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PROPULSION

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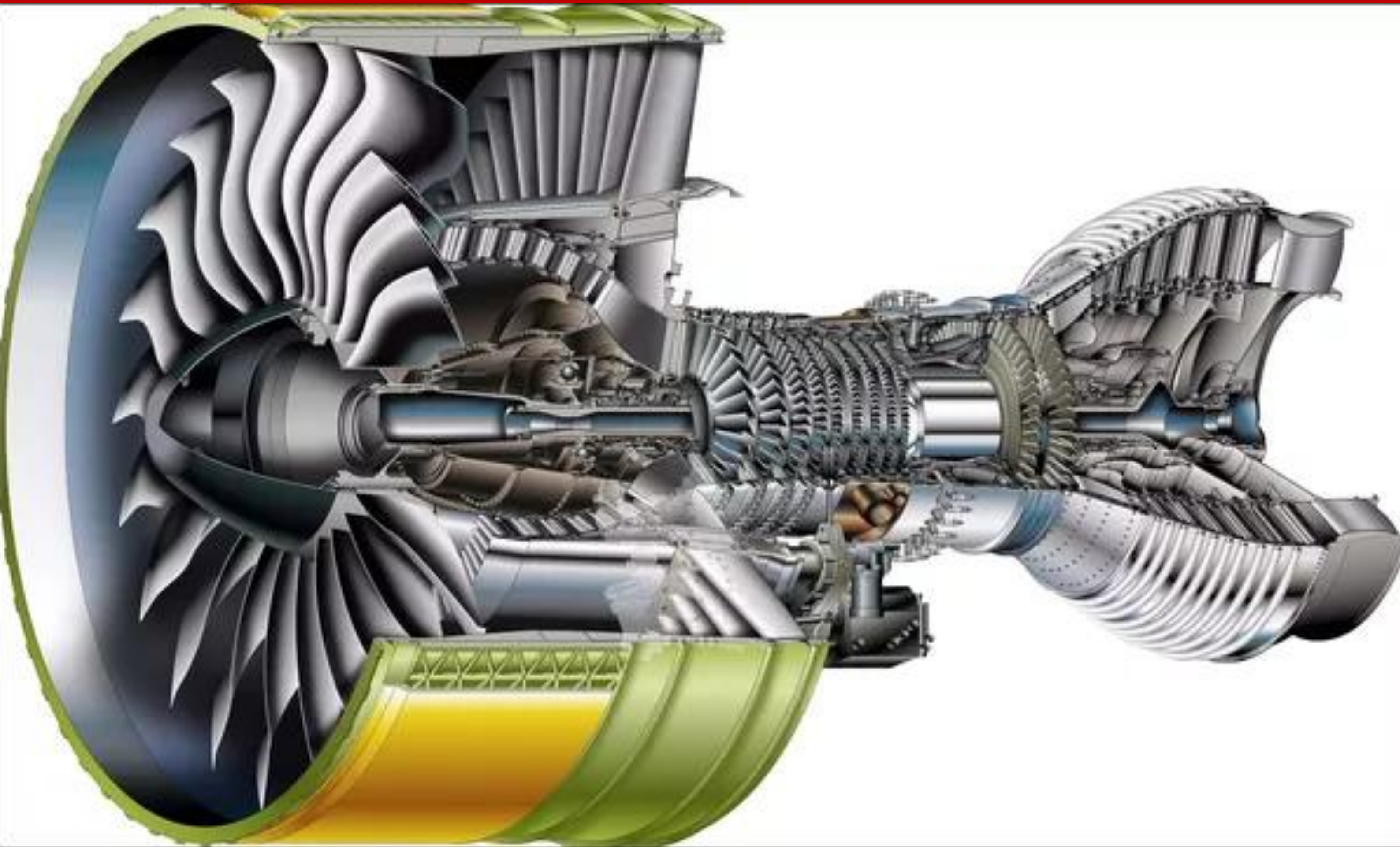

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Third Edition

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GATE 2020

ORGANIZING INSTITUTE :

IIT DELHI

AEROSPACE ENGINEERING

Propulsion Syllabus

Core Topics:

Basics: Thermodynamics, boundary layers and heat transfer and combustion thermochemistry.

Thermodynamics of aircraft engines: Thrust, efficiency and engine performance of turbojet, turboprop, turbo shaft, turbofan and ramjet engines, thrust augmentation of turbojets and turbofan engines. Aerothermodynamics of non-rotating propulsion components such as intakes, combustor and nozzle.

Axial compressors: Angular momentum, work and compression, characteristic performance of a single axial compressor stage, efficiency of the compressor and degree of reaction.

Axial turbines: Axial turbine stage efficiency

Centrifugal compressor: Centrifugal compressor stage dynamics, inducer, impeller and diffuser.

Rocket propulsion: Thrust equation and specific impulse, vehicle acceleration, drag,
gravity losses, multi-staging of rockets. Classification of chemical rockets, performance of solid and liquid propellant rockets.

