KARPAGAM ACADEMY OF HIGHER EDUCATION

(Deemed to be University Established Under Section 3 of UGC Act, 1956)

Eachanari post, Coimbatore-641021. INDIA.

FACULTY OF ENGINEERING

DEPARTMENT OF MECHANICAL ENGINEERING

UG / B.Tech -AEROSPACE ENGINEERING

16BTAR303 AERO ENGINEERING THERMODYNAMICS 3 2 0 4 100

OBJECTIVES:

- Apply Mathematical foundations, principles in solving thermodynamics problems.
- Critically analyse the problem, and solve the problems related to heat transfer and propulsion

UNIT I BASIC THERMODYNAMICS

Systems, Zeroth Law, First Law – Heat and work Transfer in flow and non- flow process, Second law, Kelvin- Plank Statement- Clausius Statement-Concept of entropy-Clausius inequality-entropy change in non flow process.

UNIT II AIR CYCLES

Otto , Diesel, Dual combustion and Brayton Combustion cycles-Air standard efficiency-Mean effective pressure- Actual and Theoretical PV diagrams of four stroke and two stroke IC engines.

UNIT III THERMODYNAMICS OF ONE DIMENSIONAL FLUID FLOW

Application of continuity and energy equations –properties of steam- Rankine Cycle – Isentropic flow of ideal gases through nozzles- Simple jet propulsion system- Thrust rocket motor- Specific impulse.

UNIT IV BASIC OF PROPULSION AND HEAT TRANSFER

Classification of jet engines – simple jet propulsion system- thrust equation- specific impulse-ideal non-ideal cycle analysis- conduction in parallel, radial and composite wall- Modes of heat transfer.

UNIT V AIR COMPRESSORS

Classification and working principle, work of compression with clearance, Isothermal and Isentropic efficiency of reciprocating air compressors, multistage compression and inter cooling. Various types of compressors

(Use of standard thermodynamic tables, Mollier diagram and tables are permitted)

TEXT BOOKS:

S.No.	AUTHOR(S) NAME	TITLE OF THE BOOK	PUBLISHER	YEAR OF PUBLICATION
1	Yunus A. Cengel and Michael A. Boles,	Thermodynamics an engineering approach	McGraw Hill Higher education,	2011.
2	Nag, P. K	Engineering Thermodynamics	McGraw Hill, New Delhi.	2013
3	R.K. Rajput	A Text book of Engineering Thermodynamics	Fourth Edition	2013

REFERENCES:

S. No.	AUTHOR(S) NAME	TITLE OF THE BOOK	PUBLISHER	YEAROF PUBLICATION
1	Rayner Joel	Basic Engineering Thermodynamics,	Addison Wesley, New York,	1996
2	Holman, J	Thermodynamics, 4th Edition	Tata McGraw Hill, PNew Delhi.	1998
3	Rathakrishnan.	Fundamentals of Engineering Thermodynamics,	E, Prentice – Hall, India.	2005.
4	Michael Moran, J., and Howard Shapiro, N.	Fundamentals of Engineering Thermodynamics,4th Edition	John Wiley & Sons, New York.	2000

KARPAGAM UNIVERSITY
COIMBATORE – 21
FACULTY OF ENGINEERING
DEPARTMENT OF MECHANICAL ENGINEERING

COURSE PLAN

Subject Name : **AERO ENGINEERING THERMODYNAMICS**
Subject Code : **17BTAR303** **(Credits - 04)**
Name of the Faculty : **Mrs.P.JAYAPRADHA**
Designation : **ASSISTANT PROFESSOR**
Year/Semester/Section : **II/III**
Branch : **B.TECH- AEROSPACE ENGINEERING**

Sl. No.	No. of Periods	Topics to be Covered	Support Materials
		UNIT – I : BASIC THERMODYNAMICS	
1.	1	Basic thermodynamic systems	T [1]
2.	1	Zeroth Law and First Law	T [1]
3.	1	Heat and work Transfer in flow process	T [1]
4.	1	Problem based on Flow process	T [1]
5.	1	Heat and work Transfer in non- flow process	T [2]
6.	1	Heat and work Transfer in non- flow process	T [2]
7.	1	Problem based on Non- Flow process	T [2]
8.	1	**Tutorial: Problem based on Non- Flow process**	T [2]
9.	1	Second law, Kelvin- Plank Statement	T [3]
10.	1	Clausius Statement and Concept of entropy	T [3]
11.	1	Clausius inequality	T [1]
12.	1	entropy change in non flow process	T [1]
13.	1	**Tutorial:** entropy change in non flow process	T [3]
14.	1	**Discussion on Competitive Examination related Questions / University previous year questions**	
		Total No. of Hours Planned for Unit - I	**14**

Sl. No.	No. of Periods	Topics to be Covered	Support Materials
		UNIT – II : AIR CYCLES	
15.	1	Introduction to Air cycles	T [3]
16.	1	Otto cycle & problems	T [3]
17.	1	Diesel cycle & problems	T [3]
18.	1	Dual combustion cycle & problems	T [3]
19.	1	Brayton Combustion cycles	T [3]
20.	1	**Tutorial: Problems based on Air cycles**	T [3]

21.	1	Air standard efficiency	T [3]
22.	1	Mean effective pressure	T [3]
23.	1	Actual PV diagrams of four stroke	T [3]
24.	1	Theoretical PV diagrams of four stroke	T [3]
25.	1	Actual PV diagrams two stroke IC engines.	T [3]
26.	1	Theoretical PV diagrams of two stroke IC engines	T [3]
27.	1	Tutorial : Actual and Theoretical PV diagrams of four stroke	T [3]
28.	1	**Discussion on Competitive Examination related Questions / University previous year questions**	
Total No. of Hours Planned for Unit - II			**14**

Sl. No.	No. of Periods	Topics to be Covered	Support Materials
UNIT – III : THERMODYNAMICS OF ONE DIMENSIONAL FLUID FLOW			
29.	1	Application of continuity and energy equations	T [3]
30.	1	Properties of steam	T [3]
31.	1	Rankine cycle	T [3]
32.	1	Problem based on Rankine Cycle	T [3]
33.	1	Isentropic flow of ideal gases through nozzles	T [3]
34.	1	**Tutorial: Problem based on Rankine Cycle**	T [3]
35.	1	Simple jet propulsion system	T [2]
36.	1	Thrust rocket motor	T [2]
37.	1	Specific impulse	T [2]
38.	1	**Tutorial: Problem based on Specific impulse**	T [2]
39.	1	**Discussion on Competitive Examination related Questions / University previous year questions**	
Total No. of Hours Planned for Unit - III			**11**

Sl. No.	No. of Periods	Topics to be Covered	Support Materials
UNIT – IV : BASIC OF PROPULSION AND HEAT TRANSFER			
40.	1	Classification of jet engines	T [1]
41.	1	Simple jet propulsion system	T [1]
42.	1	Thrust equation	T [1]
43.	1	Specific impulse	T [1]
44.	1	Problem based on specific impulse	T [1]
45.	1	Ideal non-ideal cycle analysis	T [1]
46.	1	Conduction in parallel composite wall	T [1]
47.	1	Conduction in radial composite wall	T [1]
48.	1	Modes of heat transfer	T [1]
49.	1	Tutorial: conduction in parallel, radial and composite wall	T [1]
50.	1	**Discussion on Competitive Examination related Questions /**	

