

## JET PROPULSION

The Principle of jet Propulsion involves imparting Momentum to a Mass of fluid in Such a Manner the reaction of imparted momentum Provides a propulsive force. it may be achieved by expanding the gas, which is at high temperature and pressure, through a nozzle due to which a high velocity jet of hot gases is produced that gives a propulsive force. for jet Propulsion the open cycle gas turbine is most suitable.

The Propulsion System may be classified:-

- ① Air stream jet Engines (Air-breathing Engines)
  - (a) Steady Combustion System; Continuous air flow
    - (i) Turbo-jet
    - (ii) Turbo-prop.
    - (iii) Ram jet
  - (b) Internal (or) Intermittent Combustion system  
Intermittent flow:
    - (i) Pulse jet or flying bomb.

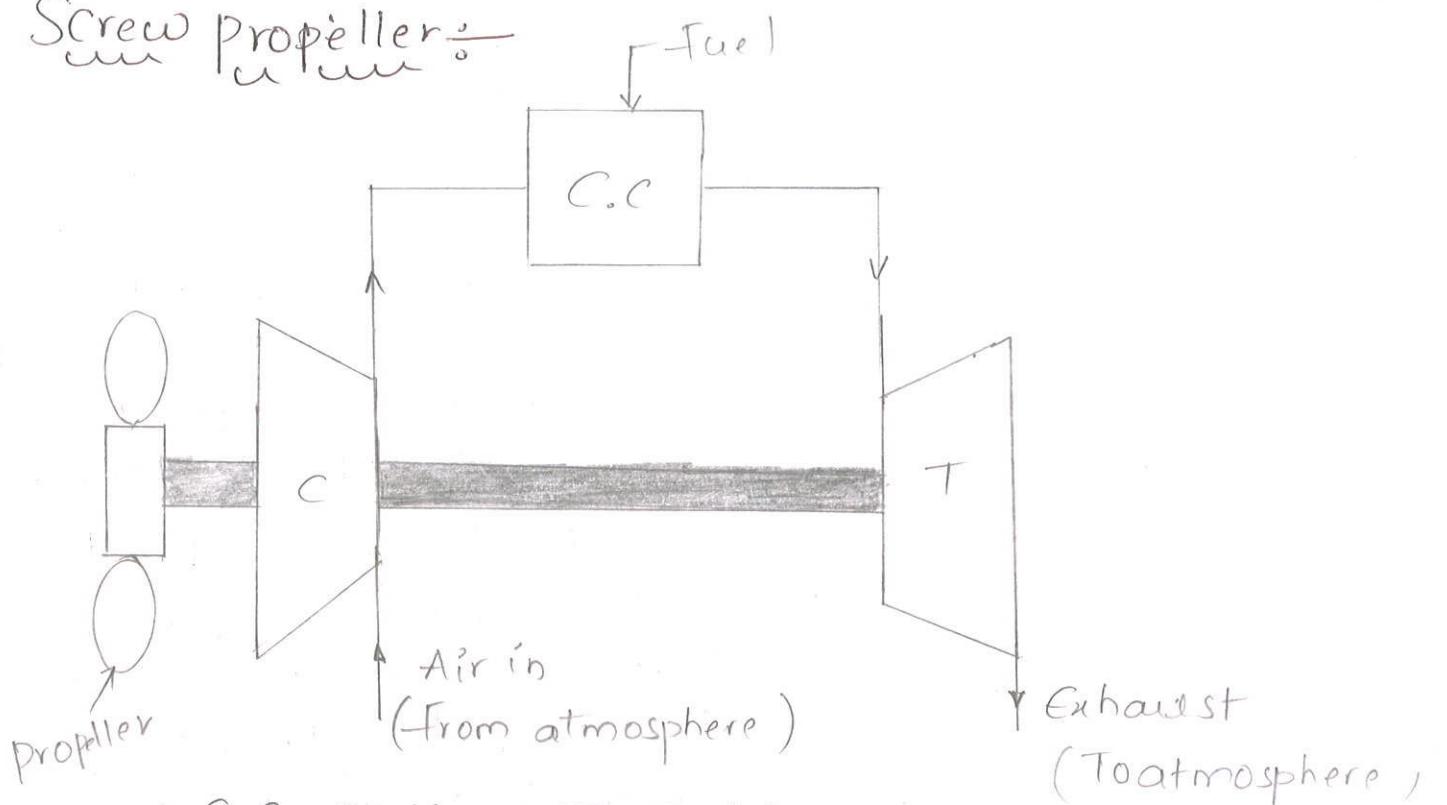
- ② Self Contained Rocket Engines (Non-air breathing)

- (i) liquid propellant
  - (ii) Solid propellant.

Air stream jet engine:- In air Stream jet Engine the oxygen necessary for the combustion is taken from the surrounding atmosphere.

Rocket Engine:- The fuel and the oxidiser are contained in the body of the unit which is to be propelled.