No Special Topics

Propulsion Year Wise Analysis

Year	No of Questions	Topics (1 marks + 2 marks)	Total Marks
2019	1M : 5 2M : 5	• Jet Propulsion (2 + 1) • Combustion (1 + 0) • CFC (1 + 0) • Thermo Basics (1 + 0) • Rocket Propulsion (0 + 2) • AFT (0 + 1) • AFC (0 + 1)	15
2018	1M : 4 2M : 5	• Axial Flow Compressor (0 + 2) • Centrifugal Flow Compressor (0 + 1) • Jet Propulsion (4 + 1) • Rocket Propulsion (0 + 1)	14
2017	1M : 5 2M : 6	• Axial Flow Compressor (1 + 1) • Axial Flow Turbine (1 + 0) • Centrifugal Flow Compressor (1 + 1) • Jet Propulsion (1 + 3) • Rocket Propulsion (1 + 1)	17
2016	1M : 3 2M : 8	• Axial Flow Compressor (0 + 1) • Axial Flow Turbine (0 + 1) • Jet Propulsion (2 + 3) • Rocket Propulsion (1 + 3)	19
2015	1M : 5 2M : 6	• Axial Flow Compressor (0 + 1) • Axial Flow Turbine (0 + 1) • Centrifugal Flow Compressor (0 + 1) • Jet Propulsion (3 + 1) • Rocket Propulsion (2 + 2)	17
2014	1M : 5 2M : 4	• Axial Flow Compressor (1 + 0) • Centrifugal Flow Compressor (0 + 1) • Jet Propulsion (3 + 1) • Rocket Propulsion (1 + 2)	13
2013	1M : 6	• Axial Flow Compressor (0	16

	2M : 5	+ 1) • Axial Flow Turbine (0 + 0) • Jet Propulsion (5 + 2) • Rocket Propulsion (1 + 2)	
2012	1M:2 2M:7	• Axial Flow Compressor (0 + 2) • Jet Propulsion (1 + 1) • Rocket Propulsion (1 + 4)	16
2011	1M:6 2M:3	• Axial Flow Compressor (1 + 0) • Jet Propulsion (3 + 2) • Rocket Propulsion (2 + 1)	12
2010	1M:5 2M:5	• Axial Flow Compressor (1 + 1) • Centrifugal Flow Compressor (1 + 0) • Jet Propulsion (2 + 3) • Rocket Propulsion (1 + 1)	15
2009	1M:5 2M:10	• Axial Flow Compressor (0 + 1) • Jet Propulsion (4 + 6) • Rocket Propulsion (1 + 3)	25
2008 (85 questions)	1M:2 2M:12	• Axial Flow Compressor (0 + 2) • Axial Flow Turbine (0 + 1) • Centrifugal Flow Compressor (0 + 1) • Jet Propulsion (1 + 5) • Rocket Propulsion (1 + 3)	26 (Total 150 marks)
2007 (85 questions)	1M:3 2M:13	• Axial Flow Compressor (0 + 3) • Axial Flow Turbine (0 + 2) • Centrifugal Flow Compressor (0 + 1) • Jet Propulsion (3 + 3) • Rocket Propulsion (0 + 4)	29 (Total 150 marks)

TABLE OF CONTENT

- GATE and Additional questions
- Previous year GATE questions solved

Chapter 1

THERMODYNAMICS BASICS

1.1 INTENSIVE PROPERTIES

It is a property that is independent of the mass of system.

Eg. Pressure, temperature, specific density, specific volume, specific internal energy, specific enthalpy, specific entropy etc.

1.2 EXTENSIVE PROPERTIES

It is a property that depends on the mass of the system.

E.g. internal energy, enthalpy, density, volume etc.

1.3 IDEAL GAS PROPERTIES AND PROCESSES

1.3.1 Boyle's law

It states that the absolute pressure of a given mass of an ideal gas is inversely proportional to its volume, if the temperature is kept constant.

$$\text{i.e. } P_1V_1 = P_2V_2$$

$$P \propto \frac{1}{v} \quad (T = \text{constant})$$

Such a process is known as isothermal process

An isothermal process is also known as hyperbolic process in case of gases.

1.3.2 Charle's law

It states that the volume of a given mass of an ideal gas is directly proportional to the absolute temperature, if the pressure of the gas is kept constant.

$$\text{i.e } \frac{V_1}{T_1} = \frac{V_2}{T_2}$$

$V \propto T$ (P= constant)

The above process is also known as isobaric process

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Ratio of specific heats (ϒ):

$$\Upsilon = \frac{C_p}{C_v} = 1.4 \text{ (for diatomic gases - air)}$$

$$= 1.67 \text{ (for monoatomic gases)}$$

$$= 1.33 \text{ (for triatomic gases – combustion products)}$$

$$\mathbf{C_p} = \frac{\Upsilon R}{(r-1)}$$

$$\mathbf{C_v} = \frac{R}{(r-1)}$$

$C_p - C_v = R$ → Meyer's equation

Example1.1: One kg of diatomic gas is heated and its temperature increases from 100 K to 600 K. The energy added at constant pressure during this process is 500 kJ. The specific heat at constant volume for the gas is ______ kJ/kgK. (round off to 2 decimal places).

[GATE 2019]

Solution: 0.71 kJ/kgK

$$Q = mC_p \Delta T$$

$$500 = 1 \times C_p \times 500$$

$$C_p = 1 \frac{kJ}{kg-K}$$

For diatomic gas, ϒ = 1.4

$$C_p = \frac{\Upsilon R}{\Upsilon - 1} = 3.5 R$$

$$\therefore R = \frac{1}{3.5} \frac{kJ}{kgK}$$

$$C_p - C_V = R$$

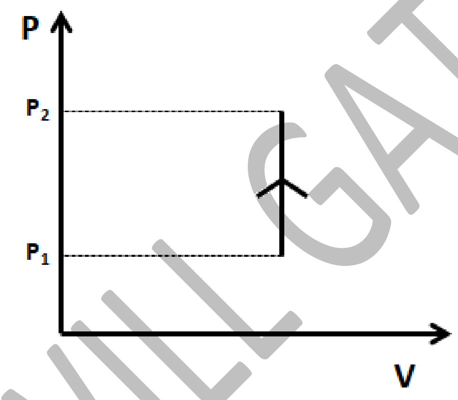
$$C_V = C_p - R$$

$$C_V = 2.5\ R$$

$$\mathbf{C_V = 0.71\ kJ/kgK}$$

1.5 GAS PROCESSES

1.5.1 Constant – volume process (V = constant) – Isochoric process



W = $\int$ Pdv (for closed system)

i.e. W = 0 [as volume is constant]