		University previous year questions	
		Total No. of Hours Planned for Unit - IV	**11**

Sl. No.	No. of Periods	Topics to be Covered	Support Materials
		UNIT – V : AIR COMPRESSORS	
51.	1	Classification and working principle of air compressor	R [4]
52.	1	Work of compression with clearance	R [4]
53.	1	Isothermal efficiency of reciprocating air compressors	R [4]
54.	1	Isentropic efficiency of reciprocating air compressors	R [4]
55.	1	Multistage compression	R [4]
56.	1	Inter cooling	R [4]
57.	1	Various types of compressors	R [4]
58.	1	Reciprocating compressors	R [4]
59.	1	Ionic liquid piston compressor	R [4]
60.	1	**Tutorial: Various types of compressors**	R [4]
61.	1	**Discussion on Competitive Examination related Questions / University previous year questions**	
		Total No. of Hours Planned for Unit - V	**11**

TOTAL PERIODS :61

TEXT BOOKS

T [1] – Yunus A. Cengel and Michael A. Boles, "Thermodynamics an engineering approach" McGraw Hill Higher education,2011.
T [2] – Nag, P. K "Engineering Thermodynamics" McGraw Hill, New Delhi, 2013.
T[3]- R.K. Rajput "A Text book of Engineering Thermodynamics" Fourth Edition, 2013.

REFERENCES

R [1] **-** Rayner Joel, "Basic Engineering Thermodynamics" Addison Wesley, New York,1996.
R [2] **-** Holman, J, "Thermodynamics, 4th Edition" Tata McGraw Hill, PNew Delhi, 1998
R [3] **-** Michael Moran, J., and Howard Shapiro, N, Fundamentals of Engineering Thermodynamics,4th Edition, John Wiley & Sons, New York, 2000.
R [4] **-** Fundamentals of Engineering Thermodynamics, E, Prentice –Hall, India, 2005.

WEBSITES

W [1] **-** http://www.brighthubengineering.com/hvac/64884-different-types-of-air-compressors
W [2] **-** www.airconditioning-systems.com/air-conditioner-compressor.html
W [3] **-** www.daveycompressor.com/differenttype.html

JOURNALS

J [1] **-**
J [2] –
J [3] –
J [4] –
J [5] –

UNIT	Total No. of Periods Planned	Lecture Periods	Tutorial Periods
I	**14**	**12**	**02**
II	**14**	**12**	**02**
III	**11**	**09**	**02**

IV	**11**	**10**	**01**
V	**11**	**10**	**01**
TOTAL	**61**	**53**	**08**

I. CONTINUOUS INTERNAL ASSESSMENT : 40 Marks

(Internal Assessment Tests: 30, Attendance: 5, Assignment/Seminar: 5)

II. END SEMESTER EXAMINATION : 60 Marks

TOTAL : 100 Marks

UNIT – I

UNIT I BASIC THERMODYNAMICS

Basic concepts - Classical and Statistical approaches - Thermodynamic systems - closed, open, isolated. Property – State - Process-adiabatic - Quasi-static process – Cycle - Point and Path function – Energy - Work transfer - Concept of temperature and heat- Zeroth law of thermodynamics - Concept of ideal gases - First law of thermodynamics –PMM1, internal energy, specific heat capacities, enthalpy, and its application to closed system and open system-steady flow energy equation.

1. Thermodynamics

Thermodynamics can be defined as the science of energy. The name thermodynamics stems from the Greek words therme (heat) and dynamis (power), which is most descriptive of the early efforts to convert heat into power.

1.1 Classical Thermodynamics (Macroscopic)& Statistical Thermodynamics (Microscopic)

- It is well-known that a substance consists of a large number of particles called molecules. The properties of the substance naturally depend on the behavior of these particles.
- For example, the pressure of a gas in a container is the result of momentum transfer between the molecules and the walls of the container.
- However, one does not need to know the behavior of the gas particles to determine the pressure in the container. It would be sufficient to attach a pressure gage to the container.
- This macroscopic approach to the study of thermodynamics that does not require knowledge of the behavior of individual particles is called **classical thermodynamics**.
- Thermodynamic approach by considering average behavior of large number of particles is termed as **Statistical Thermodynamics**.

1.2 Application of Thermodynamics:

- Thermodynamics is commonly encountered in many engineering systems and other aspects of life, and one does not need to go very far to see some application areas of it.
- Many ordinary household utensils and appliances are designed, in whole or in part, by using the principles of thermodynamics.
- Some examples include the electric or gas range, the heating and air-conditioning systems, the refrigerator, the humidifier, the pressure cooker, the water heater, the shower, the iron, and even the computer and the TV.
- On a larger scale, thermodynamics plays a major part in the design and analysis of automotive engines, rockets, jet engines, and conventional or nuclear power plants, solar collectors, and the design of vehicles from ordinary cars to airplanes.

1.3 Measuring Mass, Length, Time, and Force

- A unit is any specified amount of a quantity by comparisonwith which any other quantity of the same kind is measured.
- For example, meters, centimeters,kilometers, feet, inches, and miles are all units of length. Seconds, minutes, andhours are alternative time units.
- Because physical quantities are related by definitions and laws, a relatively small numberof physical quantities suffice to conceive of and measure all others. These may be calledprimary dimensions.
- The others may be measured in terms of the primary dimensions andare called secondary.
- For example, if length and time were regarded as primary, velocity andarea would be secondary.
- Let usillustrate these ideas by considering briefly the SI system of units.

	SI		
Quantity	Unit	Dimension	Symbol
mass	kilogram	M	kg
length	meter	L	m
time	second	t	s

1.3.1 Density (ρ)

Density is defined as the ratio of mass of the object to its volume occupied.

$$\rho = \frac{mass}{volume} = \frac{m}{V}, kg/m^3$$

1.3.2 Specific volume (v)

It is defined as the inverse of density that is volume occupied by an object per unit mass of the same.

$$v = \frac{1}{\rho}, m^3/kg$$

1.3.3 Specific gravity (SG)

Sometimes the density of a substance is given relative to the density of a well-known substance. Then it is called specific gravity, or relative density, and is defined as the ratio of the density of a substance to the density of some standard substance at a specified temperature (usually water at 4°C, for which ρ_{H2O}= 1000 kg/m^3).

$$SG = \frac{\rho}{\rho_{H_2O}}$$

1.3.4 Velocity (V)

The rate of change of distance of an object with respect to time is defined as velocity. m/sec is the unit of velocity and it is expressed as

$$V = \frac{Change\ in\ Distance}{Time\ Taken}, \qquad m/sec$$

1.3.5 Acceleration (a)

The rate of change of velocity of an object with respect to time is defined as acceleration. m/sec^2 is the unit of acceleration. The acceleration due to gravity effect of our earth's atmosphere is termed as acceleration due to gravity (g) and its value is 9.81 m/sec^2.