## Screw Propeller:



C=Compressor ; T=Turbine C.C.= Combustion chamber

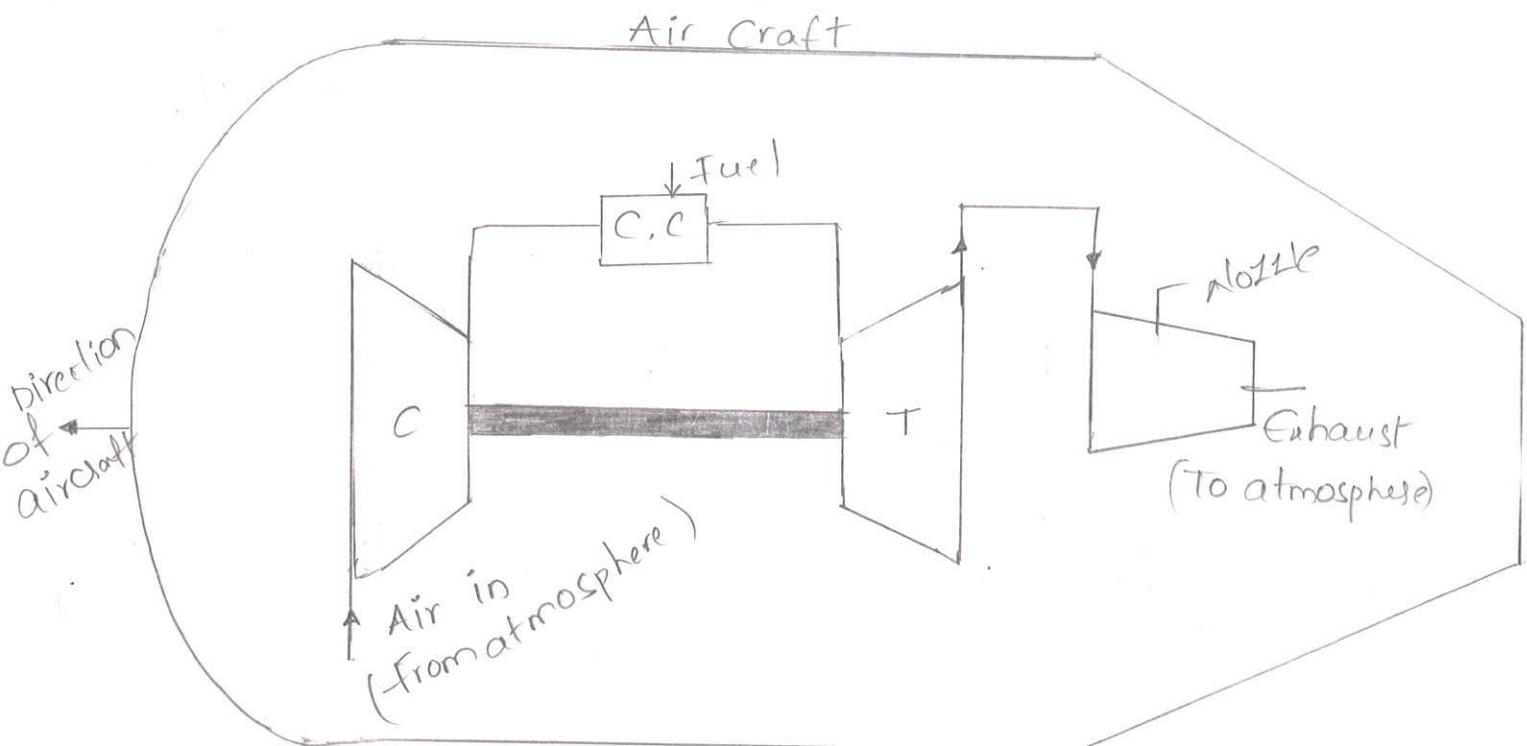
In the Past air propulsion was achieved by a Screw propeller. in this System the total power developed by the turbine is used to drive the Compressor and Propeller. Power plant for Screw propeller. By controlling the supply of fuel in the Combustion chamber the power supplied to the propeller can be controlled. The rate of increase of efficiency of screw propeller is higher at lower speeds but its efficiency falls rapidly at higher speeds above the sonic velocity.

## Turbo-jet:

### Description:-

\* it consists of diffuser at entrance which slows the down and part of the kinetic energy of the air stream is converted into pressure this type of compression is called as ram Compressor.

- \* The air is further compressed to a pressure of 3 to 4 bar in a rotary Compressor.
- \* The Compressed air then enters the Combustion chamber (C.c) where fuel is added the Combustion of fuel takes place at sensibly constant Pressure and subsequently temperature rises supply.
- \* The hot gases then enter the gas turbines where Partial Expansion takes place. The power produced is jet sufficient to drive the Compressor, fuel Pump and other auxiliaries.



## Advantages of Turbojet:

1. Construction much simpler
  2. Engine vibrations absent
  3. Much higher speeds possible
  4. Power Supply is uninterrupted and smooth
  5. Weight to Power ratios superior
  6. Rate of climb higher
  7. Requirement of Major overheads less frequent.
- unit - 5, pg - 3/20*

8. Radio interference much less
9. Maximum altitude ceiling as compared to turbo-prop and conventional piston type engines
10. frontal area smaller
11. fuel can be burnt over a large range of mixture strength.

disadvantages :-

1. Less efficient
2. Life of the unit comparatively shorter.
3. The turbo-jet becomes rapidly inefficient below 550 km/h.
4. More noisy.
5. Materials required are quite expensive
6. Require longer strip since length of take-off is too much.
7. At take-off the thrust is low, this effect is overcome by boosting.

Basic cycle for Turbo-jet Engine.

The basic cycle for turbo-jet engine is the Joule or Brayton cycle. The various process

