = \frac{\cos^2\alpha_1}{2}(1+k)$$

If the friction over blade surface is neglected

$$(\eta_b)_{\max} = \cos^2\alpha_1$$

The fixed blades are used to guide the outlet steam/gas from the previous stage in such a manner so as to smooth entry at the next stage is ensured.

K, the blade velocity coefficient may be different in each row of blades

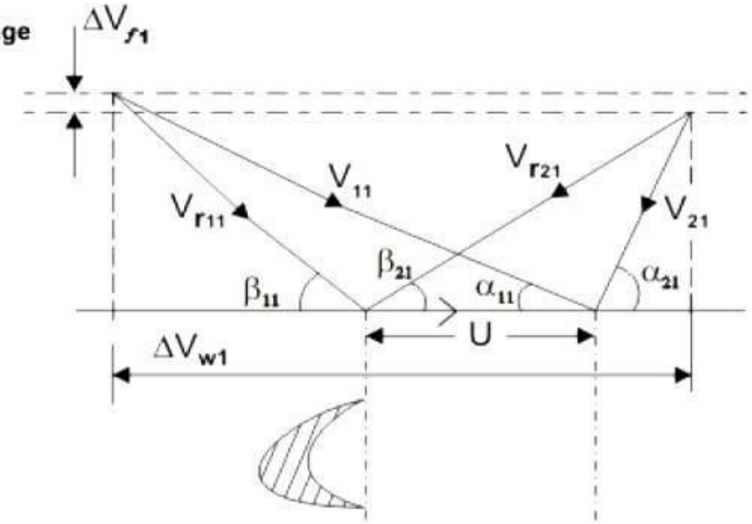
Work done = $\dot{m}.U(\Delta V_{w1} + \Delta V_{w2})$

$$\textbf{End thrust} = \dot{m}(\Delta V_{f1} + \Delta V_{f2})$$

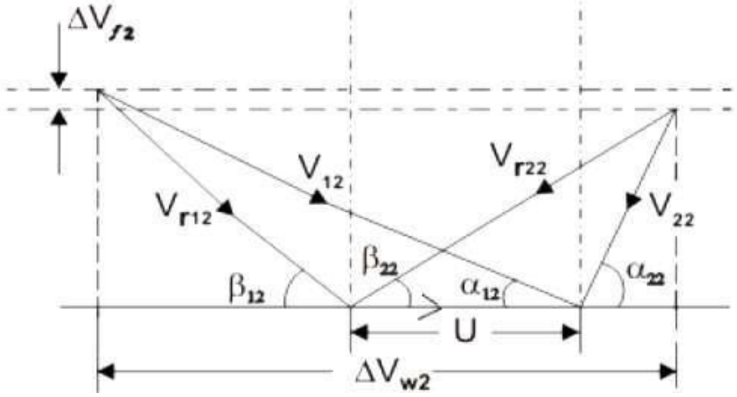
The optimum velocity ratio will depend on number of stages and is given by $P_{opt} = \dfrac{\cos \alpha_{11}}{2n}$

Velocity diagram of the velocity compounded turbines:

First Stage

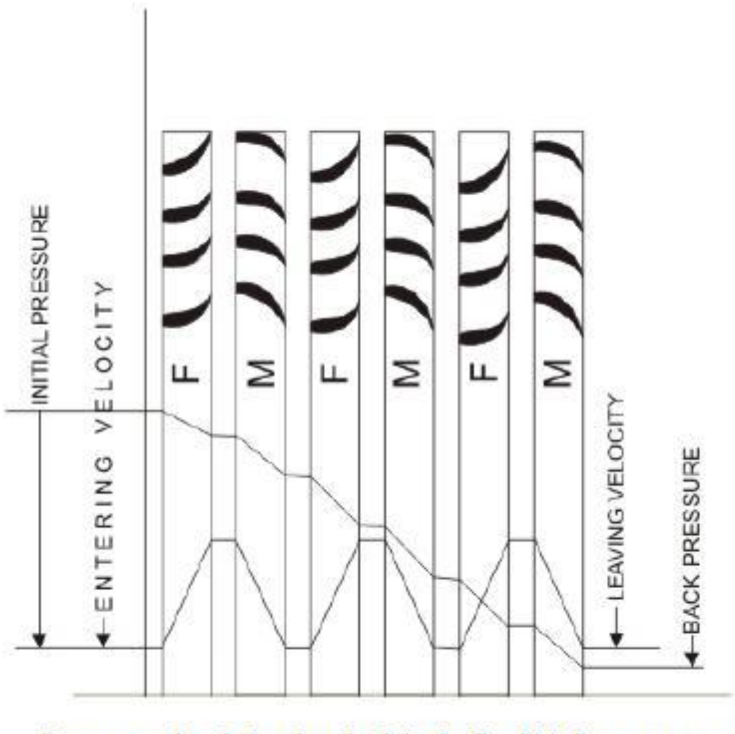


Second Stage



Reaction Turbine:

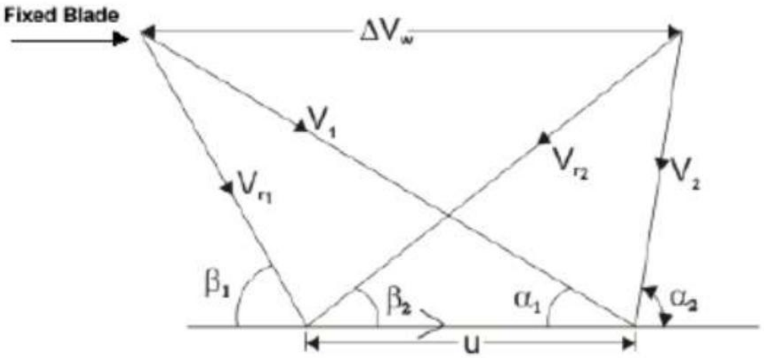
A *reaction turbine*, therefore, is one that is constructed of rows of fixed and rows of moving blades.The fixed blades act as nozzles. The moving blades move as a result of the impulse of steam received (caused by change in momentum) and also as a result of expansion and acceleration of the steam relative to them. In other words, they also act as nozzles. The enthalpy drop per stage of one row fixed and one row moving blades is divided among them, often equally. Thus a blade with a 50 percent degree of reaction, or a 50 percent reaction stage, is one in which half the enthalpy drop of the stage occurs in the fixed blades and half in the moving blades. The pressure drops will not be equal, however. They are greater for the fixed blades and greater for the high-pressure than the low-pressure stages. The moving blades of a reaction turbine are easily distinguishable from those of an impulse turbine in that they are not symmetrical and, because they act partly as nozzles, have a shape similar to that of the fixed blades, although curved in the opposite direction. The schematic pressure line in figure shows that pressure continuously drops through all rows of blades, fixed and moving. The absolute steam velocity changes within each stage as shown and repeats from stage to stage. The second figure shows a typical velocity diagram for the reaction stage.



Pressure and enthalpy drop both in the fixed blade or stator and in the moving blade or Rotor

$$\textbf{Degree of Reaction} = \frac{\text{Enthalpy drop in Rotor}}{\text{Enthalpy drop in Stage}}$$

or, $$R = \frac{h_1 - h_2}{h_0 - h_1}$$



A very widely used design has half degree of reaction or 50% reaction and this is known as Parson's Turbine. This consists of symmetrical stator and rotor blades.

The velocity triangles are symmetrical and we have

$$\alpha_1 = \beta_2 \quad , \quad \beta_1 = \alpha_2$$

$$V_1 = V_{r2} \quad , \quad V_{r1} = V_2$$

Energy input per stage (unit mass flow per second)

$$E = \frac{V_1^2}{2} + \frac{V_{r2}^2 - V_{r1}^2}{2}$$

$$E = V_1^2 - \frac{V_{r1}^2}{2}$$

$$E = V_1^2 - \frac{V_1^2}{2} - \frac{U^2}{2} + \frac{2V_1 U \cos\alpha_1}{2}$$

$$E = \left(V_1^2 - U^2 + 2V_1 U \cos\alpha_1\right)/2$$

From the inlet velocity triangle we have,

$$V_{r1}^2 = V_1^2 - U^2 - 2V_1 U \cos\alpha_1$$

Work done (for unit mass flow per second) $= W = U \Delta V_W$

$$= U(2V_1 \cos\alpha_1 - U)$$

Therefore, the Blade efficiency

$$= \eta_b = \frac{2U(2V_1 \cos\alpha_1 - U)}{V_1^2 - U^2 + 2V_1 U \cos\alpha_1}$$

Governing of Steam Turbine: The method of maintaining the turbine speed constant irrespective ofthe load is known as governing of turbine. The device used for governing of turbines is called Governor. There are 3 types of governors in steam turbine,