1.3.6 Force (F)

According to Newton's second law (The rate of change of momentum is directly proportional to force) is expressed as the equality

$$F = ma$$

The newton, N, is the force required to accelerate a mass of 1 kilogram at the rate of 1 meterper second per second.

$$1\ \text{N} = (1\ \text{kg})(1\ \text{m/s}^2) = 1\ \text{kg} \cdot \text{m/s}^2$$

Quantity	Dimensions	Units	Symbol	Name
Velocity	Lt^{-1}	m/s		
Acceleration	Lt^{-2}	m/s^2		
Force	MLt^{-2}	kg m/s^2	N	newtons
Pressure	$ML^{-1}\,t^{-2}$	kg m/s^2 (N/m^2)	Pa	pascal
Energy	$ML^2\,t^{-2}$	kg m^2/s^2 (N m)	J	joule
Power	$ML^2\,t^{-3}$	kg m^2/s^3 (J/s)	W	watt

1.4 Pressure (p)

- **Pressure** is defined as a normal force exerted by a fluid per unit area. pressure is defined as force per unit area, it has the unit of newtons per square meter (N/m^2), which is called a **pascal**(Pa). That is, 1 Pa = 1 N/m^2

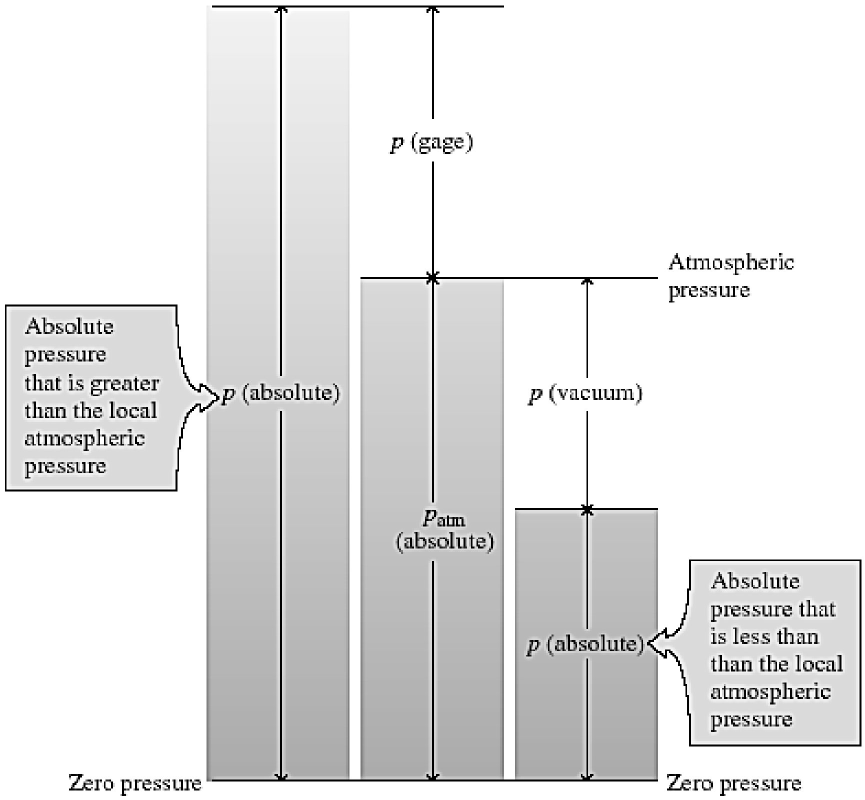
$$1\ \text{kPa} = 10^3\ \text{N/m}^2$$
$$1\ \text{bar} = 10^5\ \text{N/m}^2$$
$$1\ \text{MPa} = 10^6\ \text{N/m}^2$$

$$1\ \text{standard atmosphere (atm)} = 1.01325 \times 10^5\ \text{N/m}^2$$

- The actual pressure at a given position is called the absolute pressure, and it is measured relative to absolute vacuum (i.e., absolute zero pressure).
- The difference between the absolute pressure and the local atmospheric pressure is called the gage pressure P_{gage}. It can be positive or negative, but pressures below atmospheric pressure are sometimes called vacuum pressures

$$p(\text{gage}) = p(\text{absolute}) - p_{atm}(\text{absolute})$$

$$p(\text{vacuum}) = p_{atm}(\text{absolute}) - p(\text{absolute})$$



- The pressure at a point in a fluid has the same magnitude in all directions. The variation of pressure with elevation is given by

$$\frac{dP}{dz} = -\rho g$$

- Where the positive z direction is taken to be upward. When the density of the fluid is constant, the pressure difference across a fluid layer of thickness Δz is

$$\Delta P = P_2 - P_1 = \rho g \Delta z$$

- The absolute and gage pressures in a liquid open to the atmosphere at a depth h from the free surface

$$P = P_{atm} - \rho g h \qquad or \qquad P_{gage} = \rho g h$$

- The atmospheric pressure is measured by a barometer and is given by

$$P_{atm} = \rho g h$$

- Where h is the height of the liquid column.

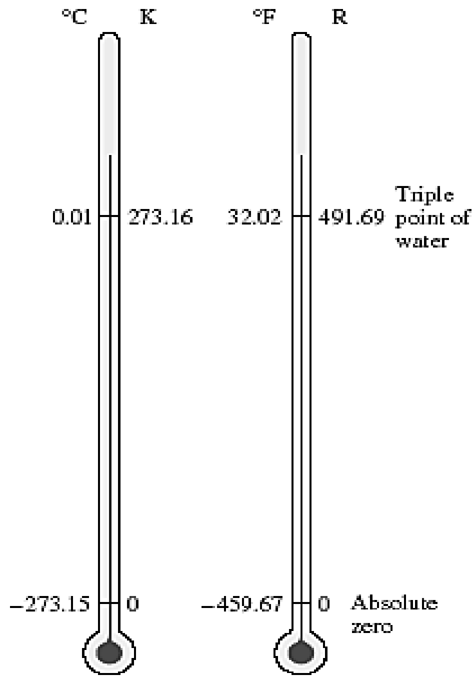
1.5 Temperature (T)

- We are familiar with temperature as a measure of "hotness" or "coldness," it is not easy to give an exact definition for it. Based on our physiological sensations, we express the level of temperaturequalitatively with words like freezing cold, cold, warm, hot, and red-hot.

1.6 Zeroth Law of Thermodynamics

- When a body A is in thermal equilibrium with a Body B and also separately with a body C, then B & C will be in thermal equilibrium with each other. This is known as the Zeroth law of Thermodynamics.

- It is the basis of temperature measurement.