Process 1-2

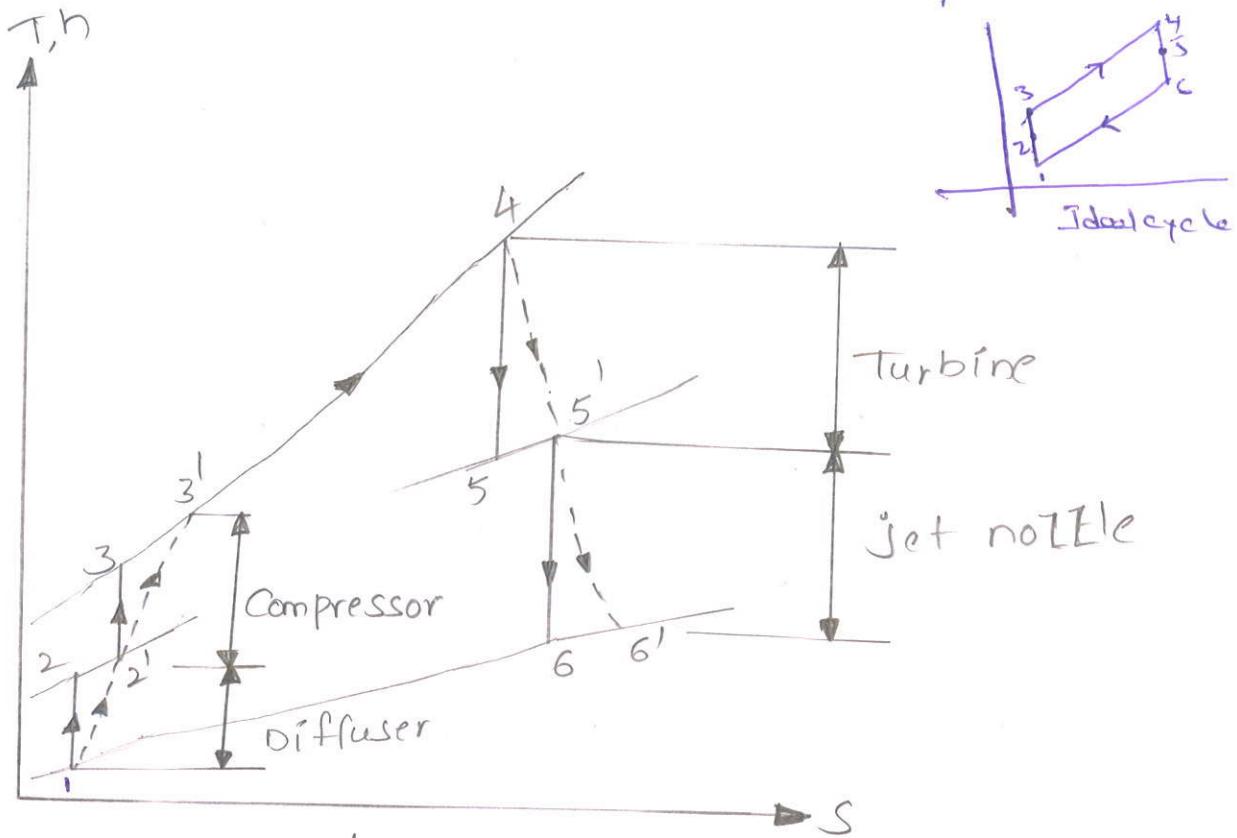
The air entering from atmosphere is diffused isentropically from velocity  $c_1$  down to zero ( $c_2=0$ ) This indicates the diffuser has an efficiency of 100%. This is termed as ram pressure.

Process 1-2' is the actual process

Process 2-3

Isentropic compression of air.

Process '2-3' shows actual compression of air.



T-s diagram of turbo-jet

Process 3-4 (Actual cycle)

Ideal addition of heat at constant pressure  $P_3 = P_4$  process 3'-4 shows the Actual addition of heat at constant pressure  $P_3 = P_4$ .

Process 4-5

Isentropic expansion of gas in the turbine Process 4-5' shows the actual expansion in the turbine.

Process 5-6

Isentropic expansion of gas in the nozzle Process 5'-6' shows the actual expansion of gas in the nozzle.

Consider 1kg of working fluid flowing through the system.

## Diffuser:-

Between the states 1 and 2, the energy equation is given by.

$$\frac{C_a^2}{2} + h_1 + Q_{1-2} = \frac{C_2^2}{2} + h_2 + w_{1-2}$$

where  $C_a (= c_1)$  = velocity of entering air from atmosphere

In an ideal diffuser  $C_2 = 0$ ;  $Q_{1-2} = 0$  and  $w_{1-2} = 0$

$\therefore$  Enthalpy at state 2 is  $h_2 = h_1 + \frac{C_a^2}{2}$  kJ/kg

$$T_2 = T_1 + \frac{\frac{C_a^2}{2}}{c_p}$$

(Or)

Process 1-2' shows actual process in diffuser

$$\text{Diffuser Efficiency } \eta_d = \frac{h_2 - h_1}{h_{2'} - h_1} = \frac{T_2 - T_1}{T_{2'} - T_1}$$

$$h_{2'} = h_1 + \frac{C_a^2}{2\eta_d}$$

$$T_{2'} = T_1 + \frac{C_a^2}{2 \cdot c_p \eta_d}$$

## Compressor:-

Energy equation between state 2 and 3

$$h_2 + \frac{C_g^2}{2} + Q_{2-3} + w_c = h_3 + \frac{C_3^2}{2}$$

$$w_c = h_3 - h_2 = c_p (T_3 - T_2)$$

The actual Compressor Work

$$h_{3'} - h_2 = \frac{h_3 - h_2}{\eta_c} = \frac{c_p (T_3 - T_2)}{\eta_c}$$

Where

$\eta_c$  = Isentropic Efficiency of Compressor.

Combustion chamber :-

Ideal heat Supplied per kg  $Q = h_4 - h_3 = Cp(T_4 - T_3)$

Actual heat Supplied =  $\left[1 + \frac{mf}{ma}\right] h_4 - h_3'$

$$Q_a = Cp_g \left[1 + \frac{mf}{ma}\right] T_4 - Cp_a \cdot T_3'$$

Where

$Cp_g$  and  $Cp_a$  are specific heats and air at constant pressure, respectively.