- Throttle governing
- Nozzle governing
- By-pass governing

Throttle Governing:

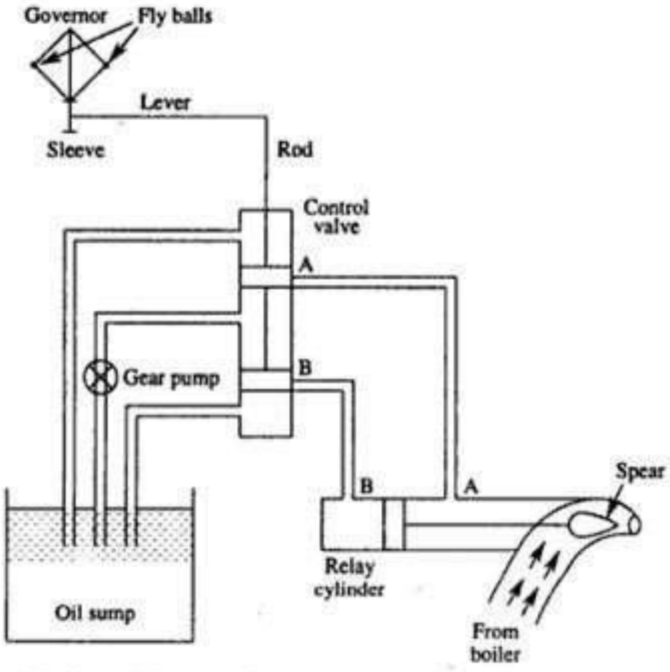


Fig 3.14 Throttle Governing

Let us consider an instant when the load on the turbine increases, as a result the speed of the turbine decreases. The fly balls of the governor will come down. The fly balls bring down the sleeve. The downward movement of the sleeve will raise the control valve rod. The mouth of the pipe AA will open. Now the oil under pressure will rush from the control valve to right side of piston in the rely cylinder through the pipe AA. This will move the piston and spear towards the left which will open more area of nozzle. As a result steam flow rate into the turbine increases, which in turn brings the speed of the turbine to the normal range.

A dynamic arrangement of nozzle control governing is shown in fig. In this nozzles are grouped in 3 to 5 or more groups and each group of nozzle is supplied steam controlled by valves. The arc of admission is limited to 180º or less. The nozzle controlled governing is restricted to the first stage of the turbine, the nozzle area in other stages remaining constant. It is suitable for the simple turbine and for larger units which have an impulse stage followed by an impulse reaction turbine.

Steam Condenser: It is a device or an appliance in which steam condenses and heat released bysteam is absorbed by water.

Elements of a steam condensing plant:

Condense: It is a closed vessel iswhich steam is condensed. The steam gives up heat energy to coolant (which is water) during the process of condensation.

Condensate pump: It is a pump,which removes condensate (i.e. condensed steam) from the condenser to the hot well.

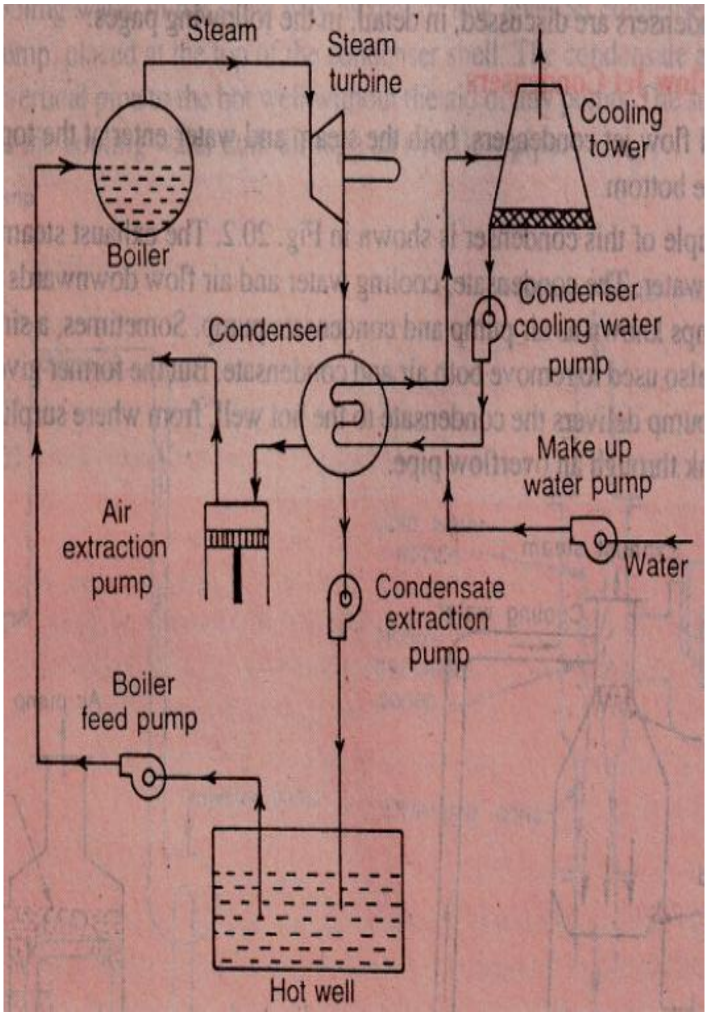
Hot well: It is a sump between thecondenser and boiler, which receives condensate pumped by the condensate pump.

Boiler feed pump: It is a pump,which pumps the condensate from the hot well to the , boiler. This is done by increasing the pressure of condensate above the boiler pressure.

Air extraction pump: It is a pumpwhich extracts (i.e. removes) air from the condenser.

Cooling tower: It is a tower usedfor cooling the water which is discharged from the condenser.

7) **Cooling water pump**: It is a pump, whichcirculates the cooling water through the condenser.



Classification of Condensers

- Jet condensers
- Surface condenser

Jet Condensers: The exhaust steam and water come in direct contact with each other andtemperature of the condensate is the same as that of cooling water leaving the condenser. The cooling water is usually sprayed into the exhaust steam to cause, rapid condensation.

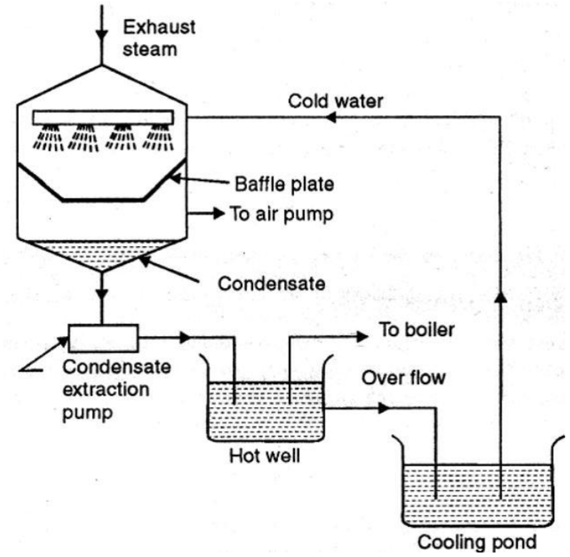
Surface Condensers: The exhaust steam and water do not come into direct contact. The steampasses over the outer surface of tubes through which a supply of cooling water is maintained.

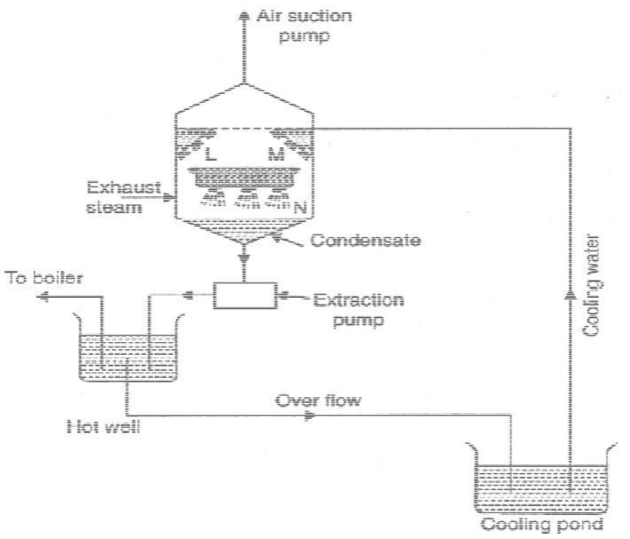
STEAM CONDESERS

- **Jet Condensers**
  - Parallel flow
  - Counter flow
  - Ejector flow
- **Surface Condensers**
  - Inverted-flow
  - Down-flow
  - Regenerative
  - Central-flow
  - Evaporative

Parallel- Flow Type of Jet Condenser: The exhaust steam and cooling water find their entry atthe top of the condenser and then flow downwards and condensate and water are finally collected at the bottom.