Relation between temperature scales

(T_c – Celsius Scale)

(T_k – Kelvin Scale)

(T_F – Fahrenheit Scale)

(T_R – Rankine Scale)

$$T(K) = T\ (°C) + 273.15$$

$$T\ (R) = T(°F) + 459.67$$

$$T(R) = 1.8\ T\ (K)$$

1.7 Energy

- Although everybody has a feeling of what energy is, it is difficult to give a precise definition for it. Energy can be viewed as the ability to cause changes.Energy can exist in numerous forms such as thermal, mechanical, kinetic, potential, electrical, magnetic, chemical, and nuclear, and their sum constitutes the **total energy** *E* (or *e* on a unit mass basis) of a system.
- The international unit of energy is joule (J) or kilojoule (1 kJ = 1000 J). In the English system, the unit of energy is the British thermal unit (Btu),
- In thermodynamic analysis, it is often helpful to consider the various forms of energy that make up the total energy of a system in two groups: macroscopic and microscopic.
- The **macroscopic** forms of energy are those a system possesses as a whole with respect to some outside reference frame, such as **kinetic and potential energies**. The **microscopic** forms of energy are those related to the molecular structure of a system and the degree of the molecular activity,

and they are independent of outside reference frames. The sum of all the microscopic forms of energy is called the **internal energy** of a system and is denoted by U.

- The term energy was coined in 1807 by Thomas Young, and its use in thermodynamics was proposed in 1852 by Lord Kelvin.
- The term internal energy and its symbol U first appeared in the works of Rudolph Clausius and William Rankine in the second half of the nineteenth century, and it eventually replaced the alternative terms inner work, internal work, and intrinsic energy commonly used at the time.
- The macroscopic energy of a system is related to motion and the influence of some external effects such as gravity, magnetism, electricity, and surface tension.
- The energy that a system possesses as a result of its motion relative to some reference frame is called **kinetic energy** (KE). When all parts of a system move with the same velocity, the kinetic energy is expressed as

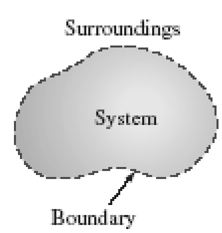
$$KE = m\frac{V^2}{2}\,(kJ)$$

$$PE = m\ g\ z\ (kJ)$$

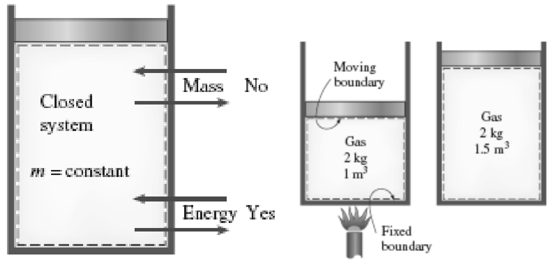
- The energy that a system possesses as a result of its elevation in a gravitational field is called **potential energy (PE)** and is expressed as
- Energy can cross the boundary of a closed system in two distinct forms: heat and work

1.8 Basic Thermodynamic Concepts:

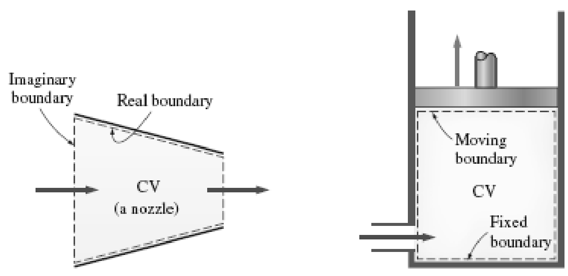
- Thermodynamic System
  A system is defined as a quantity of matter or a region in space chosen for study.
- Surroundings
  The mass or region outside the system is called the surroundings.
- Boundary
  The real or imaginary surface that separates the system from its surroundings is called the boundary. The boundary of a system can be fixed or movable.



- Systems may be considered to be closed or open, depending on whether a fixed mass or a fixed volume in space is chosen for study.
- A closed system (also known as a control mass or just system when the context makes it clear) consists of a fixed amount of mass, and no mass can cross its boundary.That is, no mass can enter or leave a closed system, as shown in figure.



- But energy, in the form of heat or work, can cross the boundary; and the volume of a closed system does not have to be fixed.
- If, as a special case, even energy is not allowed to cross the boundary, that system is called an isolated system.
- An open system, or a control volume, as it is often called, is a properly selected region in space. It usually encloses a device that involves mass flow such as a compressor, turbine, or nozzle.
- Flow through these devices is best studied by selecting the region within the device as the control volume. Both mass and energy can cross the boundary of a control volume.
- A large number of engineering problems involve mass flow in and out of a system and, therefore, are modeled as control volumes.
- A water heater, a car radiator, a turbine, and a compressor all involve mass flow and should be analyzed as control volumes (open systems) instead of as control masses (closed systems).



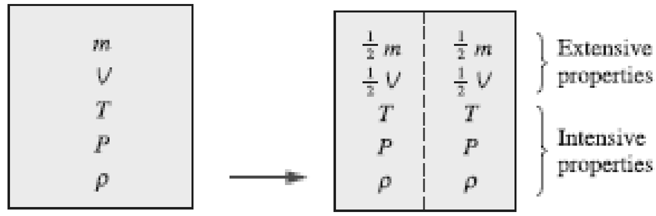
(a) A control volume (CV) with real and imaginary boundaries

(b) A control volume (CV) with fixed and moving boundaries as well as real and imaginary boundaries

- The boundaries of a control volume are called a control surface, and they can be real or imaginary.

1.9 Thermodynamic Properties

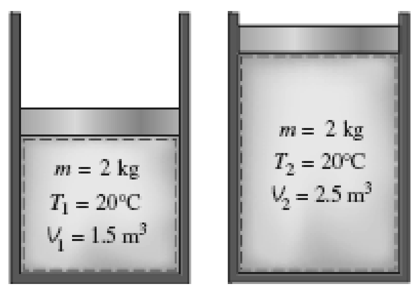
- Any characteristic of a system is called a **property**.
- Some familiar properties are pressure P, temperature T, volume V, and mass m. It also include less familiar ones such as viscosity, thermal conductivity, modulus of elasticity, thermal expansion coefficient, electric resistivity, and even velocity and elevation.
- Properties are considered to be either **intensive or extensive**.
- **Intensive properties** are those that are independent of the mass of a system, such as temperature, pressure, and density.
- **Extensive properties** are those whose values depend on the size—or extent—of the system. Total mass, total volume, and total momentum are some examples of extensive properties.



- Extensive properties per unit mass are called **specific properties**. Some examples of specific properties are specific volume, specific gravity and specific total energy.
- Matter is made up of atoms that are widely spaced in the gas phase. Yet it is very convenient to disregard the atomic nature of a substance and view it as a continuous, homogeneous matter with no holes known as a **continuum**.
- **Point Functions** are the thermodynamic properties, it results in an idealization concept known as **continuum**

1.10 Thermodynamic State

- Consider a system not undergoing any change. At this point, all the properties can be measured or calculated throughout the entire system, which gives us a set of properties that completely describes the condition, or **the state**, of the system. At a given state, all the properties of a system have fixed values.