From 1st Law of thermodynamics,

$$Q = \Delta U + W$$

$$Q = m\ C_v\ (T_2 - T_1) + 0$$

$$\mathbf{Q = m\ C_v\ \Delta T}$$

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SUMMARY OF ALL PROCESSES

S.No	Process	PV^n = Constant	Relation between P,T,V	Work W	ΔU	Q
1	constant volume (isochoric)	n = ∞	$P \propto T$ $\frac{P_2}{P_1} = \frac{T_2}{T_1}$	0	$mC_v\Delta T$	$Q = \Delta U = mC_v\Delta T$
2	constant pressure (isobaric)	n = 0	$V \propto T$ $\frac{V_2}{V_1} = \frac{T_2}{T_1}$	$P(V_2 - V_1) = mR(T_2 - T_1)$	$mC_v\Delta T$	$Q = mC_p\Delta T$
3	constant temperature (isothermal)	n = 1	$P \propto \frac{1}{V}$ $\frac{P_1}{P_2} = \frac{V_2}{V_1}$	$P_1V_1 \ln\left(\frac{V_2}{V_1}\right)$ $P_1V_1 \ln\left(\frac{P_1}{P_2}\right)$ $mRT_1 \ln\left(\frac{V_2}{V_1}\right)$	0	Q = W
4	Isentropic (reversible adiabatic)	n = ϒ	$\frac{P_2}{P_1} = \left(\frac{T_2}{T_1}\right)^{\frac{\gamma}{\gamma-1}}$ $\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1}$	$\frac{P_1V_1 - P_2V_2}{\gamma - 1}$	$mC_v\Delta T$	Q = 0 W = -ΔU
5	Polytropic	n = n	$\frac{P_2}{P_1} = \left(\frac{T_2}{T_1}\right)^{\frac{n}{n-1}}$ $\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{r-1}$	$\frac{P_1V_1 - P_2V_2}{n - 1}$	$mC_v\Delta T$	Q = ΔU + W

1.6 GAS POWER CYCLE

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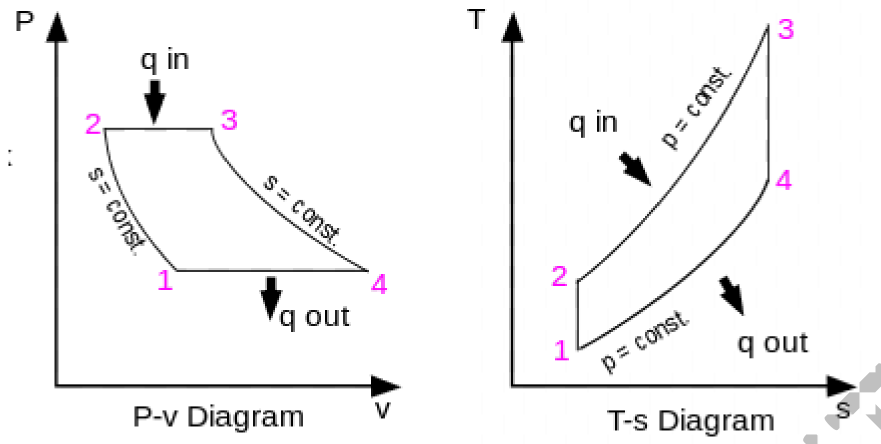
1.6.5 Brayton cycle

It consists of two reversible adiabatic and two isobaric process



Process 1 – 2: isentropic compression

Process 2 – 3: heat addition @ constant pressure (isochoric)

Process 3 – 4: isentropic expansion

Process 4 – 1: heat rejection @ constant pressure (isochoric)

$$\eta_{Brayton} = \frac{1}{(r)^{\frac{\gamma-1}{\gamma}}}$$

where, r = compression ratio = $\frac{P_3}{P_2}$

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1.8 FIRST LAW OF THERMODYNAMICS

It is also known as Conservation of energy principle

It states that , "Energy can neither be created nor be destroyed but can only be transformed from one form to another"

Q = ΔU + W (for a closed system)

1. **Internal energy** – defined as a storable energy in the system indicated by the level of temperatures

$$\Delta U = mC_v\Delta T$$

2. **Pdv work** – this work is defined for quasi-static process

$$dW = Pdv$$

$$W = \int Pdv$$

NOTE:

- for a cyclic pressure $\sum Q = \sum W$
- work done by the system is positive i.e turbine produced by turbine
- work done on the system is negative i.e. work done on compressor
- heat given to the system is positive i.e combustor
- heat given by the system is negative

Example 1.2 Linked answer Questions

A piston compresses 1 kg of air inside a cylinder as shown. The rate at which the piston does work on the air is 3000 W. At the same time heat is being lost through the walls of the cylinder at the rate 847.5 W **[GATE 2009]**

Q1. After 10 sec the change in specific interval energy of the air is _______

(a) 21252 J/kg **(b) -21525 J/kg**

(c) 30000 Jkg **(d) -8475 J/kg**

Solution: (a) 21252 J/kg

Given: W = -3000 W (word done on the system)

Q = -847.5 W (heat given by the system)

$$Q = \Delta U + W$$

$$\Delta U = 2152.5 \text{ W} = 2152.5 \text{ J/S}$$

In 10s,

ΔU = 21525 J/Kg

Q2. Given that the specific heats of air at constant pressure and volume are C_p = 1004.5 J/Kg K, C_v = 717.5 J/Kg K respectively, the corresponding change in temperature of air is ________