Counter- Flow Type jet Condenser: The steam and cooling water enter the condenser fromopposite directions. Generally, the exhaust steam travels in upward direction and meets the cooling water which flows downwards.





Low Level Jet Condenser (Counter-Flow Type Jet Condenser): Figure Shows, L, M andN are the perforated trays which break up water into jets. The steam moving upwards comes in contact with water and gets condensed.

The condensate and water mixture is sent to the hot well by means of an extraction pump and the air is removed by an air suction pump provided at the top of the condenser.

High Level Jet Condenser (Counter-Flow Type Jet Condenser): It is also calledbarometric condenser. In this type the shell is placed at a height about 10.363 meters above hot well and thus the necessity of providing an extraction pump can be obviated. However provision of own injection pump has to be made if water under pressure is not available.

Ejector Condenser Flow Type Jet Condenser:Here the exhaust steam and cooling water mix inhollow truncated cones. Due to this decreased pressure exhaust steam along with associated air is drawn through the truncated cones and finally lead to diverging cone.

In the diverging cone, a portion of kinetic energy gets converted into pressure energy which is more than the atmospheric so that condensate consisting of condensed steam, cooling water and air is discharged into the hot well. The exhaust steam inlet is provided with a non-return valve which does not allow the water from hot well to rush back to the engine in case a failure of cooling water supply to condenser.

Down-Flow Type:The cooling water enters the shell at the lower half section and after travelingthrough the upper half section comes out through the outlet. The exhaust steam entering shell from the top flows down over the tubes and gets condensed and is finally removed by an extraction pump. Due to the fact that steam flows in a direction right angle to the direction of flow of water, it is also called cross-surface condenser.

Central Flow Type: In this type of condenser, the suction pipe of the air extraction pump islocated in the centre of the tubes which results in radial flow of the steam. The better contact between the outer surface of the tubes and steam is ensured; due to large passages the pressure drop of steam is reduced.

Evaporative Type: The principle of this condenser is that when a limited quantity of water isavailable, its quantity needed to condense the steam can be reduced by causing the circulating water to evaporate under a small partial pressure.

The exhaust steam enters at the top through gilled pipes. The water pump sprays water on the pipes and descending water condenses the steam. The water which is not evaporated falls into the open tank (cooling pond) under the condenser from which it can be drawn by circulating water pump and used over again.

The evaporative condenser is placed in open air and finds its application in small size plants.

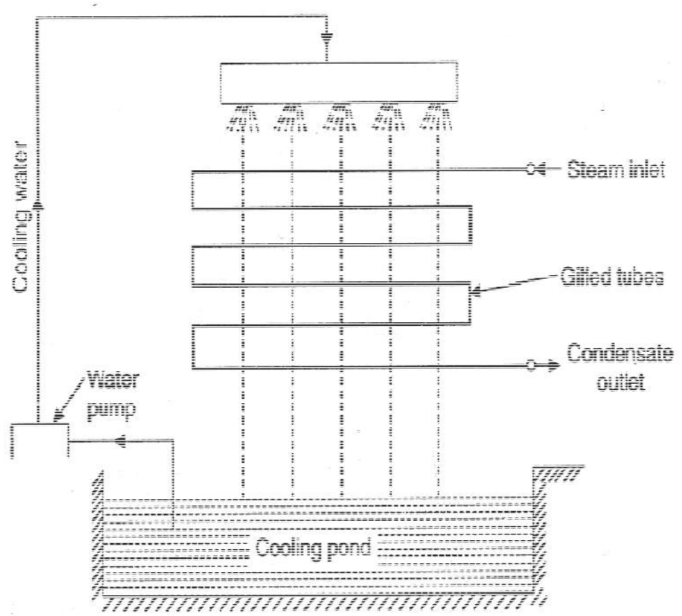


Fig. Evaporative Type

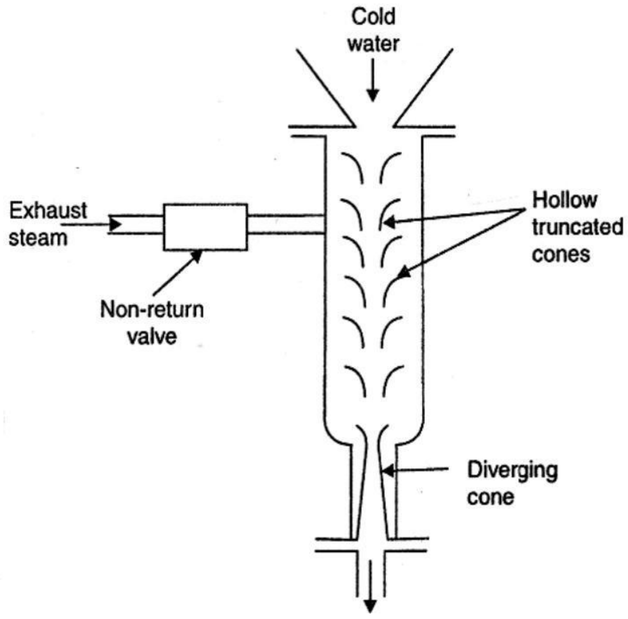


Fig. Ejector flow type condenser

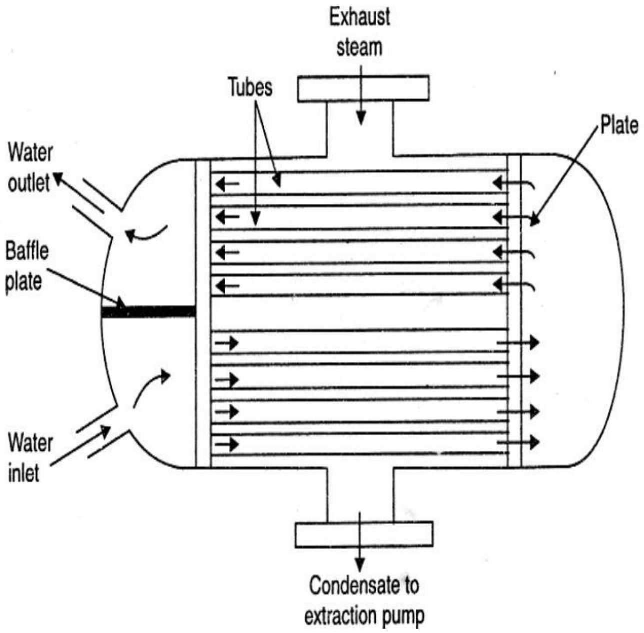


Fig. Down-Flow Type

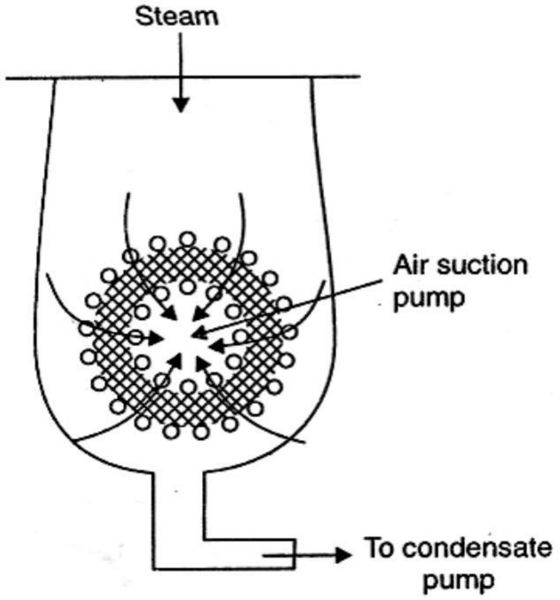
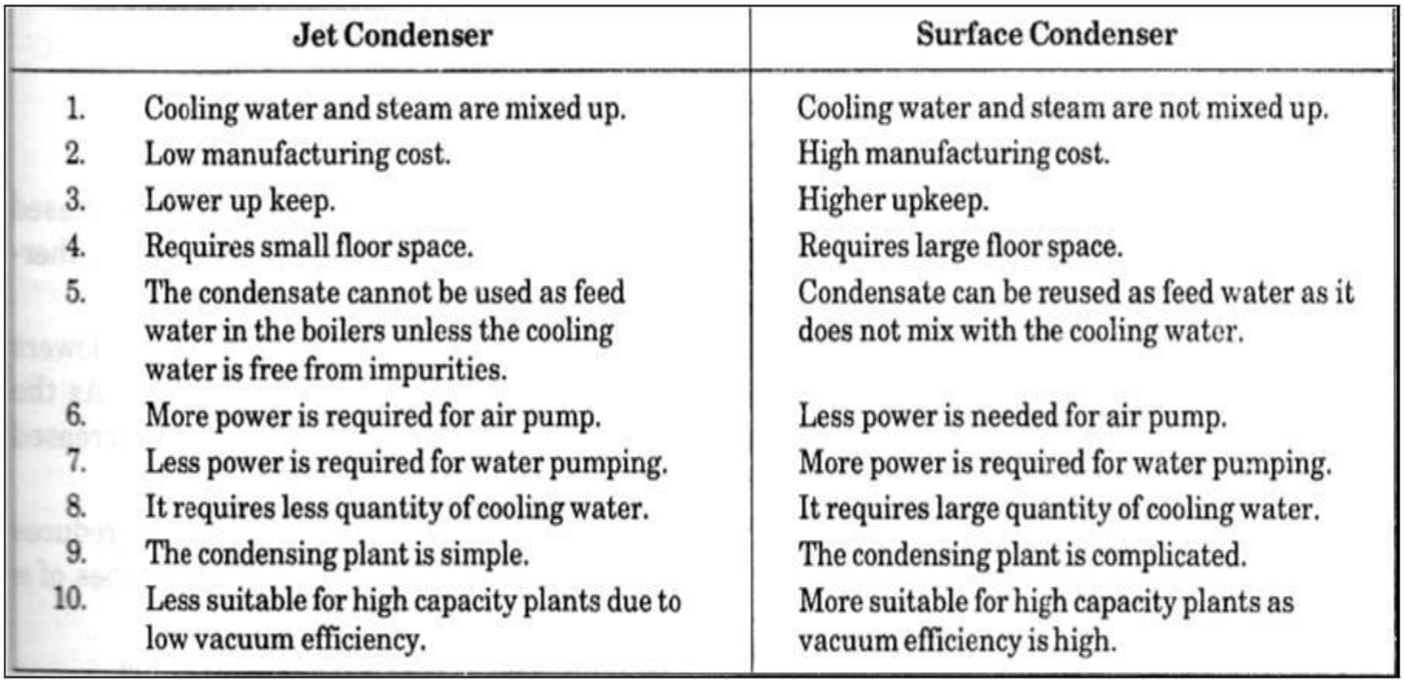