Turbine :-

Between States 4 and 5, the Energy Equations

$$h_4 + \frac{C_4^2}{2} + Q_{4-5} = h_5 + \frac{C_5^2}{2} + w_t$$

if  $Q_{4-5} = 0$  then turbine work.

$$w_t = (h_4 - h_5) + \frac{(C_4^2 - C_5^2)}{2}$$

If the change in k.e is neglected

$$w_t = (h_4 - h_5) = Cp(T_4 - T_5)$$

$$= h_4 - h_5' = Cp(T_4 - T_5') = Cp(T_4 - T_5) \times \eta_t$$

$$Cp(T_4 - T_5') = Cp(T_4 - T_5) \eta_t = \frac{Cp(T_3 - T_2)}{\eta_c}$$

$$T_5' = T_4 - (T_4 - T_5) \eta_t = T_4 - \frac{Cp(T_3 - T_2)}{\eta_c}$$

Jet nozzle :-

Energy Equation. 5 and 6

$$h_5 + \frac{C_5^2}{2} = h_6 + \frac{C_6^2}{2}$$

$$h_5 + \frac{c_5'^2}{2} = h_6' + \frac{c_6'^2}{2}$$

$$h_5' = h_6' + \frac{c_6'^2}{2}$$

$$c_6' = \sqrt{2(h_5' - h_6')} = \sqrt{2\eta_n(h_5' - h_6)}$$

$$c_6' = \sqrt{2\eta_n c_p (T_5' - T_6)}$$

$\eta_n$  = Nozzle Efficiency.

$$\begin{aligned}\eta_{th} &= \frac{(h_4 - h_6') - (h_3' - h_1)}{(h_4 - h_3')} \\ &= \frac{(T_4 - T_6') - (T_3' - T_1)}{(T_4 - T_3')} \quad (\text{Jet propulsion})\end{aligned}$$

Thrust, Thrust Power, Propulsive Efficiency and Thermal Efficiency.

Thrust ( $T$ ) :-

Let  $C_a$  = forward Velocity of aircraft through air, m/s Assuming the atmospheric air to be still the Velocity of air, relative to the aircraft, at entry to the aircraft be  $C_a$ . It is called Velocity of approach of a

$C_j$  = Velocity of jet relative to the exit nozzle / aircraft; m/s

$\left[ 1 + \frac{\text{fuel}}{\text{air}} \frac{(m_f)}{(m_a)} \right]$  = Mass of products leaving the nozzle for 1 kg of air

Thrust is the force produced due to change of Momentum.

Now, absolute Velocity of gas leaving aircraft =  $(C_j - C_a)$

Absolute Velocity of air entering the aircraft = 0

$$\therefore \text{change of momentum} = \left[ 1 + \frac{m_f}{m_a} \right] (C_j - C_a)$$

$$\text{thrust } T = \left[ 1 + \frac{m_f}{m_a} \right] (C_j - C_a) \text{ N/kg of air/s}$$

$$T = (C_j - C_a) \text{ N/kg of air/s}$$

Thrust Power:

it is defined as the rate at which work must be developed by the engine if the aircraft is to be kept moving at a constant velocity  $C_a$  against friction force or drag.

$$T.P = \left[ \left( 1 + \frac{m_f}{m_a} \right) (C_j - C_a) \right] C_a \text{ W/kg of air}$$

$$= (C_j - C_a) C_a \text{ W/kg of air if mass of fuel neglected}$$

$$= \frac{(C_j - C_a) C_a}{1000} \text{ kW/kg of air}$$

Propulsive Power (P.P.):

The energy required to change the momentum of the mass flow of gas represents the propulsive power. It is expressed as the difference between the rate of kinetic energy of the entering air and exit gases.

$$\text{Mathematically, } P.P. = \Delta K.E. = \left[ 1 + \frac{m_f}{m_a} \right] C_j^2 - \frac{C_a^2}{2} \text{ kW/kg}$$

neglecting mass of unit  $\rightarrow 5, pg-a/20$  fuel

$$= \frac{C_j^2 - C_a^2}{2} \text{ m/kg, neglecting mass of fuel}$$

$$= \frac{C_j^2 - C_a^2}{2 \times 1000} \text{ kw/kg of air.}$$

### Propulsive Efficiency.

The ratio of thrust power to propulsive power is called the propulsive efficiency of the propulsive unit.

$$\eta_{\text{Prop}} = \frac{\text{Thrust Power}}{\text{Propulsive Power}} = \frac{\left[ \left[ 1 + \frac{m_f}{m_a} \right] (C_j - C_a) \right] C_a}{\left[ \frac{\left[ 1 + \frac{m_f}{m_a} \right] C_j^2}{2} - \frac{C_a^2}{2} \right]}$$

$$= 2 \left[ \frac{\left[ \left[ 1 + \frac{m_f}{m_a} \right] (C_j - C_a) \right] C_a}{\left[ \left[ 1 + \frac{m_f}{m_a} \right] C_j^2 - C_a^2 \right]} \right].$$

Neglecting the mass of fuel.

$$\eta_{\text{Prop}} = \frac{2(C_j - C_a)}{C_j^2 - C_a^2} = \frac{2(C_j - C_a) C_a}{(C_j + C_a)(C_j - C_a)}$$

$$\eta_{\text{Prop}} = \frac{2 C_a}{C_j + C_a} \quad \text{or} \quad \frac{2}{\left[ \frac{C_j}{C_a} + 1 \right]}$$

From eqn is evident that the propulsive efficiency increases with an increase in aircraft velocity  $C_a$ .  $\eta_{\text{Prop}}$  becomes 100%.

When  $C_a$  approaches  $C_j$ ; thrust reduces to zero.