(a) 21.4 K (b) -21.4 K

(c) 30 K (d) -30 K

Solution: (c) 30 K

$$\Delta U = mC_v\Delta T$$

$$21525 = 717.5 \times \Delta T$$

$$\mathbf{\Delta T = 30\ K}$$

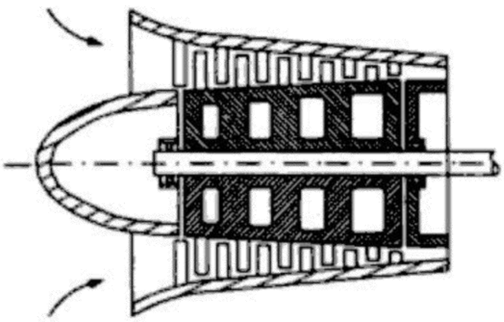
Chapter 2

AXIAL FLOW COMPRESSOR

2.1 WORKING PRINCIPLE

An AFC is a pressure producing machine. The energy level of air or gas flowing through it is increased by the action of the rotor blades which exerts a torque on the fluid. This torque is supplied by external source, an electric motor or a gas turbine.

An AFC had the potential for both higher pressure ratio and higher efficiency than the centrifugal flow compressor. Another advantage for jet engines is much larger air flow for given frontal area.



2.2 CONSTRUCTION

- It consists of an alternating sequence of fixed and moving sets of blades.
- The set of fixed blades are spaced around an outer stationary casing called the **stator**. The set of moving blades are fixed to a spindle called **rotor**.
- The rotor and stator blades must be as close as possible for smooth and efficient flow. The radius of the rotor hub and the length of the blades are designed so that there is only a very small tip clearance at the end of the rotor and stator blades.
- One set of stator blades and one set of rotor blades constitute a **stage.** The number of stages depends on the pressure ratio required.

2.3 OPERATION

- In an AFC the flow of air and fluid is along the initial direction and there is no change of radius for the flow.
- In this the rotating blades impart kinetic energy to the air which is then converted into pressure rise.
- Stator serves to recover part of kinetic energy imparted to the working fluid.
- This process is repeated in as many stages as necessary to yield the required overall pressure ratio.
- It also redirects the fluid at an angle suitable for entry into the rotating blades of the following stage. Usually, at the entry one more stator is provided to guide the air to correctly enter the first rotor. These blades are sometimes referred as **inlet guide vanes (IGV)**.
- In many compressors, one to three rows of diffuser or straightening blades are installed after the last stage to straighten and slow down the air before it enters the combustion chamber.

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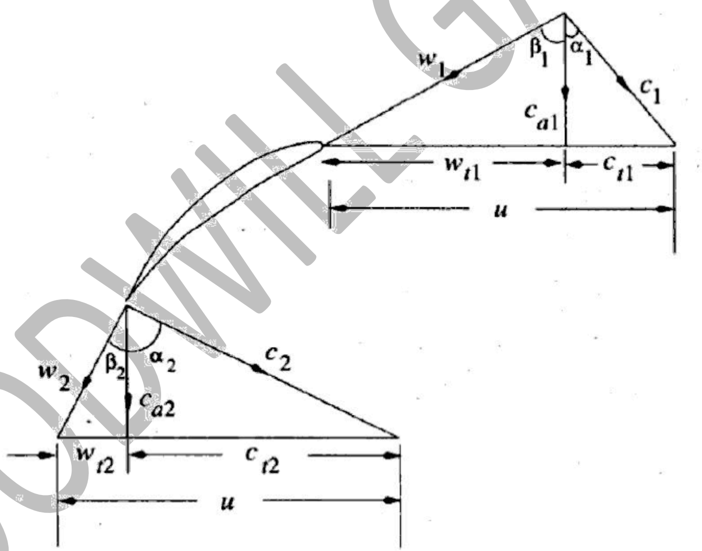
2.4 STAGE VELOCITY TRIANGLES

C: Absolute Velocity
U: Blade speed
w: Relative velocity
α_1 and α_2 : Air angles
β_1 and β_2 : Blade angles

Assumptions made –
Axial velocity is constant i.e. $Ca_1 = Ca_2 = Ca$
Blade speed i.e. $U_1 = U_2 = U$



From the Inlet velocity triangle,

$U = Ct_1 + Wt_1$
$U = Ca\tan \alpha_1 + Ca\tan \beta_1$
$\mathbf{U = Ca(\tan \alpha_1 + \tan \beta_1)}$

From exit velocity triangle,
$U = Ct_2 + Wt_2$
$U = Ca\tan \alpha_2 + Ca\tan \beta_2$
$\mathbf{U = Ca (\tan \alpha_2 + \tan \beta_2)}$

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Example2.1: Air at a temperature of 290 K enters a ten stage axial flow compressor, at the rate of 3.0 kg/s. The pressure ratio is 6.5 and the isentropic efficiency is 90%, the compression process being adiabatic. The compressor has symmetrical stages. The axial velocity of 110 m/s is uniform across the stage and the mean blade speed of each stage is 180 m/s.

Determine the direction of the air to entry to and exit from the rotor and the stator blades and also the power given to the sir. C_P = 1.005 KJ/kgK and ϒ = 1.4

Solution:

Given: $T_{01} = 290\,K, n = 10, \dot{m}_a = 3\,kg/s, r = 6.5, \eta_{ic} = 0.9, R = 0.5 (symmetrical\ stages), C_a = 110\,m/s\ , U = 180\,m/s$