Fig. Central Flow Type

Inverted Flow Type: This type of condenser has the air suction at the top; the steam afterentering at the bottom rises up and then again flows down to the bottom of the condenser, by following a path near the outer surface of the condenser. The condensate extraction pump is at the bottom.

Regenerative Type: This type is applied to condensers adopting a regenerative method ofheating of the condensate. After leaving the tube nest, the condensate is passed through the entering exhaust steam from the steam engine or turbine thus raising the temperature of the condensate, for use as feed water for the boiler.

Comparison Between Jet And Surface Condensers



	Jet Condenser	Surface Condenser
1.	Cooling water and steam are mixed up.	Cooling water and steam are not mixed up.
2.	Low manufacturing cost.	High manufacturing cost.
3.	Lower up keep.	Higher upkeep.
4.	Requires small floor space.	Requires large floor space.
5.	The condensate cannot be used as feed water in the boilers unless the cooling water is free from impurities.	Condensate can be reused as feed water as it does not mix with the cooling water.
6.	More power is required for air pump.	Less power is needed for air pump.
7.	Less power is required for water pumping.	More power is required for water pumping.
8.	It requires less quantity of cooling water.	It requires large quantity of cooling water.
9.	The condensing plant is simple.	The condensing plant is complicated.
10.	Less suitable for high capacity plants due to low vacuum efficiency.	More suitable for high capacity plants as vacuum efficiency is high.

Mixture of Air and Steam (Dalton's Law of Partial Pressures):

It states "The pressure of the mixture of air and steam is equal to the sum of the pressures, which each constituent would exert, if it occupied the same space by itself" Mathematically, pressure in the condenser containing mixture of air and steam,

$$P_c = P_a + P_s$$

Where, P_c = Pressure in condenser
P_a = Partial pressure of air and,
P_s = Partial pressure of steam

Measurement of Vacuum in a Condenser:

Vacuum: The difference between the atmospheric pressure and the absolute pressure.

In the study of condensers, the vacuum is generally converted to correspond with a standard atmospheric pressure, which is taken as the barometric pressure of 760 mm of mercury (Hg). Mathematically, vacuum gauge reading corrected to standard barometer or in other words:

Corrected vacuum in the condenser = 760 - (Barometer reading - Vacuum gauge reading)

Note: We know that; Atmospheric pressure = 760 mm of Hg = 1.013 bar

Vacuum Efficiency: The minimum absolute pressure (also called ideal pressure) at the steam inletof a condenser is the pressure corresponding to the temperature of the condensed steam. The corresponding vacuum (called ideal vacuum) is the maximum vacuum that can be obtained in a condensing plant, with no air present at that temperature. The pressure in the actual condenser is greater than the ideal pressure by an amount equal to the pressure of air present in the condenser. The ratio of the actual vacuum to the ideal vacuum is known as vacuum efficiency. Mathematically, vacuum efficiency

$$= \text{Actual Vacuum} / \text{Ideal Vacuum}$$

Where η = Vacuum efficiency

Actual vacuum = Barometric pressure - Actual pressure

And Ideal vacuum = Barometric pressure - Ideal pressure

Condenser Efficiency

It is defined as the ratio of the difference between the outlet and inlet temperatures of cooling water to the difference between the temperature corresponding to the vacuum in the condenser and inlet temperature of cooling water, i.e.,

$$\text{Condenser efficiency} = \frac{\text{Rise in temperature of cooling water}}{\begin{bmatrix}\text{Temp. corresponding to vacuum}\\ \text{in the condenser}\end{bmatrix} - \begin{bmatrix}\text{Inlet temp. of}\\ \text{cooling water}\end{bmatrix}}$$

$$= \frac{\text{Rise in temperature of cooling water}}{\begin{bmatrix}\text{Temp. corresponding to the absolute}\\ \text{pressure in the condenser}\end{bmatrix} - \begin{bmatrix}\text{Inlet temp. of}\\ \text{cooling water}\end{bmatrix}}$$

Sources of air into the condensers:

The dissolved air in the feed water enters into the boiler, which in turn enters into the condenser with the exhaust steam.

The air leaks into the condenser, through various joints, due to high vacuum pressure in the condenser.

In case of jet condensers, dissolved air with the injection water enters into the condenser.

Effects of Air Leakage:

It reduces the vacuum pressure in the condenser.

Since air is a poor heat conductor, particularly at low densities, it reduces the rate of heat transmission.

It requires a larger air pump. Moreover, an increased power is required to drive the pump.

Cooling Towers

In a cooling tower water is made to trickle down drop by drop so that it comes in contact with the air moving in the opposite direction. As a result of this some water is evaporated and is taken away with air. In evaporation, the heat is taken away from the bulk of water, which is thus cooled.