(*a*) State 1 (*b*) State 2

1.11 Thermodynamic equilibrium

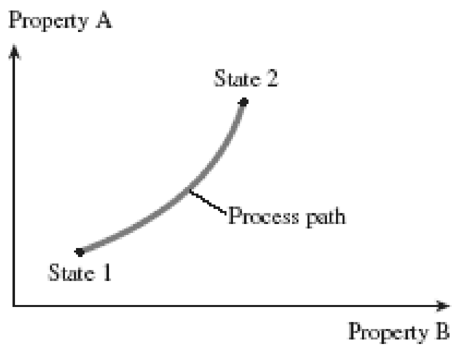
- Thermodynamics deals with equilibrium states. The word **equilibrium implies a state of balance**.
- In an equilibrium state there are no unbalanced potentials (or driving forces) within the system.
- A system in equilibrium experiences no changes when it is isolated from its surroundings.
- There are many types of equilibrium, and a system is not in thermodynamicequilibrium unless the conditions of all the relevant types of equilibriumare satisfied.
- For example, a system is in **thermal equilibrium**if the temperature is the same throughout the entire system. That is, the system involves no temperature differential, which isthe driving force for heat flow.
- **Mechanical equilibrium** is related to pressure,and a system is in mechanical equilibrium if there is no change inpressure at any point of the system with time.
- If a system involves two phases, it is in **phase equilibrium** when the mass of each phase reaches an equilibrium level and stays there.

- Finally, a system is in **chemical equilibrium** if its chemical composition does not change with time, that is, no chemical reactions occur.
- The number of properties required to fix the state of a system is given by the state postulate:
- The state of a simple compressible system is completely specified by two independent, intensive properties.

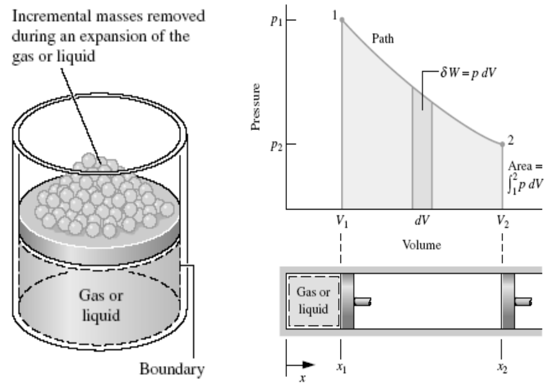
The state of nitrogen is fixed by two independent, intensive properties.

1.12 Process:

- Any change that a system undergoes from one equilibrium state to another is called a **process**, and the series of states through which a system passes during a process is called the **path of the process**.
- To describe a process completely, one should specify the initial and final states of the process, as well as the path it follows, and the interactions with the surroundings.



- When a process proceeds in such a manner that the system remains infinitesimally close to an equilibrium state at all times, it is called **a quasi-static, or quasi-equilibrium, process**.
- **A quasi-equilibrium process** can be viewed as a sufficiently slow process that allows the system to adjust itself internally so that properties in one part of the system do not change any faster than those at other parts.



- A system is said to have undergone a **cycle** if it returns to its initial state at the end of the process. That is, for a cycle the initial and final states are identical.

1.13 First law of Thermodynamics

- The first law of thermodynamics, also known as the conservation of energy principle, provides a sound basis for studying the relationships among the various forms of energy and energy interactions. Based on experimental observations, the first law of thermodynamics states that energy can be neither created nor destroyed during a process; it can only change forms.

1.14 Energy Balance

- In the light of the preceding discussions, the conservation of energy principle can be expressed as follows: The net change (increase or decrease) in the total energy of the system during a process is equal to the difference between the total energy entering and the total energy leaving the system during that process.

$$\begin{pmatrix} Total\ energy\ entering \\ the\ system \end{pmatrix} - \begin{pmatrix} Total\ energy\ leaving \\ the\ system \end{pmatrix} = \begin{pmatrix} change\ in\ the\ total \\ energy\ of\ the\ system \end{pmatrix}$$

$$Or$$

$$E_{in} - E_{out} = \Delta E_{sys}$$

1.15 Energy Change of a System, ΔE_{system}

- The determination of the energy change of a system during a process involves the evaluation of the energy of the system at the beginning and at the end of the process, and taking their difference. That is,

Energy change = Energy at final state – Energy at initial state

or

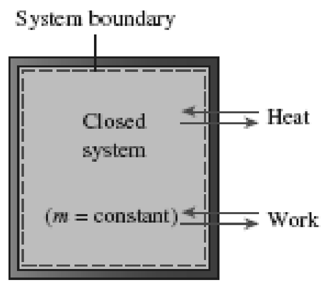
$$\Delta E = E_{final} - E_{initial} = E_2 - E_1$$

1.16 Mechanisms of Energy Transfer, E_{in} And E_{out}

- Energy can be transferred to or from a system in three forms: heat, work, and mass flow.
- Energy interactions are recognized at the system boundary as they cross it, and they represent the energy gained or lost by a system during a process.
- The only two forms of energy interactions associated with a fixed mass or closed system are heat transfer and work.

1.17 Heat (Q)

- Heat is defined as the form of energy that is transferred between two systems (or a system and its surroundings) by virtue of a temperature difference. That is, an energy interaction is heat only if it takes place because of a temperature difference.



- A process during which there is no heat transfer is called an adiabatic process
- The amount of heat transferred during the process between two states (states 1 and 2) is denoted by Q_{12}, or just Q& heat has energy units, kJ (or Btu). Heat transfer *per unit mass* of a system is denoted by q and is determined from

$$q = \frac{Q}{m}, \qquad kJ/kg$$

- **Sign Convention,**

  Q > 0 (+ve value): heat transfer to the system
  Q < 0 (-ve value): heat transfer from the system

1.18 Work (W)

- Work, like heat, is an energy interaction between a system and its surroundings. Energy can cross the boundary of a closed system in the form of heat or work. Therefore, if the energy crossing the boundary of a closed system is not heat, it must be work.

  Forms of Work:

- Mechanical form of work
  Example: Shaft work, Spring work, Work Done on Elastic Solid Bars, Work Associated with the Stretching of a Liquid Film, Work Done to Raise or to Accelerate a Body,
- Non mechanical form of work
  Example: Electrical work, Magnetic work, magnetic polarization work
- Sign Convention

  W > 0 (+ve value): work done by the system
  W < 0 (-ve value): work done on the system

(compressible fluid)	$W = \int_1^2 p\,dV$		
Electrical work	$W = \int_1^2 E\,dC = \int_1^2 EI\,d\tau$	Surface film	$W = -\int_1^2 \sigma\,dA$
Shaft work	$W = \int_1^2 T\,d\theta$	Stretched wire	$W = -\int_1^2 \mathcal{F}\,dL$

Magnetised solid $\quad W = -\int_1^2 H\,dI$

1.19 Power

The rate of energy transfer by work is called power and denoted by P. The unit for power is Watt (W).