Find: $\boldsymbol{\beta_1} = ?\,, \boldsymbol{\beta_2} = ?\,, \boldsymbol{\alpha_1} = ?\,, \boldsymbol{\alpha_2} = ?\,, \boldsymbol{Power}$

$$\frac{T'_{02}}{T_{01}} = (\frac{P_{02}}{P_{02}})^{\frac{\Upsilon-1}{\Upsilon}} = (r)^{\frac{\Upsilon-1}{\Upsilon}} = (6.5)^{0.286}$$

$$T'_{02} = 495.33\,K$$

$$\eta_{ic} = \frac{T'_{02} - T_{01}}{T_{02} - T_{01}}$$

$$0.9 = \frac{495.33 - 290}{T_{02} - 290}$$

$$T_{02} = 518.14\,K$$

Power given to the air $= \dot{m}_a C_P (T_{02} - T_{01})$

$$= 3 \times 1005 \times (518.14 - 290)$$

$$= \boldsymbol{687.84\ KW}$$

Temperature rise across 1 stage (ΔT_{0s}) = $\frac{\Delta T_{0C}}{n} = \frac{518.4-290}{10} = 22.81\,K$

$$22.81 = \frac{180 \times 110}{1005} (tan\,\beta_1 - tan\,\beta_2) \text{ -------- (1)}$$

We know,

$$R = \frac{Ca}{2U}\ (\tan \beta_1 + \tan \beta_2)$$

$$\frac{1}{2} = \frac{110}{2\times 180}\ (\tan \beta_1 + \tan \beta_2) \text{-------- (2)}$$

Solving equations (1) and (2) simultaneously, we get

$$\boldsymbol{\beta_1 = 54.41^0, \beta_2 = 13.5^0}$$

Also, For 50% reaction stage (R = 0.5)

$$\alpha_1 = \beta_2$$

$$\alpha_2 = \beta_1$$

i.e.

$$\boldsymbol{\alpha_1 = \beta_2 = 13.5^0 \ and \ \alpha_2 = \beta_1 = 54.41^0}$$

GATE QUESTIONS

Q1. An axial compressor operates such that it has an inlet and an exit total temperature of 300 K and 430 K, respectively. The isentropic efficiency of the compressor is 85 %. If the ratio of specific heats is 1.4, then the total pressure ratio across the compressor is ____________. **[GATE 2016]**

Ans: 2.99

Given: T_{01} = 300K, T_{02} = 430K

$$\eta_{ic} = \frac{T'_{02} - T_{01}}{T_{02} - T_{01}} = 0.85$$

$$\therefore T'_{02} = 410.5\ K$$

$$\frac{P_{02}}{P_{01}} = \left(\frac{T'_{02}}{T_{01}}\right)^{\frac{\gamma}{\gamma-1}} = \mathbf{2.99}$$

Q2. Following are the operational parameters of an axial compressor stage:

Air mass flow rate = 24 kg/s

Static temperature of air at the rotor inlet = 278 K

Velocity of air at the rotor inlet (zero whirl velocity) = 140 m/s
Work done on the compressor rotor = 734 kW
Isentropic efficiency of the compressor stage = 0.86
Ratio of specific heats = 1.4
Specific heat at constant pressure = 1.005 kJ/kgK

The stagnation pressure ratio across the axial compressor stage is ________. **[GATE 2015]**

Ans: 1.35

$$T_{01} = T_1 + \frac{C_1^2}{2\,C_p} = 278 + \frac{140^2}{2\,(1005)}$$

$$\therefore T_{01} = 287.75\,K$$

Chapter 4

CENTRIFUGAL COMPRESSOR

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4.2 ADVANTAGES OF CENTRIFUGAL-FLOW COMPRESSOR OVER THE AXIAL-FLOW COMPRESSOR

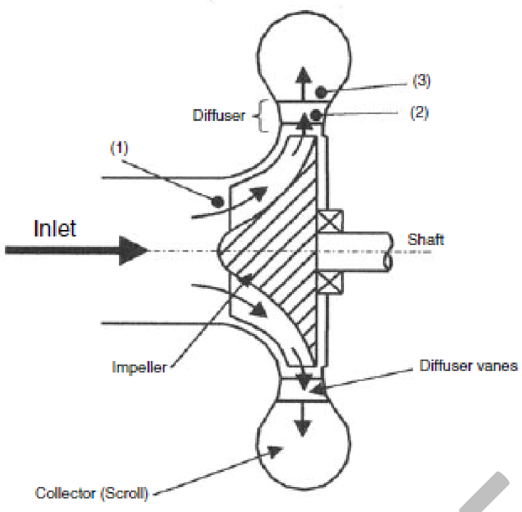
- Higher stage pressure ratio (5:1 or even 10:1).
- Simplicity and ruggedness of construction.
- Shorter length for the same overall pressure ratio.
- Generally less severe stall characteristics.
- Fewer drops in performance with the adherence of dust to blades.

- Cheaper to manufacture for equal pressure ratio.
- Flow direction of discharge air is convenient for the installation of an intercooler and/or heat exchanger in gas turbines.
- Wider range (margin) of stable operation between surging and choking limits at a given rotational speed.