Types of Cooling Tower

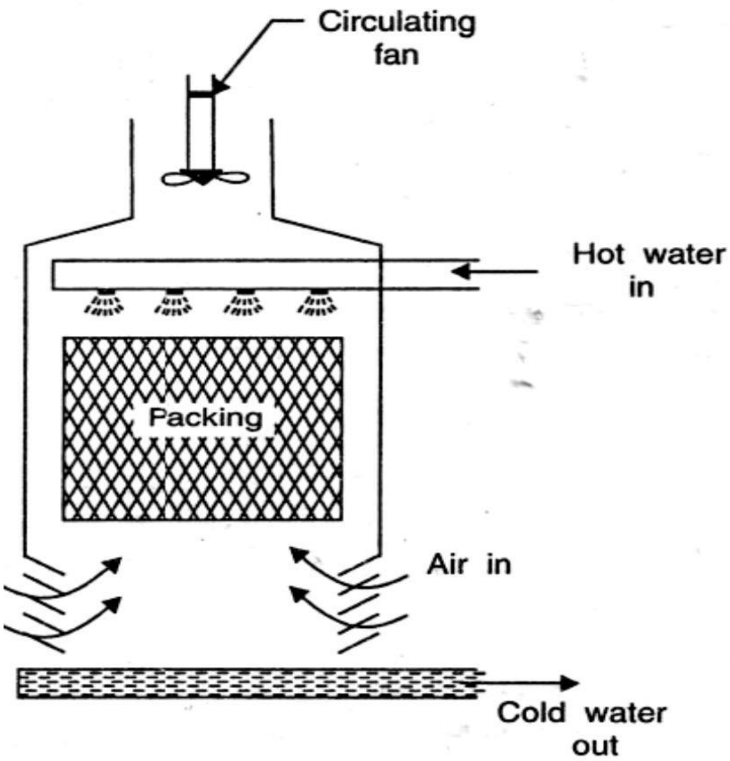


Fig. Natural draught cooling tower

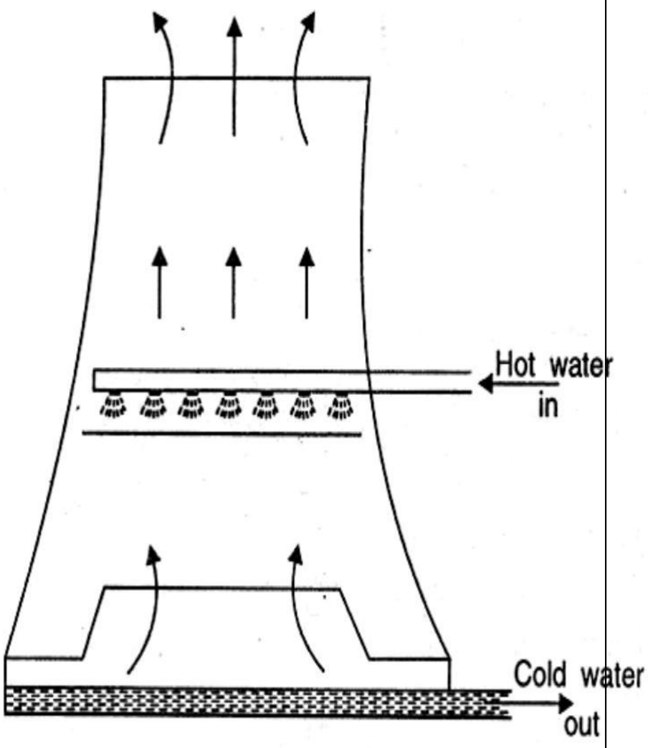


Fig. Forced draught cooling
tower

UNIT -IV
GAS TURBINES

Open Gas- Turbine Cycle

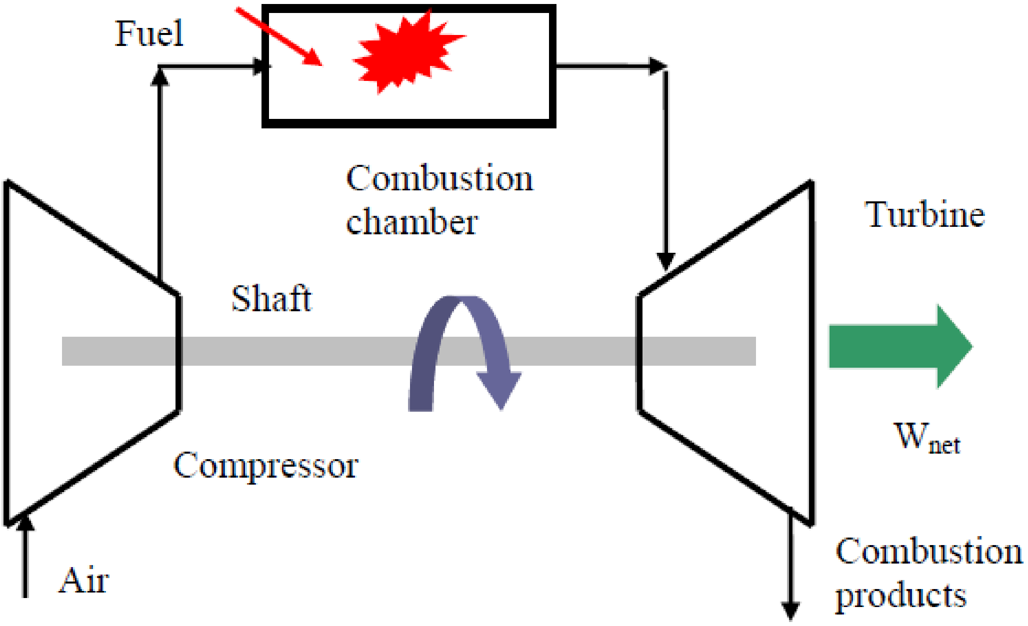


Fig.1: Schematic for an open gas-turbine cycle.

Working Principal

Fresh air enters the compressor at ambient temperature where its pressure and temperature areincreased.

The high pressure air enters the combustion chamber where the fuel is burned at constant pressure.

The high temperature (and pressure) gas enters the turbine where it expands to ambient pressure and produces work.

Features:

- Gas-turbine is used in aircraft propulsion and electric powergeneration.
- High thermal efficiencies up to44%.
- Suitable for combined cycles (with steam powerplant)
- High power to weight ratio, high reliability, longlife
- Fast start up time, about 2 min, compared to 4 hr for steam-propulsionsystems
- High back work ratio (ratio of compressor work to the turbine work), up to 50%, compared to few percent in steam powerplants.

Brayton Cycle

Brayton cycle is the ideal cycle for gas-turbine engines in which the working fluid undergoes a closed loop. That is the combustion and exhaust processes are modeled by constant-pressure heat addition and rejection, respectively.

The Brayton ideal cycle is made up of four internally reversible processes:

1-2	isentropic compression (in compressor)
2-3	const. pressure heat-addition (in combustion chamber)
3-4	isentropic expansion (in turbine)
4-1	const. pressure heat rejection (exhaust)

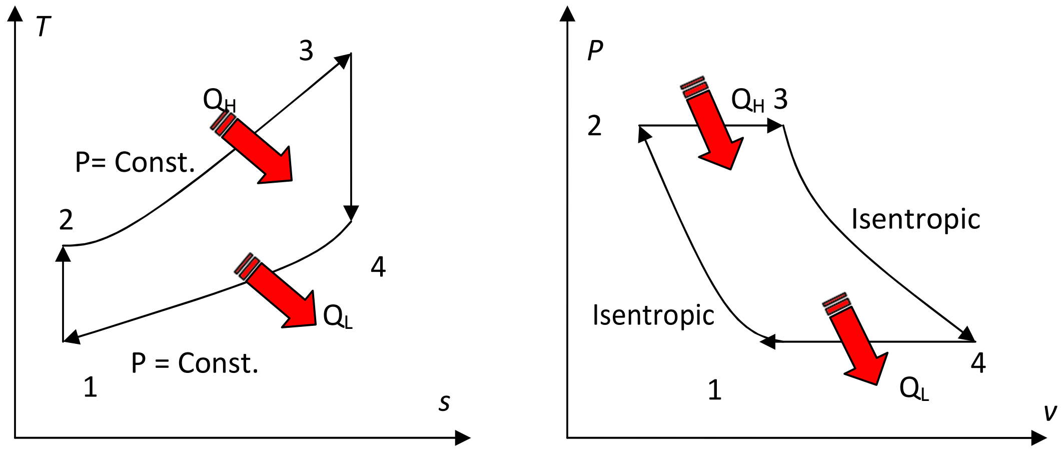


Fig. 2: T-s and P-v diagrams for ideal Brayton cycle.

Thermal efficiency for the Brayton cycle is:

$$\eta_{th,Brayton} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)} = 1 - \frac{T_1(T_4/T_1 - 1)}{T_2(T_3/T_2 - 1)}$$

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(k-1)/k} = \left(\frac{P_3}{P_4}\right)^{(k-1)/k} = \frac{T_3}{T_4}$$

thus

$$\eta_{th,Brayton} = 1 - \frac{1}{r_P^{(k-1)/k}}$$

$$r_P = \frac{P_2}{P_1} = \frac{P_3}{P_4}$$

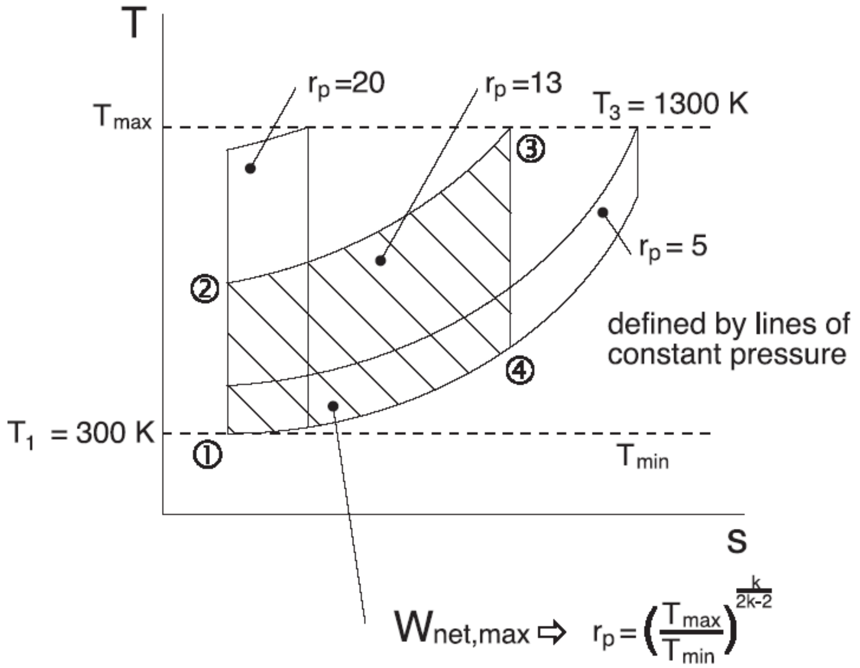
where r_P is called the pressure ration and $k = c_p / c_v$ is the specific heat ratio.