Thermal Efficiency  $\equiv (\eta_{th})$

It is defined as the ratio of propulsive work and the energy released by the combustion of fuel.

$$\eta_{th} = \frac{\text{Propulsive work}}{\text{Heat released by the combustion of fuel}}$$

$$= \frac{\text{Increases in kinetic energy of the gases}}{\text{Heat released by the combustion of fuel}}$$

$$\eta_{th} = \frac{\left[1 + \frac{mf}{ma}\right] c_j^2 - c_a^2}{2 \left[\frac{mf}{ma}\right] \times \text{calorific value.}}$$

Overall Efficiency ( $\eta_o$ )

$$\eta_o = \eta_{th} \times \eta_{prop.} = \frac{(c_j^2 - c_a^2)}{2 \times \left[\frac{mf}{ma}\right] \times \text{calorific value}} \times \frac{2 c_a}{c_j + c_a}$$

$$= (c_j - c_a) c_a$$

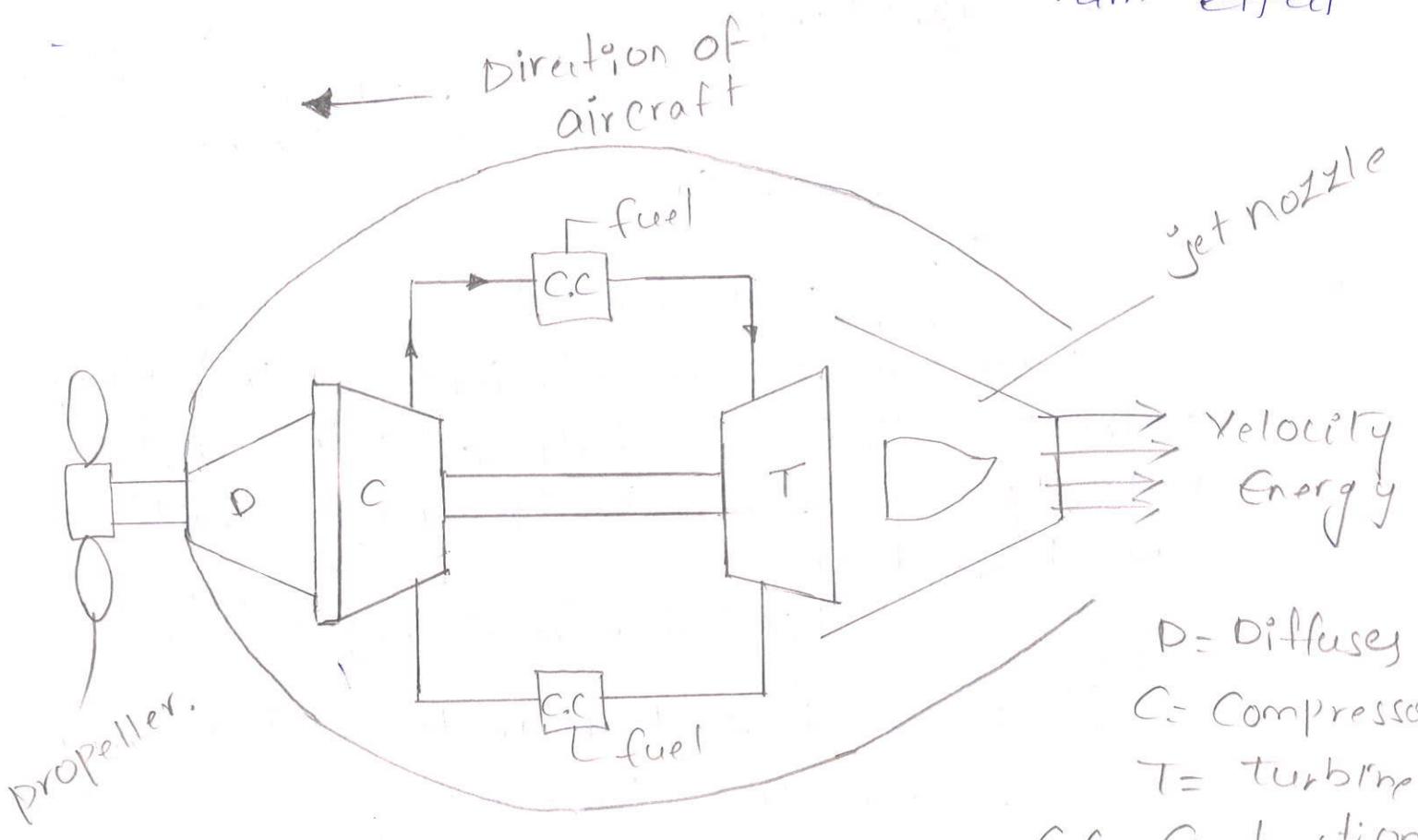
$$\left[\frac{mf}{ma}\right] \times \text{calorific value}$$

For Maximum Overall Efficiency the aircraft Velocity  $c_a$  is one half of the jet Velocity  $c_j$  the jet efficiency ( $\eta_{jet}$ ) is defined as

$$\eta_{jet} = \frac{\text{Final kinetic energy in the jet}}{\text{Isentropic heat drop in the jet + carry over from the turbine}}$$