The energy balance can be written more explicitly as

$$= (Q_{in} - Q_{out}) + (W_{in} - W_{out}) + (E_{mass,in} - E_{mass,out}) = \Delta E_{sys}$$

- For a closed system undergoing a cycle, the initial and final states are identical, and thus

$$\Delta E_{sys} = E_2 - E_1 = 0$$
$$W_{net,out} = Q_{net,in} (for\ a\ cycle)$$

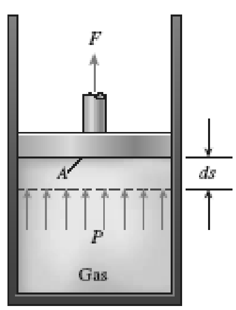
- The energy balance relation for a closed system undergoing a process (i.e. from state 1 to state 2) becomes

$$Q_{net,in} - W_{net,out} = \Delta E_{sys} (or) \quad Q - W = \Delta E$$

1.20 Moving boundary work

- Consider the gas enclosed in the piston–cylinder device shown in Fig. 4–2. The initial pressure of the gas is P, the total volume is V, and the cross sectional area of the piston is A.
- If the piston is allowed to move some distance ds in a quasi-equilibrium manner, the differential work done during this process is

$$\delta W_b = F\,ds = PA\,ds = P\,dV$$



A gas does a differential amount of work δW_b as it forces the piston to move by a differential amount ds.

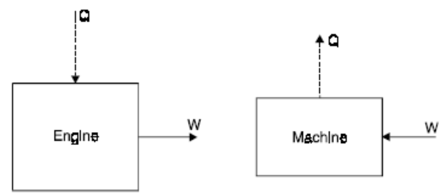
- The total boundary work done during the entire process as the piston moves is obtained by adding all the differential works from the initial state to the final state:

$$W_b = \int_1^2 P\,dV, \quad kJ$$

- The compression or expansion process can occur with keeping any one of the thermodynamic properties constant and such processes are given name starting with iso. (Isothermal, Isobaric, Isochoric etc.)

1.21 Perpetual Motion Machine of the First Kind—PMM 1

- The first law of thermodynamics states the general principle of the conservation of energy. Energy is neither created nor destroyed, but only gets transformed from one form to another.
- There can be no machine which would continuously supply mechanical work without some form of energy disappearing simultaneously. Such a fictitious machine is called a perpetual motion machine of the first kind, or in brief, PMM 1. A PMM 1 is thus impossible.
- The converse of the above statement is also true, i.e., there can be no machine which would continuously consume work without some other form of energy appearing simultaneously.



1.22 The Characteristic Equation of State

- At temperatures that are considerably in excess of critical temperature of a fluid, and also at very low pressure, the vapour of fluid tends to obey the equation

$$\frac{PV}{T} = constant = R$$

- In practice, no gas obeys this law rigidly, but many gases tend towards it.
- An imaginary ideal gas which obeys this law is called a perfect gas, and the equation

$$\frac{PV}{T} = R$$

  is called the characteristic equation of a state of a perfect gas. The constant R is calledthe gas constant. Each perfect gas has a different gas constant.
- Units of R are Nm/kg K or kJ/kg K.
- Usually, the characteristic equation is written as

$$Pv = RT$$

  or for, m kg, occupying V m^3

$$PV = mRT$$

- The characteristic equation in another form can be derived by using kilogram-mole asa unit.
- The kilogram-mole is defined as a quantity of a gas equivalent to M kg of the gas, where M is the molecular weight of the gas (e.g., since the molecular weight of oxygen is 32, then 1 kg mole of oxygen is equivalent to 32 kg of oxygen).
- As per definition of the kilogram-mole, for m kg of a gas, we have

$$m = nM$$

- Where n = number of moles.
- Since the standard of mass is the kg, kilogram-mole will be written simply as mole.

$$PV = nMRT$$

- According to Avogadro's hypothesis the volume of 1 mole of any gas is the same as the volume of 1 mole of any other gas, when the gases are at the same temperature and pressure.
- Therefore, $\frac{V}{n}$ is the same for all gases at the same value of p and T. That is the quantity $\frac{pV}{nT}$ is a constant for all gases. This constant is called universal gas constant, and is given the symbol, R_u.

$$\text{i.e., } MR = R_u = PV/nT$$

or

$$PV = nR_uT$$

- Since $MR = R_u$, then

$$R = \frac{R_u}{M}$$

1.23 Types of process:

1.23.1 Reversible and Irreversible Processes

a) Reversible process

A reversible process (also sometimes known as quasi-static process) is one which can be stopped at any stage and reversed so that the system and surroundings are exactly restored to their initial states.

This process has the following characteristics:

1. It must pass through the same states on the reversed path as were initially visited on the forward path.
2. This process when undone will leave no history of events in the surroundings.
3. It must pass through a continuous series of equilibrium states.

No real process is truly reversible but some processes may approach reversibility, to close approximation.

b) Irreversible process

An irreversible process is one in which heat is transferred through a finite temperature.

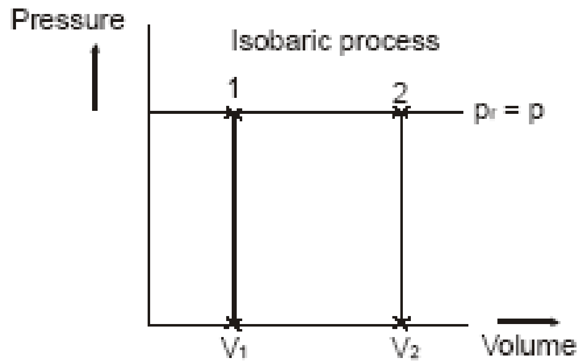
An irreversible process is usually represented by a dotted (or discontinuous) line joining the end states to indicate that the intermediate states are indeterminate.

Irreversibility's are of two types:

1. External irreversibility's. These are associated with dissipating effects outside the working fluid. Example. Mechanical friction occurring during a process due to some external source.
2. Internal irreversibility's. These are associated with dissipating effects within the working fluid.

1.23.2 ConstantPressure Process or Isobaric Process:

It refers to the thermodynamic process in which there is no change in pressure during the process. Such types of processes are also known as isobaric processes.



It refers to the thermodynamic process in which there is no change in pressure during the process. Such types of processes are also known as isobaric processes.

The P-v-T relation of an ideal gas for such a process becomes

$$\frac{P_1 v_1}{T_1} = \frac{P_2 v_2}{T_2}$$

And since pressure remains constant in this process ($P_1 = P_2$), therefore

$$\frac{v_1}{T_1} = \frac{v_2}{T_2}$$

Heat transfer & work transfer is given as

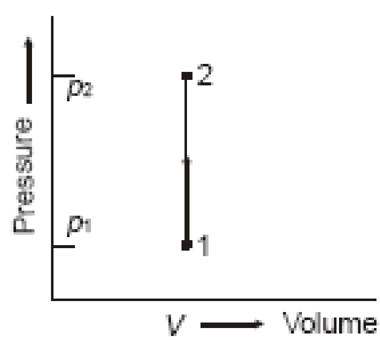
$$Q = m\, c_p \Delta T \quad \& \quad W = P\,(V_2 - V_1),\ \text{kJ}$$

And the change in internal energy & enthalpy is given as

$$\Delta U = m\, c_v \Delta T \quad \& \quad \Delta H = m\, c_p \Delta T,\ kJ$$

1.23.3 Constant Volume Process or Isochoric Process:

When a fluid undergoes a thermodynamic process in a fixed enclosed space such that the process occurs at constant volume, then the process is called constant volume process or isochoric process.