Maximum Pressure Ratio

Given that the maximum and minimum temperature can be prescribed for the

Brayton cycle, a change in the pressure ratio can result in a change in the work output from the cycle.

The maximum temperature in the cycle T_3 is limited by metallurgical conditions because the turbine blades cannot sustain temperatures above 1300 K. Higher temperatures (up to 1600 K can be obtained with ceramic turbine blades). The minimum temperature is set by the air temperature at the inlet



Actual Brayton Cycle

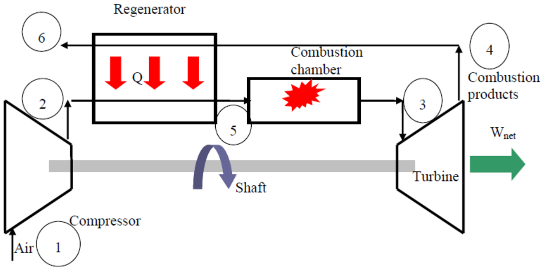
Irreversibilities exist in actual cycle. Most important differences are deviations of actual compressor and turbine from idealized isentropic compression/expansion, and pressure drop in combustion chamber.

2a

The Brayton Cycle with Regeneration

The high pressure air leaving the compressor can be heated by transferring heat from exhaust gases in a counter-flow heat exchanger which is called a egenerator.

Fig. 5: Schematic for a Brayton c



The Brayton Cycle with Intercooling, Reheating, and Regeneration

The net work output of the cycle can be increased by reducing the work input to the compressor and/or by increasing the work output from turbine (or both).

Using multi-stage compression with intercooling reduces the work input the compressor. As the number of stages is increased, the compression process becomes nearly isothermal at the compressor inlet temperature, and the compression work decreases.

Likewise utilizing multistage expansion with reheat (in a multi-turbine arrangement) will increase the work produced by turbines.

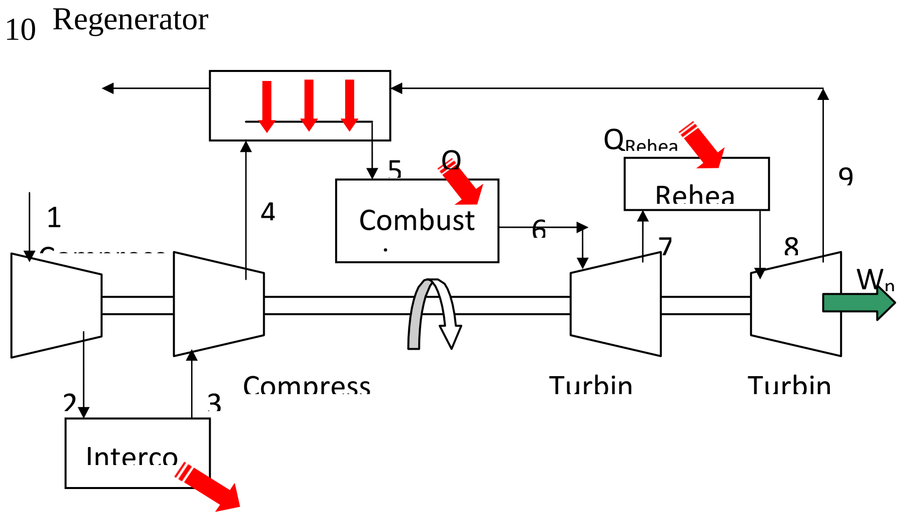


Fig. 7: A gas-turbine engine with two-stage compression with intercooling, two-stage expansion with reheating, and regeneration.

When intercooling and reheating are used, regeneration becomes more attractive since a greater potential for regeneration exists.

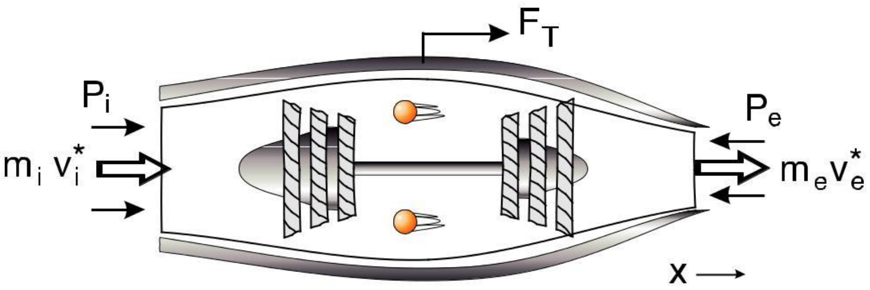
The back work ratio of a gas-turbine improves as a result of intercooling and reheating. However; intercooling and reheating *decreases thermal efficiency* unless they are accompanied with regeneration.

UNIT -V
JET PROPULSION AND ROCKET

Gas Turbines for Aircraft Propulsion

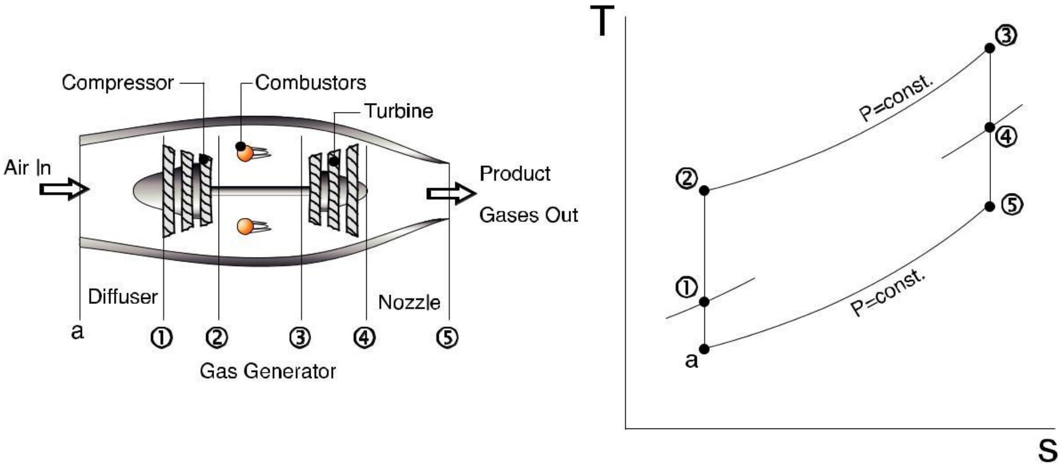
Gas turbines are well suited to aircraft propulsion because of their favorable power-to-weight ratiogases are expanded in the turbine to a pressure where the turbine work is just equal to the compressor work plus some auxiliary power for pumps and generators i.e. the network output is zerotypically operate at higher pressure ratios, often in the range of 10 to 25

Conservation of Momentum



where v_i is the velocity of the aircraft

Turbojet Engine



Sections

a-1: diffuser

– decelerates the incoming flow relative to the engine

1-4: gas generator

– compressor, combustor and turbine

– turbine power just enough to drive the compressor

– $P_T >> P_{atm}$

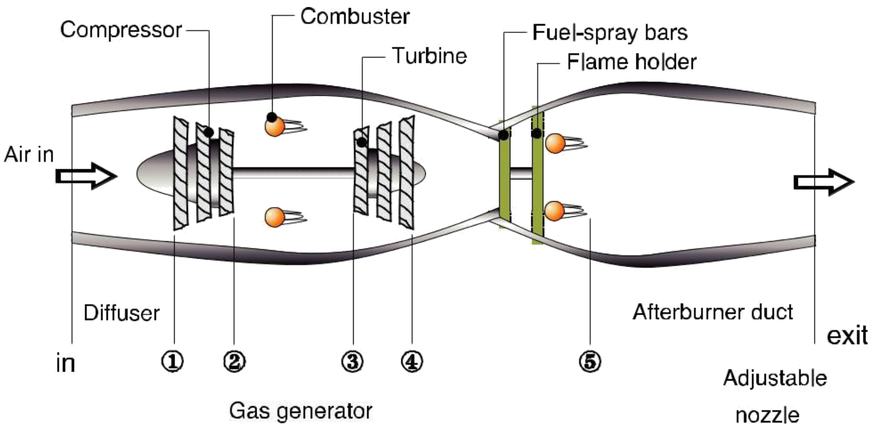
4-5: nozzle

– gases are expanded to produce a high velocity, $v_e >> v_i$ results in a thrust