## Turbo-Prop

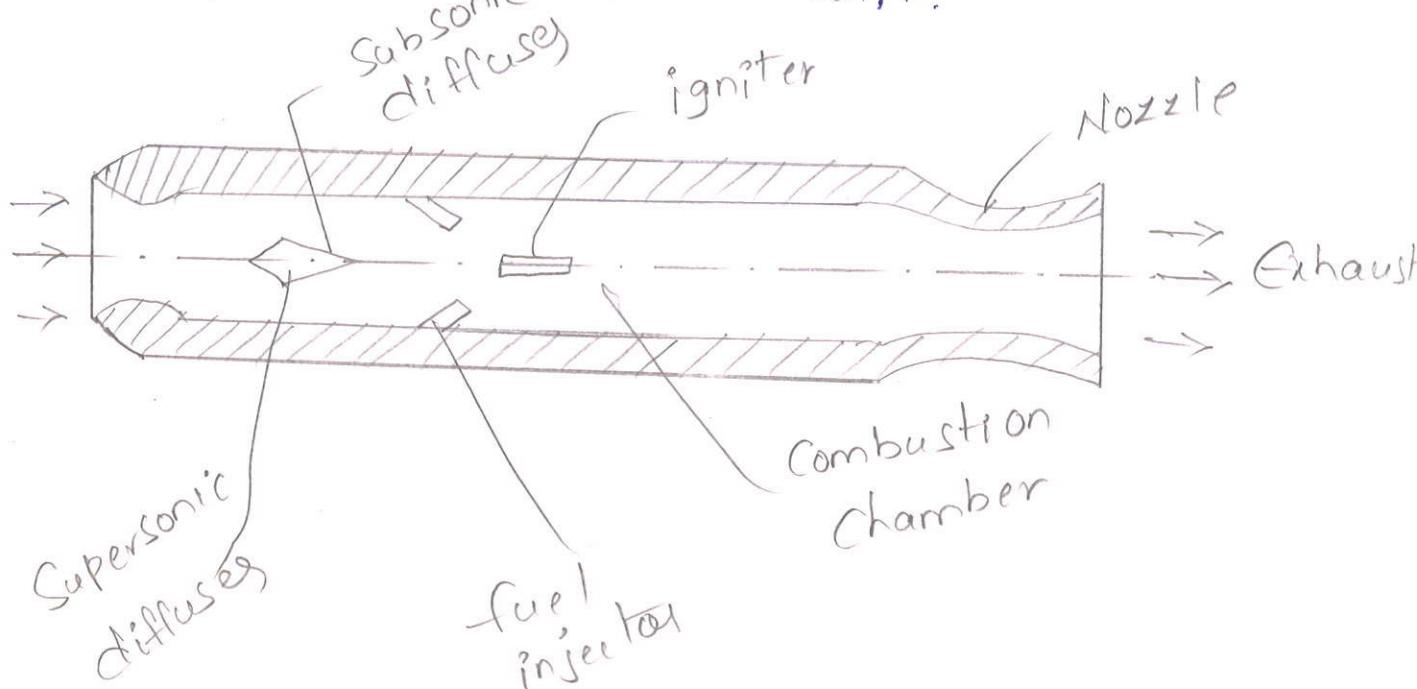
a turbo-prop system employed in aircrafts. Here the expansion of gases takes place partly in turbine (80%) and partly (20%) in the nozzle. The power developed by the turbine is consumed in running the compressor and the propeller. The propeller and jet produced by the nozzle give forward motion to the aircraft. The turbo-prop entails the advantages of turbo-off and propeller. The overall efficiency of the turbo-prop is improved by providing the diffuser before the compressor as shown. The pressure rise takes place in the diffuser. This pressure rise takes place due to conversion of kinetic energy of the incoming air into pressure energy by the diffuser. This type of compression is known as "ram effect".



## Ram jet

Ram jet is also called athodyd, Lorin tube or flying stovepipe. Ram jet engines have the capability to fly at supersonic speeds.

- The ram-jet engine consist of diffuser, Combustion chamber and nozzle.
- The air enters the ram-jet plant with supersonic speed and slowed down to sonic velocity in the supersonic diffuser; consequently the pressure suddenly increases in the supersonic diffuser to the formation of shock wave.
- In the Combustion chamber, the fuel is injected through injection nozzles. The fuel air mixture is then ignited by means of a spark plug and combustion temperatures of the order of 2000K. are attained.
- Energy is converted into kinetic energy. The high velocity gases leaving the nozzles provide forward thrust to the craft.