Comparison Between Axial and Centrifugal Compressors

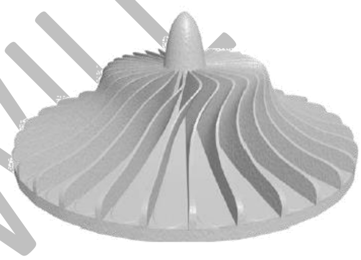
	Axial Compressor	Centrifugal Compressor
Dimensions (frontal area)	Smaller	Larger
Dimensions (length)	Longer	Shorter
Number of blades per stage	Great	Less
Weight	Heavier	Lighter
rpm	Low	High
Efficiency	High (85% or greater)	Moderate (75–80%)
Pressure ratio per stage	Small	High
Overall pressure ratio	Higher (30:1)	Much smaller (<10)
Mass flow rate	Higher	Smaller
Flow direction at outlet	Axial	Radial
Manufacturing and its cost	Difficult and expensive	Simple and cheaper
Balance	Difficult	Easier
Construction	Complex	Simple
Rapid change of inlet mass flow	Cannot accept	Can accept
Maintenance and its cost	Difficult and expensive	Simple and cheap
Balancing	More difficult due to blade scatter effect	Easier owing to support bearings
FOD	Less resistant	Good resistant
Fouling	Greatly influenced	Less influenced
Reliability	Lower	Higher
Operating range (between choking and surge points)	Narrow	Wide
Ruggedness	Fragile	Strong
Material	Impeller (aluminum alloy), Inlet section (steel)	Rotor: Front stages (steel alloy), Mid stages (aluminum alloy), Rear stages (titanium alloys);
Material	Impeller (aluminum alloy), Inlet section (steel)	Rotor: Front stages (steel alloy), Mid stages (aluminum alloy), Rear stages (titanium alloys); Drum or discs: steel; Casing: Magnesium alloy at the front, Steel at the rear
Engine operation	1. Trouble usually experienced when starting due to lack of initial axial flow (blade stall) 2. Reluctant to respond to rapid acceleration	1. Works satisfactorily at all speeds provided turbine is properly matched 2. Can accept rapid changes of mass air flow (acceleration)
Starting power requirement	Higher	Lower
Engine thrust	Higher	Lower
Engine-specific fuel consumption (SFC)	Lower	Higher
Aircraft altitude	Higher	Lower
Application	All aero engines	Small aero engines and APU

4.3 COMPONENTS AND DESCRIPTION



Layout of Centrifugal compressor

- The centrifugal compressor illustrated in above Figure defines three states, namely, the impeller inlet (state 1), impeller outlet (state 2), and diffuser outlet (state 3).
- The principle components are the impeller and the diffuser.
- When the impeller is rotary at high speed air drawn in through the impeller



Impeller Shape

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SUMMARY

1. Ideal energy transfer:
   $C_{t1} = 0$, $C_{t2} = U_2$ (no slip condition)
   W = U_2^2

2. Actual work transfer:
   W = $P_{if}\,\boldsymbol{\mu}\, U_2^2$

Where P_{if} is the power input factor, μ is slip factor.

3. $\eta_{ic} = \frac{T_{02}' - T_{01}}{T_{02} - T_{01}}$

4. $\Delta T_0 = \frac{P_{if} \mu u^2}{Cp}$

5. Slip factor : $\mu = \frac{Ct2}{Ct2'} = \frac{Ct2}{U_2}$

6. Slip velocity : $C_s = C_{t2}' - C_{t2}$

$= U_2 - C_{t2}$

Chapter 5

JET PROPULSION

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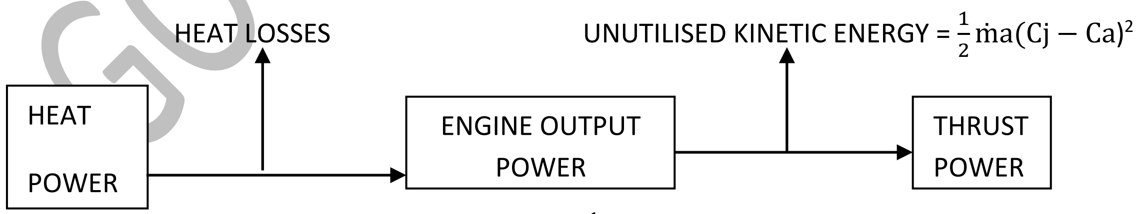
5.2 EFFICIENCIES



($\dot{m}f$ x CV) **(Propulsive Power =$\frac{1}{2}\dot{m}a\ (Cj^2 - Ca^2)$)** **(T.P. = F .Ca)**

Propulsive power available to propel aircraft forward is propulsive power and actual power available to propel aircraft forward is thrust power.

1. Propulsive Efficiency / Froude Efficiency

It is the ratio of useful energy or thrust power to the sum of that energy and unused kinetic energy of jet relative to the earth.

$$\eta_P = \frac{\text{Thrust power}}{\text{Engine output power}}$$

$$= \frac{F \times Ca}{F \times Ca + \frac{1}{2}\dot{m}a\,(C_j - C_a)^2}$$

$$= \frac{F \times Ca}{F \times Ca + \frac{F}{2}\,(Cj - Ca)}$$

$$= \frac{F \times Ca}{F \times Ca + \frac{F \times Ca}{2}\,(\frac{Cj}{Ca} - 1)}$$

$$= \frac{1}{1 + \frac{1}{2}\,(\frac{1}{\alpha} - 1)}$$

$$\boldsymbol{\eta_P = \frac{2\,\alpha}{1 + \alpha}, \quad \text{where } \alpha = \frac{Ca}{Cj}}$$

NOTE:

1. η_P is the measure of effectiveness with which the propelling duct is being used for propelling the aircraft.
2. The above expression for η_P is valid for all air breathing engines.
3. For maximum thrust, $\alpha = 0$ i.e. $\eta_P = 0$.
4. For maximum efficiency, $\alpha = 1$ i.e. $F = 0$.
5. For maximum thrust power,

   Thrust power = $F \times Ca$

   $= \dot{m}a\,(Cj - Ca)Ca$

   $= \dot{m}a\,Cj^2\,(1 - \alpha)\alpha$

   For maximum thrust power, differentiate with respect to α and equate to zero.

$$\frac{dT.P.}{d\alpha} = \dot{m}a\,Cj^2\,(\,\alpha\,(-1) + (1 - \alpha)) = 0$$

$$\therefore \alpha = \frac{1}{2} = \frac{Ca}{Cj}$$

$$\therefore Cj = 2\,Ca$$

$$\boldsymbol{\therefore \quad \eta_P = 66.67\,\%}$$

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Example5.3: A simple Turbojet is operating with a compressor pressure ratio of 8, a turbine inlet temperature of 1200 K and a mass flow of 15 kg/s. When the aircraft is flying at 260 m/s at an altitude of 7000m, assuming the following component efficiency and ISA conditions. Calculate the propelling nozzle area required, the net thrust developed and the SFC. ($P_a = 0.405\ bar, T_a = 242.5\ K$)