It refers to the thermodynamic process in which there is no change in volume during the process. Such types of processes are also known as isochoric processes.

The P-v-T relation of an ideal gas for such a process becomes

$$\frac{P_1 v_1}{T_1} = \frac{P_2 v_2}{T_2}$$

And since pressure remains constant in this process ($v_1 = v_2$), therefore

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

Heat transfer & work transfer is given as

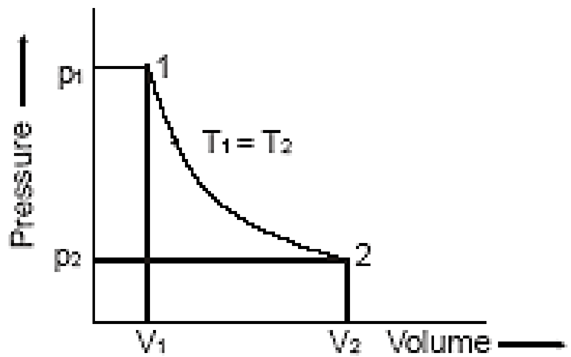
$$Q = m\, c_v \Delta T,\ kJ \quad \& \quad W = 0,\ \text{kJ}$$

And the change in internal energy & enthalpy is given as

$$\Delta U = m\, c_v \Delta T \quad \& \quad \Delta H = m\, c_p \Delta T,\ kJ$$

1.23.4 Constant Temperature Process or Isothermal Process:

Thermodynamic process in which the temperature remains constant is called constant temperature or isothermal process.



It refers to the thermodynamic process in which there is no change in temperature during the process. Such types of processes are also known as isothermal processes.

The P-v-T relation of an ideal gas for such a process becomes

$$\frac{P_1 v_1}{T_1} = \frac{P_2 v_2}{T_2}$$

And since pressure remains constant in this process ($T_1 = T_2$), therefore

$$P_1 v_1 = P_2 v_2 = constant$$

Heat transfer & work transfer is given as

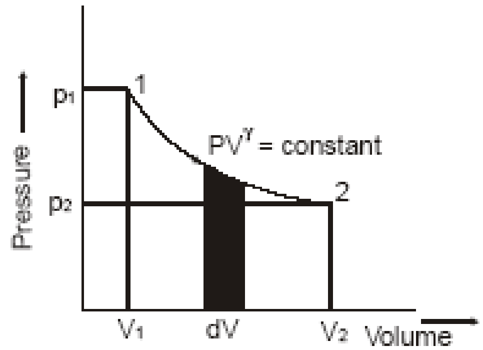
$$Q = W = P_1 V_1\ \ln\left(\frac{V_2}{V_1}\right) = \text{m R T} \ln\left(\frac{V_2}{V_1}\right),\ \text{kJ}$$

And the change in internal energy & enthalpy is given as

$$\Delta U = 0 \quad \& \quad \Delta H = 0,\ kJ$$

1.23.5 Adiabatic Process:

An adiabatic process is the thermodynamic process in which there is no heat interaction during the process, i.e. during the process, Q = 0. The adiabatic process follows the law PV^{γ}= constant where γ is called adiabatic index and is given by the ratio of two specific heats.



An adiabatic process is the thermodynamic process in which there is no heat interaction during the process, i.e. during the process, Q = 0. The adiabatic process follows the law PV^{γ} = constant where γ is called adiabatic index and is given by the ratio of two specific heats.

The P-v-T relation of an ideal gas for such a process becomes

$$P_1 v_1^{\gamma} = P_2 v_2^{\gamma} \leftrightarrow \frac{P_1}{P_2} = \left(\frac{v_2}{v_1}\right)^{\gamma}$$

Also

$$\frac{T_2}{T_1} = \frac{P_2}{P_1} \times \frac{v_2}{v_1} = \left(\frac{v_2}{v_1}\right)^{-\gamma} \times \frac{v_2}{v_1} = \left(\frac{v_2}{v_1}\right)^{1-\gamma} \leftrightarrow \frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma-1}$$

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\gamma-1/\gamma}$$

Heat transfer & work transfer is given as

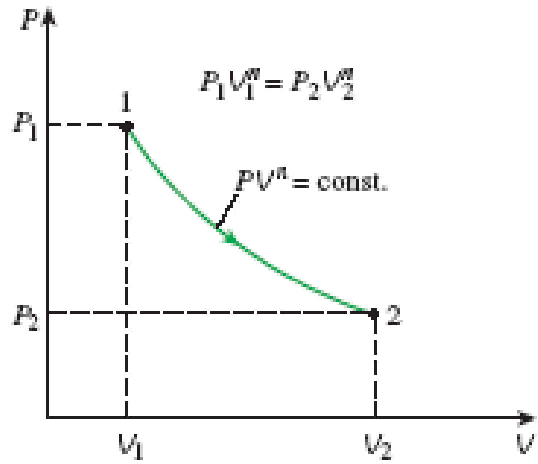
$$Q = 0 \;\&\; W = \frac{P_1 V_1 - P_2 V_2}{\gamma - 1} = \frac{\mathrm{m\,R}\,(T_1 - T_2)}{\gamma - 1},\ \mathrm{kJ}$$

And the change in internal energy & enthalpy is given as

$$\Delta U = m\, c_v \Delta T \;\;\&\;\; \Delta H = m\, c_p \Delta T,\ kJ$$

1.23.6 Polytropic Process:

Polytropic process is the most commonly used process in practice. In this, the thermodynamic process is said to be governed by the law PV^n = constant where n is the index which can vary from –∞ to + ∞.



Polytropic process is the most commonly used process in practice. In this, the thermodynamic process is said to be governed by the law PV^n = constant where n is the index which can vary from –∞ to + ∞.

The P-v-T relation of an ideal gas for such a process becomes

$$P_1 v_1^n = P_2 v_2^n \leftrightarrow \frac{P_1}{P_2} = \left(\frac{v_2}{v_1}\right)^n$$

Also

$$\frac{T_2}{T_1} = \frac{P_2}{P_1} \times \frac{v_2}{v_1} = \left(\frac{v_2}{v_1}\right)^{-n} \times \frac{v_2}{v_1} = \left(\frac{v_2}{v_1}\right)^{1-n} \leftrightarrow \frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{n-1}$$

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{n-1/n}$$

Heat transfer & work transfer is given as

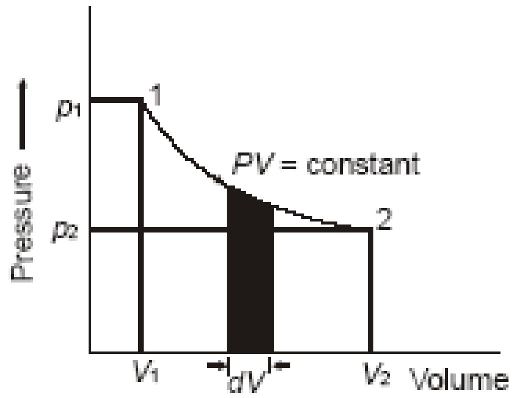
$$Q = W \times \left(\frac{\gamma - n}{\gamma - 1}\right) \ \& \ W = \frac{P_1V_1 - P_2V_2}{n-1} = \frac{\text{m R} (T_1 - T_2)}{n-1}, \ \text{kJ}$$