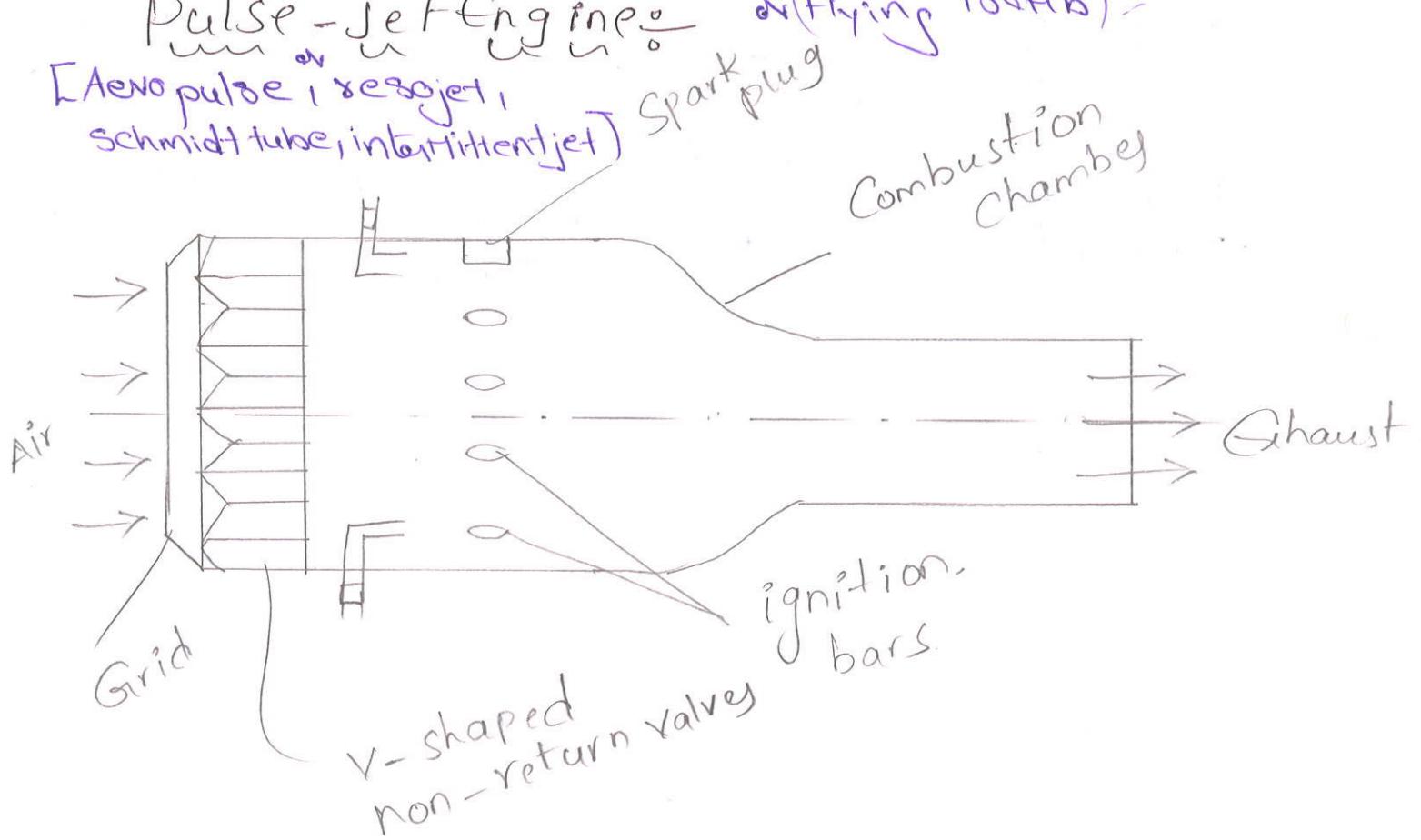
## Advantages of Ram-jet Engine :-

1. No Moving Parts
2. Light in weight
3. Wide variety of fuels may be used.

## Disadvantages:-

1. It cannot be started of its own. It has to be accelerated to a certain flight velocity by some launching device.
2. The fuel consumption is too large at low and moderate speeds.
3. To obtain the steady combustion, certain devices in form flame holders or pilot flame are required.

## Pulse-jet Engine or (Flying Bomb) :-



A Pulse Jet Engine is an intermittent Combustion Engine and it operates on a cycle similar to a reciprocating engine, whereas the turbo-jet and ram-jet engines are continuous in operation and are based on Brayton Cycle.

A Pulse-jet Engine like an athodyd, develops thrust by a high velocity of jet of exhaust gases without the aid of compressor or turbines.

- The incoming air completed by ram effect in the diffusey section and grid passage.
- Which are opened closed v-shaped Non-return Valves.
- The fuel is then injected into the Combustion chamber by fuel injectors.
- As a result of combustion the temperature of combustion products increase.

#### Advantages:

1. Simple in Construction and very inexpensive as compared to turbo-Jet Engine.
2. Capable of Producing static thrust and thrust in excess of drag at which the much low speed.

#### disadvantages:

1. High intensity of noise
2. Severe vibrations
3. High rate of fuel Consumption and Low thermodynamic efficiency
4. Intermittent Combustion as compared to continuous Combustion in turbo jet
5. The operating altitude is Limited
6. Serious limitation mechanical valve arrangement

(ii) Volume of air compressed/min.

$$\text{propulsive force} = \dot{m}_a(c_j - c_a)$$

$$6100 = \dot{m}_a(585.8 - 222.2)$$

$$\dot{m}_a = 16.77 \text{ kg/s}$$

$$\therefore \text{volume of air compressed/min} = \frac{16.77}{0.17} \times 60 = 5918.8 \text{ kg/min}$$

(iii) Diameter of the jet, d:-

$$\text{Now } \frac{\pi}{4} d^2 \times c_j = 5918.8$$

$$\frac{\pi}{4} d^2 \times 585.8 = (5918.8 / 60)$$

$$d = \left( \frac{5918.8 \times 4}{60 \times \pi \times 585.8} \right)^{1/2} = 0.463 \text{ m} = 463 \text{ mm}$$

(iv) Power output of the unit:-

Thrust power = propulsive power  $\times$  velocity of turbine jet

$$= 6100 \times 222.2 \text{ N-m/s}$$

$$= \frac{6100 \times 222.2}{1000} = 1355.4 \text{ kW}$$

$$\text{Turbine output} = \frac{\text{Thrust power}}{\text{propulsive efficiency}} = \frac{1355.4}{0.55} = 2464.4 \text{ kW}$$

(v) Overall efficiency  $\eta_o = \frac{\text{Heat equivalent of output}}{\dot{m}_f \times C.V}$

$$0.17 = \frac{2464.4}{\dot{m}_f \times 46000} = 0.315 \text{ kg/s} = \dot{m}_f$$

$$\therefore \text{Air-fuel ratio} = \frac{\text{Air used (in kg/s)}}{\text{Fuel used (in kg/s)}} = \frac{16.77}{0.315} = 53.24$$

$$\text{Air-fuel ratio} = 53.24 : 1$$

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## Rocket Engines

Similar to jet propulsion, the thrust required for required for Rocket propulsion is produced by the high velocity jet of gases passing through the nozzle. But the main difference is that in case of jet propulsion the oxygen required for combustion is taken from the atmospheric air and fuel is stored whereas for Rocket Engine.

Rockets may be classified as.

1. According to the type of Propellents

(i) Solid Propellant Rocket

(ii) Liquid Propellant Rocket.