– $v_1 << v_a$ v_1 is negligible

– $v_4 << v_5$ v_4 is negligible

Afterburner



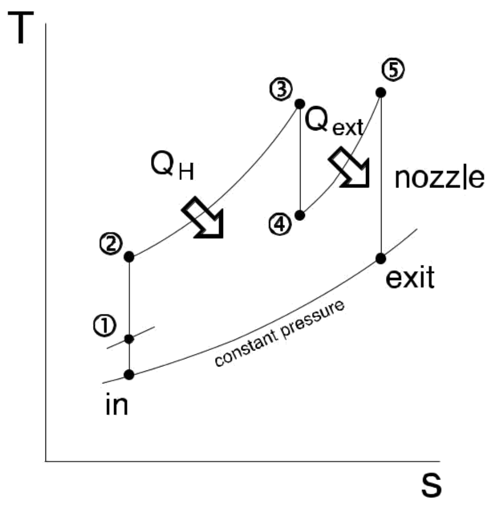
similar to a reheat deviceproduces a higher temperature at the nozzle inlet, $T_5 > T_4$

exit velocity proportional to v_e / $\sqrt{2c_p(T_4 \quad T_e)}$

afterburner is used to increase T_4

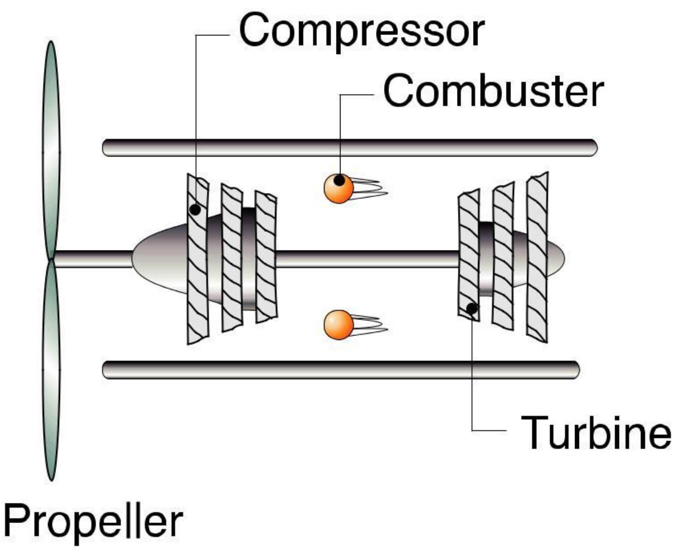
to T_5 similar to a reheat device

produces a higher temperature at the nozzle inlet



Other Types of Engines

Turbo-Prop Engine

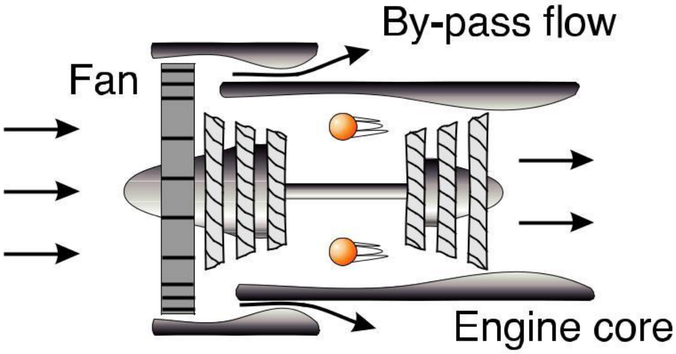


gas turbine drives the compressor and the propeller

- works by accelerating large volumes of air to moderate velocities
- propellers are best suited for low speed (< 300 mph) flight
- by-pass ratio of 100:1 or more
- by-pass ratio defined as:

$$\text{bypass ratio} = \frac{\text{mass flow bypassing the combustion chamber}}{\text{mass flow through the combustion chamber}}$$

Turbo-Fan Engine (Ducted Turbo-Prop Engine)

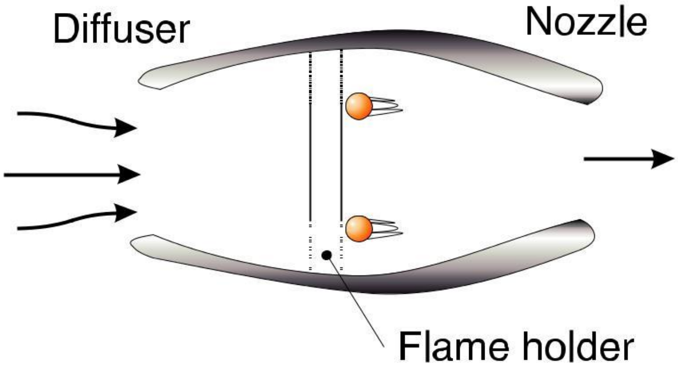


high speed exhaust gases are mixed with the lower speed air in the by-pass resulting in a considerable noise reduction

typically used for speeds up to 600

mph typical by-pass ratios are 5-6

Ramjet



compression is achieved by decelerating the high-speed incoming air in

the diffuser aircraft must already be in flight at a high speed

Pulse Jet Engine

similar to a ram jet but lets in a slug of air at a time and then closes a damper during the combustion stage

used in German V1 missile

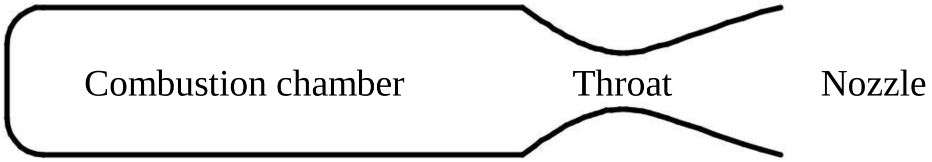
the combustion firing rate was approximately 40 cycles/sec with a maximum flight velocity of 600 mph

Rocket Propulsion

In the section about the rocket equation we explored some of the issues surrounding the performance of a whole rocket. What we didn’t explore was the heart of the rocket, the motor. In this section we’ll look at the design of motors, the factors which affect the performance of motors, and some of the practical limitations of motor design. The first part of this section is necessarily descriptive as the chemistry, thermodynamics and maths associated with motor design are beyond the target audience of this website.

General Principles of a Rocket Motor

In a rocket motor a chemical reaction is used to generate hot gas in a confined space called the combustion chamber. The chamber has a single exit through a constriction called the throat. The pressure of the hot gas is higher than the surrounding atmosphere, thus the gas flows out through the constriction and is accelerated.



It sounds simple, so why is rocket science so complex? Well, firstly there’s chemistry and the selection of the right reagents from many thousands of possibilities. Then there’s the design of the motor to make it capable of withstanding the temperatures and pressures of the reaction while still being as light as possible. There’s also the design of the throat and nozzle to ensure that the exhaust velocity is as fast as possible. Putting all these bits together, the average rocket scientist needs (as a minimum) to understand chemistry, mechanical engineering, thermodynamics, materials science and aerodynamics.

Propellants

The chemical reaction in model rocket motors is referred to as an “exothermal redox” reaction. The term “exothermal” means that the reaction gives off heat, and in the case of rocket motors this heat is mainly absorbed by the propellants raising their temperature. The term “redox” means that it is an oxidation/reduction reaction, in other words one of the chemicals transfers oxygen atoms to another during the reaction (OK chemists, I know that this is not a comprehensive definition but it will suffice!). The two chemicals are called the oxidising agent and the reducing agent.

The most popular rocket motors are black powder motors, where the oxidising agent is saltpetre and the reducing agents are sulphur and carbon. Other motors include Potassium or ammonium perchlorate as the oxidising agent and mixtures of hydrocarbons and fine powdered metals as the reducing agents. Other chemicals are often added such as retardants to slow down the rate of burn, binding agents to hold the fuel together (often these are the hydrocarbons used in the reaction), or chemicals to colour the flame or smoke for effects. In hybrid motors a gaseous oxidiser, nitrous oxide, reacts with a hydrocarbon, such as a plastic, to produce the hot gas.