$C_P(air) = 1.005\ kJ/kgK, \gamma = 1.4$

$C_P(gas) = 1.147\ kJ/kgK, \gamma = 1.33$

Heating value of fuel(HV or CV) – 43100 KJ/kg

Polytropic efficiency of Compressor and Turbine 0.87

$\eta_i\ of\ intake$ 0.95

$\eta_i\ of\ nozzle$ 0.95

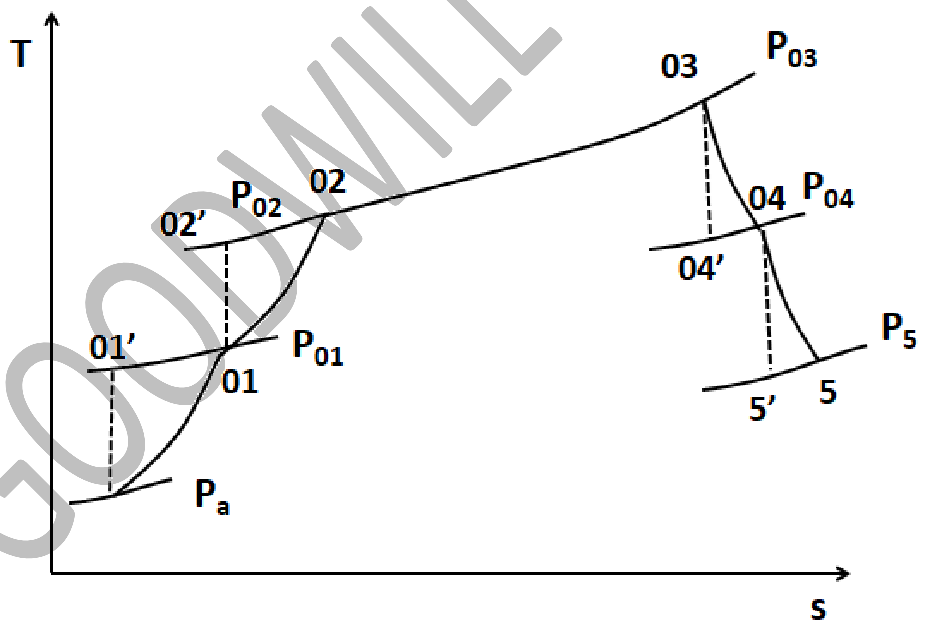
$mechinical\ efficiency$ 0.99

$\eta_i\ of\ combustion\ chamber$ 0.97

ΔP_B $6\%\ of\ compressure\ delivery\ pressure$

Solution:

Given: $r = 8, T_{03} = 1200\ K, \dot{m}_a = 15\ kg/s, C_a = 260\ m/s$



Intake:

$$T_{01} = T_{0a} = T_a + \frac{C_a^2}{2C_P}$$

$$\boldsymbol{T_{01} = 276.132\ K}$$

$$M = \frac{C_a}{\sqrt{\gamma R T_a}} = 0.833$$

$$\frac{P_{01}}{P_a} = \left\{1 + \frac{\gamma - 1}{2} M^2 \eta_{id}\right\}^{\frac{\gamma}{\gamma-1}}$$

$$\boldsymbol{P_{o1} = 0.625\ bar}$$

Compressor:

$$r = \frac{P_{02}}{P_{01}} = 8$$

$$\boldsymbol{P_{02} = 5\ bar}$$

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Chapter 7

ROCKET PROPULSION

7.1 THRUST

$$\mathbf{F = F_{momentum} + F_{pressure\ difference}}$$

$$\mathbf{F} = \dot{m}_P C_e + (p_e - p_a)\,\mathbf{A}$$

$\dot{m}_P C_e$= momentum trust

$(p_e - p_a)$ A = pressure thrust

$\dot{m}_P$ = mass rate of the propellant

p_e = exit pressure at the nozzle

A_e = area of exit of nozzle

p_a= ambient pressure

C_e = velocity of exit gases

Note: The flight speed term 'u' is absent in the equation. Therefore, the thrust is independent of the flight speed.

7.2 EFFECTIVE JET VELOCITY (c_j)

It is the velocity of jet when gases are expanded through the nozzle to the ambient pressure

$p_e = p_a$Then $c_e = c_j$

$$F=\dot{m}_P c_j$$

$$\dot{m}_P c_j = \dot{m}_P C_e + (p_e - p_a)A$$

$$c_j = c_e + \frac{(p_e - p_a)A_e}{m}$$

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7.17 MULTI-STAGES VERTICAL FLIGHT

t_{p1}= power flight duration for 1st stage

t_{p2}= power flight duration for 2nd stage

t_{p3}= power flight duration for 3rd stage & so on

u_1= version gain during 1st stage

u_2= version gain during 2nd stage

u_3= version gain during 3rd stage

$u_{max} = u_p = u_1 + u_2 + u_3$ is the maximum velocity at the end of the powered flight

$t_p = t_{p1} + t_{p2} + t_{p3}$ is the total duration of powered flight.

$$\text{Payload ratio } (\lambda) = \frac{\textit{Payload mass}}{\textit{propellant mass} + \textit{structural mass}}$$

$$= \frac{m_L}{m_S + m_P}$$

$$\text{Structure ratio } (\epsilon) = \frac{\textit{structural mass}}{\textit{propellant mass} + \textit{structural mass}}$$

$$= \frac{m_S}{m_S + m_P}$$

Where,

m_S = Structural mass

m_P = Propellant mass

m_L = Payload mass

$$u_p = C_j ln \frac{1}{MR}$$

$$u_p = C_j ln \frac{m_1}{m_2}$$

$$\boldsymbol{u_p = C_j ln(\frac{1 + \lambda}{\lambda + \epsilon})}$$

Example7.1: A two stage chemical rocket having the same specific impulse (I_{sp}) of 300 s for both the stages is designed in such a way that the payload ratio and the structural ratio are same for both the stages. The second stage of the rocket has following mass distribution:

Propellant mass = 10208 kg

Structural mass = 1134 kg

Payload mass = 1700 kg

g = 9.81 m/s^2

If the rocket is fired from rest and if flies in a zero gravity field and a drag-free environment, the final velocity attained by the payload is **[GATE 2010]**

(a) 9729.3 m/s (b) 897.3 m/s

(c) 9360.2 m/s (d) 8973.2 m/s

Ans: (d) 8973.2 m/s

Given: $m_S = 1134$ kg, $m_P = 10208$ kg, $m_L = 1700$ kg

$\lambda_1 = \lambda_2, \epsilon_1 = \epsilon_2$

$$\text{Payload ratio } (\lambda) = \frac{Payload\ mass}{propellant\ \ mass + structural\ mass}$$

$$= \frac{1700}{1134 + 10208} = 0.15$$

$$\text{Structure ratio } (\epsilon) = \frac{structural\ mass}{propellant\ mass + structural\ mass}$$

$$= \frac{1134}{1134 + 10208} = 0.10$$

$$C_j = I_{sp} \times g$$

$$C_j = 300 \times 9.81 = 2943 \text{ m/s}$$

$$u_p = 2 \times C_j ln\left(\frac{1 + \lambda}{\lambda + \epsilon}\right)$$

$$\boldsymbol{u_p = 8973.2\ m/s}$$

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7.22 SOLID PROPELLANT ROCKET

PROPELLANT: It is the mixture of fuel and oxidizer in the form of fine powder. It is hold together by binding material like rubber; additives may be added to improve their physical and chemical properties.

CLASSIFICATION OF SOLID PROPELLANT

1. *DOUBLE BASE PROPELLANT:*

It is homogeneous propellant grain usually nitrocellulose type of gun powder dissolved in nitro-glycerine plus additives. Both the major ignition is exploded and contributes to the function of fuel oxidizer and binder.

ADVANTAGES:

- Uniform combustion due to homogeneity

- No separate binder required.

2. *COMPOSITE PROPELLANT:*

It is heterogeneous propellant grain with the oxidizer crystal and the powdered fuel usually Aluminium held together in a matrix of symmetric rubber or plastic binder such as polybutadine.

It is less dangerous or hazardous to manufacture and handle in comparison to double base propellant.

3. *COMPOSITE DOUBLE BASE:*

It is a combination of double base propellant and composite propellant, usually crystalline oxidizer (aluminium per chlorate and powder fuel aluminium) are held together in a matrix of nitro cellulose or nitro-glycerine.

It is dangerous as double propellant.

NOTE:

Additives are the materials added in small quantity for the following function:

- To accelerate or length in quire time
- To improve viscous property
- To control heat transfer
- To control burning rate
- To improve bonding properties.

Solid fuels

- **Aluminium**
  - Powdered aluminium
  - Prominent solid fuel 14 – 18 % by weight
  - Used in Composite propellant and combination of composite double base.
- **Boron**
  - It is energy fuel – lighter than Al
  - Difficult to burn with high efficiency in combustion chamber of reasonable length
  - Rarely used as fuel but mainly used as igniter
- **Beryllium**

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GATE QUESTIONS

Q1. A rocket has an initial mass of 150 kg. After operating for a duration of 10s, its fial mass is 50 kg. If the acceleration due to gravity is 9.81 m/s^2 and the thrust produced by the rocket is 19.62 kN, the specific impulse of the rocket is **[GATE 2018]**

(a) 400 s (b) 300s (c) 200s (d) 100s

Ans: (c) 200s

$$\dot{m}_P = \frac{150 - 50}{10} = 10\ kg/s$$

$$F = \dot{m}_P \times C_j$$

$$\mathbf{19620 = 10} \times C_j$$

$$C_j = 1962\ m/s$$

$$I_{sp} = \frac{C_j}{g} = \mathbf{200\ sec}$$

Q2. Among the following engines, which one is expected to have the maximum Specific Impulse?

(a) Cryogenic Rocket (b) Solid propellant Rocket

(c) Liquid propellant Rocket (d) SCRAM Jet **[GATE 2017]**

Ans: (d) SCRAM Jet

Scramjet has a higher specific impulse (change in momentum per unit of propellant) than a rocket engine; it could provide between 1000 and 4000 seconds, while a rocket typically provides around 450 sec or less.

Q3. A single stage chemical rocket, having an initial mass of 10000 kg and specific impulse of 450 s, is launched from the surface of the earth and has to reach the escape velocity (11 K./s) at burn out. Consider g_e = 9.8 m/s^2. If the atmospheric drag and the effect of gravity are to be neglected, the mass of propellant to be carried by the rocket is equal to _________kg (in one decimal place). **[GATE 2017]**

Ans: 9174.5 kg

Given: m_0 = 10000 kg, I_{sp} = 450s, u_p = 11 Km/s

$$I_{sp} = \frac{C_j}{g_e} = 450\ sec$$

$u_p = C_j ln\frac{1}{MR}$(Neglecting gravity)

$$u_p = I_{sp}g_e \times ln\frac{m_0}{m_f}$$

$$11 \times 10^3 = 450 \times 9.8 \times ln\frac{10000}{m_f}$$

$$m_f = 825.51\ kg$$

$$m_0 - m_P = m_f$$

$$\boldsymbol{m_P = 9174.5\ kg}$$

$$\boldsymbol{C_j = 2133.33\ m/s}$$

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