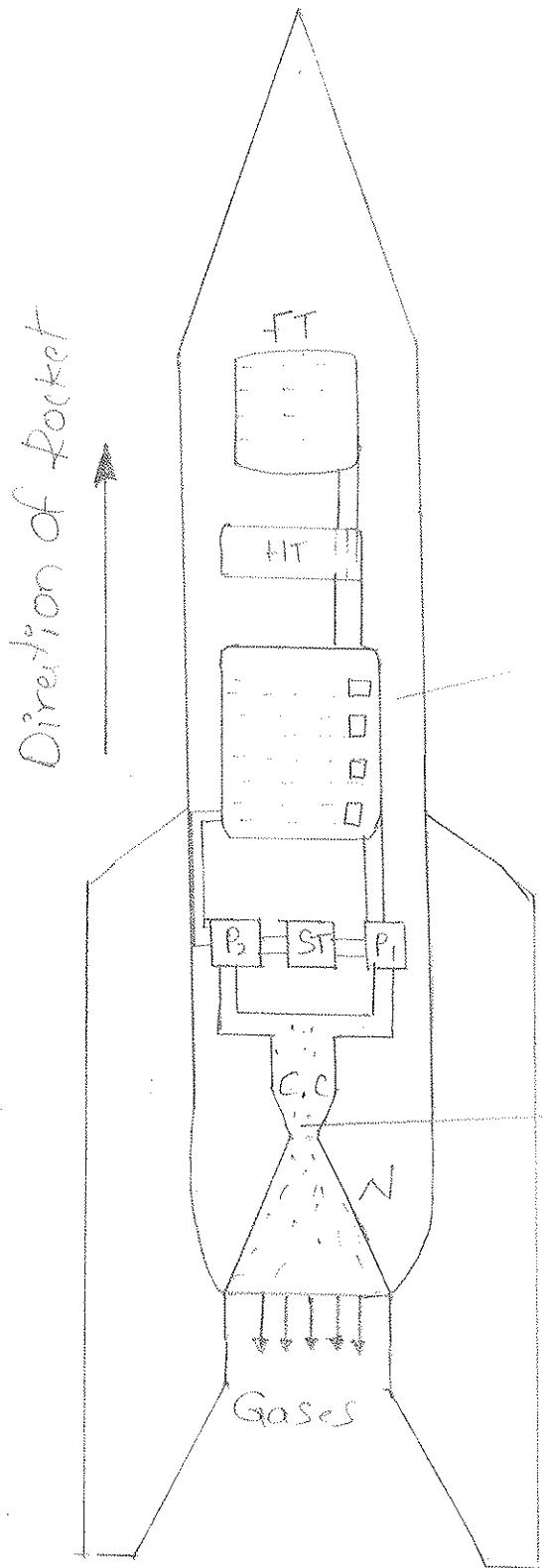
2. According to the number of Motors,

(i) Single-stage Rocket

(ii) Multi-stage Rocket.

A Simple Single Stage Compressor liquid Propellant Rocket. It consists of a fuel tank FT, oxidiser tank "O," two Pumps  $P_1, P_2$  a Steam turbine "ST" and a Combustion chamber "C.C." The fuel tank contains alcohol and Oxidiser tank contains Liquid Oxygen. The fuel and the Oxidiser are supplied by the Pumps to the Combustion chamber, where the fuel is ignited by electrical means.

The Pumps are driven with the help of a Steam turbine. Here the steam is produced by mixing a very concentrated hydrogen peroxide with Potassium Permanganate.



FT = Fuel tank

HT = Hydrogen Peroxide  
tank

O = Oxidiser tank

O ST = Steam turbine

P<sub>1</sub>, P<sub>2</sub> = Pumps

C.C = Combustion  
Chamber

HG<sub>1</sub> = Hot gas

HG<sub>1</sub> N = Nozzle

Rocket diagram.

Unit - 5, Pg - 17/20

## Requirements of an ideal-Rocket Propellant

1. High Heat Value
2. Reliable Smooth Ignition
3. Stability and ease of handling and storing
4. Low Toxicity and Corrosiveness
5. Highest Possible density so that it occupies less space.

## Applications of Rockets

1. Long range artillery
2. Lethal weapons
3. Signalling and fire work display
4. Jet assisted tank-off
5. For satellites
6. For Space Ships
7. Research. (Rocket)

Thrust work, Propulsive work and Propulsive  $\eta$ :

$$\text{Thrust work} = c_j c_a.$$

$$\text{Propulsive Work} = c_j c_a + \frac{(c_j - c_a)^2}{2} = \frac{c_j^2 + c_a^2}{2}$$

$$\text{Rocket propulsive Efficiency} = \frac{c_j c_a}{(c_j^2 + c_a^2)/2}$$

$$= \frac{2 c_j c_a}{c_j^2 + c_a^2}$$
$$= \frac{2 \left[ \frac{c_a}{c_j} \right]}{1 + \left[ \frac{c_a}{c_j} \right]^2}$$

The following data pertain to a turbo-jet flying at an altitude of 9500m:

Speed of the turbo-jet = 800 km/h

Propulsive efficiency = 55%.

Overall efficiency of the turbine plant = 17%.

Density of air at 9500m altitude = 0.17 kg/m³

Drag on the plane = 6100N

Assuming calorific value of the fuel used as 46000 kJ/kg  
calculate:

- (i) Absolute velocity of the jet (i.e. volume of air compressed per min.)
- (iii) Diameter of the jet      (iv) power output of the unit @ Air-fuel ratio.

Sol: Given Altitude = 9500m,  $c_a = \frac{800 \times 1000}{60 \times 60} = 222.2 \text{ m/s}$

Propulsive = 55%, Overall = 17%; density of air at 9500m altitude = 0.17 kg/m³

drag on the plane = 6100N

(i) Absolute velocity of the jet, ( $c_j - c_a$ ):

$$\eta_{\text{propulsive}} = 0.55 = \frac{2c_a}{c_j + c_a}$$

$\therefore c_j$  = velocity of gases at nozzle exit relative to the aircraft

$c_a$  = velocity of the turbo-jet / aircraft.

$$\therefore 0.55 = \frac{2 \times 222.2}{c_j + 222.2}$$

$$c_j = \frac{2 \times 222.2}{0.55} - 222.2 = 585.8 \text{ m/s}$$

$$\therefore \text{Absolute velocity of jet} = c_j - c_a = 585.8 - 222.2$$

$$= 363.6 \text{ m/s}}$$

(ii) Volume of air compressed/min.

$$\text{propulsive force} = \dot{m}_a(c_j - c_a)$$

$$6100 = \dot{m}_a(585.8 - 222.2)$$

$$\dot{m}_a = 16.77 \text{ kg/s}$$

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