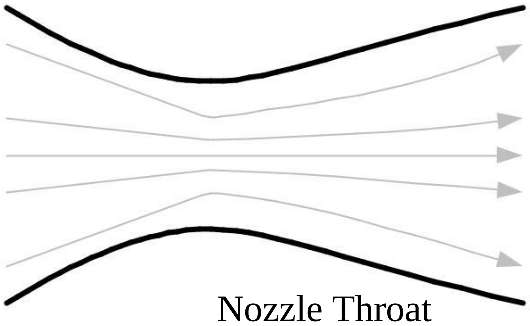
Energy Conversion

This reaction releases energy in the form of heat, and by confining the gas within the combustion chamber we give it energy due to its pressure. We refer to the energy of this hot pressurised gas as its “enthalpy”. By releasing the gas through the throat the rocket motor turns the enthalpy of the gas into a flow of the gas with kinetic energy. It is this release of energy which powers the rocket. So the energy undergoes two conversions:

(4) Chemical energy to enthalpy
(5) Enthalpy to kinetic energy

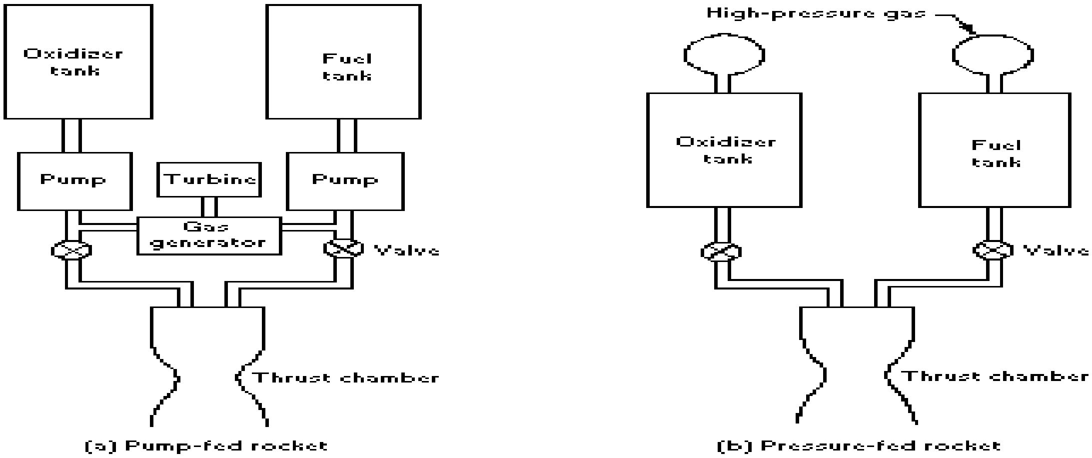
The conversion from chemical energy to enthalpy takes place in the combustion chamber. To obtain the maximum enthalpy it is clearly important to have a reaction which releases lots of heat and generates lots of high energy molecules of gas to maximise pressure. There is clearly a limit to the temperature & pressure, as the combustion chamber may melt or split if these are too high. The designer has a limitation placed on his choice of reagents in that the reaction must not heat the combustion chamber to a point where it is damaged, nor must the pressure exceed that which the chamber can survive.

Changing enthalpy to kinetic energy takes place in the throat and the nozzle. Our mass of hot gas flows into the throat, accelerating as the throat converges. If we reduce the diameter of the throat enough, the flow will accelerate to the speed of sound, at which pint something unexpected occurs. As the flow diverges into the nozzle it continues to accelerate beyond the speed of sound, the increase in velocity depending on the increase in area. This type of nozzle is called a De Laval nozzle.



Nozzle Throat

If we consider a small volume of gas, it will have a very low mass. As we accelerate this gas it gains kinetic energy proportional to the square of the velocity, so if we double the velocity we get four times the kinetic energy. The velocity of the supersonic flow increases proportional to the increase in area of the nozzle, thus the kinetic energy increases by the fourth power of the increase in nozzle diameter. Thus doubling the nozzle diameter increases the kinetic energy by 16 times! The De Laval nozzle make rocket motors possible, as only such high velocity flows can generate the energy required to accelerate a rocket.



(a) Pump-fed rocket

(b) Pressure-fed rocket

In model rockets the reaction is chemical generally short lived, a few seconds at most, so the amount of heat transferred to the structural parts of the motor is limited. Also, the liner of the motor casing acts to insulate the casing from the rapid rise in temperature which would result from a reaction in direct contact with the metal casing. Model rocket motors also run at quite low pressure, well below the limits if the motor casing, further protecting the casing. It can be seen that the enthalpy of a model rocket motor is thus quite low. In large launch vehicles such as Ariane, the pressure and temperature are high, the burn may last several minutes, and the mass budget for the designer is very tight. Designing motors for these purposes is highly complex.

LIQUID BIPROPELLANT CHEMICAL ROCKETS

The common liquid rocket is bipropellant; it uses two separate propellants, a liquid fuel and liquid oxidizer. These are contained in separate tanks and are mixed only upon injection into the combustion chamber. They may be fed to the combustion chamber by pumps or by pressure in the tanks (fig 2).

Fig. 2-Schematic of liquid-propellant rocket

Propellant flow rates must be extremely large for high-thrust engines, often hundreds of gallons per second. Pump-fed systems may require engines delivering several thousand horsepower to drive the pumps.[4] This power is usually developed by a hot gas turbine, supplied from a gas generator which is actually a small combustion chamber. The main rocket propellants can be used for the gas generator

The pressure-feed system eliminates the need for pumps and turbines; however the high pressure, perhaps 500 pounds per square inch, required in the tanks leads to the necessity for heavier structures, thus adding dead weight to the vehicle that may more than offset the weight saved by removing the pumping system.[6] On the other hand, removal of pumping equipment may raise overall reliability,

The walls of the combustion chamber and nozzle must be protected from the extremely high gas temperature. The method most commonly used is to provide passage in the nozzle wall through which one of the propellants can be circulated. In this way the walls are cooled by the propellant, which is later burned. This technique is referred to as regenerative cooling.[7]

Thrust termination is easily accomplished with the liquid rocket by simply shutting the propellant valves; however, this operation must be precisely timed and controlled. The amount of thrust delivered can be controlled by controlling the rate of propellant flow.

LIQUID MONOPROPELLANT ROCKET

Certain liquid chemicals can be made to form hot gas for thrust production by *decomposition* in a rocket chamber. The most common such *monopropellant* is hydrogen peroxide. When this liquid is passed through a platinum *catalyst* mesh it decomposes into hot steam and oxygen. These gases can then be ejected to develop thrust.

Engines of this kind have comparatively low specific impulse, but have the advantage of simplicity, require only one tank in the vehicle and can be readily turned on and off. Since they are adaptable to repetitive operation they find application in various control systems where efficiency of propellant utilization is of minor importance

SOLID-PROPELLANT ROCKET

In the solid-chemical rocket, the fuel and oxidizer are intimately mixed together and cast into a solid mass, called a *grain*, in the combustion chamber. The propellant grain is firmly cemented to the inside of the metal or plastic case, and is usually cast with a hole down the center. This hole, called the *perforation*, may be shaped in various ways, as star, gear, or other more unusual outlines, The perforation shape and dimension affects the burning rate or number of pounds of gas generated per second and, thereby, the thrust of the engine.

After being ignited by a pyrotechnic device, which is usually triggered by an electrical impulse, the propellant grain burns on the entire inside surface of the perforation. The hot combustion gases pass down the grain and are ejected through the nozzle to produce thrust.

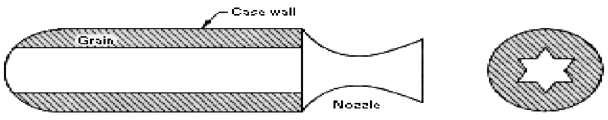


Fig.1-Schematic of solid-propellant rocket

The propellant grain usually consist of 1 of 2 types of chemical. One type is the *double-base*, which consists largely of *nitroglycerine* and *nitrocellulose*. It resembles smokeless gunpowder. The second type, which is now predominant, is the *composite* propellant, consisting of an oxidizing agent, such as *ammonium nitrate* or *ammonium perchlorate* intimately mixed with an organic or metallic fuel. Many of the fuels used are plastics, such as *polyurethane*.

A solid propellant must not only produce a desirable specific impulse, but it must also exhibit satisfactory mechanical properties to withstand ground handling and the flight environment. Should the propellant grain develop a crack, for example, ignition would cause combustion to take place in the crack, with explosion as a possible result.

It can be seen from figure 1 that the case walls are protected from the hot gas by the propellant itself. Therefore, it is possible to use heat-treated alloys or plastics for case construction. The production of light-weight, high-strength cases is a major development problem in the solid-rocket field.

Since nozzles of solid rockets are exposed to the hot gas flowing through them, they must be of heavy construction to retain adequate strength at high temperature. Special inserts are often used in the region of the nozzle throat to protect the metal from the erosive effects of the flowing gas.

For vehicle guidance it is necessary to terminate thrust sharply upon command. This may be accomplished with solid rockets by blowing off the nozzle or opening vents in the chamber walls. Either of these techniques causes the pressure in the chamber to drop and, if properly done, will extinguish the flame.

The specific impulse of various solid-propellant rockets now falls in the range 175 to 250 seconds. The higher figure of 250 applies to ammonium perchlorate-biased propellants