And the change in internal energy & enthalpy is given as

$$\Delta U = m\, c_v \Delta T \ \ \& \ \ \Delta H = m\, c_p \Delta T, \ kJ$$

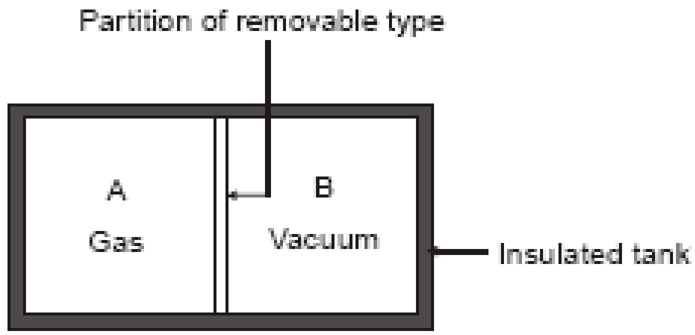
1.23.7 Hyperbolic Process:

Hyperbolic process is the one in which product of pressure and volume remains constant during the process. The curve for such an expansion process is a rectangular hyperbola and hence this is known as hyperbolic expansion.



1.23.8 Free Expansion:

Free expansion, as the name implies refers to the unrestrained expansion of a gas.



1.24 Enthalpy

Enthalpy (H) of a substance at any point is quantification of energy content in it, which could be given by summation of internal energy and flow energy. Enthalpy is very useful thermodynamic property for the analysis of engineering systems.

Mathematically, it is given as,

$$H = U + PV$$

On unit mass basis, the specific enthalpy could be given as,

$$h = u + Pv$$

1.25 Specific Heats

The specific heat is defined as the energy required to raise the temperature of a unit mass of a substance by one degree. In general, this energy depends on how the process is executed.

In thermodynamics, we are interested in two kinds of specific heats: specific heat at constant volume c_v and specific heat at constant pressure c_p.

Physically, the specific heat at constant volume c_v can be viewed as the energy required to raise the temperature of the unit mass of a substance by one degree as the volume is maintained constant.

The energy required to do the same as the pressure is maintained constant is the specific heat at constant pressure c_p. The specific heat at constant pressure c_p is always greater than c_v because at constant pressure the system is allowed to expand and the energy for this expansion work must also be supplied to the system.

$$c_v = \left(\frac{\partial u}{\partial T}\right)_v \& c_p = \left(\frac{\partial h}{\partial T}\right)_P$$

Using the definition of enthalpy and the equation of state of an ideal gas, we have

$$\left.\begin{aligned} h = u + Pv \\ Pv = RT \end{aligned}\right\} h = u + RT$$

Since R is constant and u =u (T), it follows that the enthalpy of an ideal gas is also a function of temperature only

$$h = h(T)$$

Since u and h depend only on temperature for an ideal gas, the specific heats c_v and c_p also depend, at most, on temperature only. Therefore, at a given temperature, u, h, c_v, and c_p of an ideal gas have fixed values regardless of the specific volume or pressure. The differential changes in the internal energy and enthalpy of an ideal gas can be expressed as

$$du = c_v(T)\, dT \qquad \& \qquad dh = c_P(T)\, dT$$

The change in internal energy or enthalpy for an ideal gas during a process from state 1 to state 2 is determined by integrating these equations

$$\Delta u = u_2 - u_1 = \int_1^2 c_v(T)\, dT = c_v(T_2 - T_1)$$

$$\Delta h = h_2 - h_1 = \int_1^2 c_v(T)\, dT = c_P(T_2 - T_1)$$

1.26 Specific Heat Relations of Ideal Gases

A special relationship between c_p and c_v for ideal gases can be obtained by differentiating the relation h = u + RT, which yields

$$dh = du + R\, dT$$

Replacing dh by c_pdT and du by c_vdT and dividing the resulting expression by dT, we obtain

$$c_P - c_v = R$$

This is an important relationship for ideal gases since it enables us to determine c_v from a knowledge of c_p and the gas constant R. At this point, we introduce another ideal-gas property called the specific heat ratio γ, defined as

$$\gamma = \frac{c_p}{c_v}$$

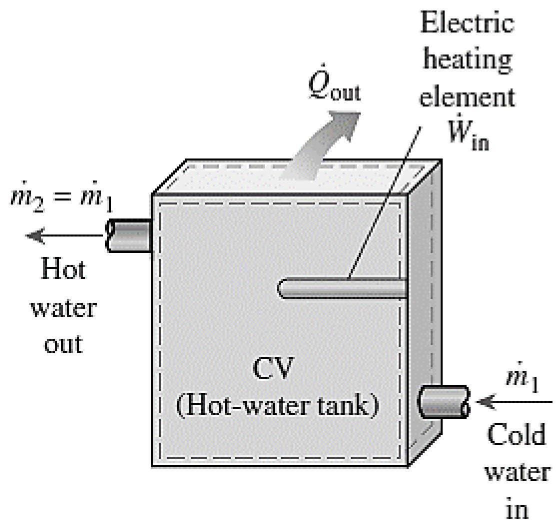
The specific ratio also varies with temperature, but this variation is very mild. For monatomic gases, its value is essentially constant at 1.667. Many diatomic gases, including air, have a specific heat ratio of about 1.4 at room temperature.

1.27 Path Function

Work & heat are termed as path functions and it is not a thermodynamic property since it does not depend on the particular state of the system but it depends on the path taken by the system undergoing a process from state 1 to state 2. Hence heat and work are considered as inexact or imperfect differentials.

1.28. Mass Flow, m

- Mass flow in and out of the system serves as an additional mechanism of energy transfer. When mass enters a system, the energy of the system increases because mass carries energy with it (in fact, mass is energy).
- Likewise, when some mass leaves the system, the energy contained within the system decreases because the leaving mass takes out some energy with it.



The energy content of a control volume can be changed by mass flow as well as heat and work interactions.

1.29 Mass and Volume Flow Rates

- The amount of mass flowing through a cross section per unit time is called the **mass flow rate** and is denoted by$\dot{m}$. The dot over a symbol is used to indicate time rate of change.

$$\dot{m} = \rho\, V\, A$$

- The volume of the fluid flowing through a cross section per unit time is called the volume flow rate $\dot{V}$

$$\dot{V} = V\, A \quad m^3/s$$

- The mass and volume flow rates are related by

$$\dot{m} = \rho\, \dot{V} = \frac{\dot{V}}{v}$$

- Where v is the specific volume. This relation is analogous to m = ρV = V/v, which is the relation between the mass and the volume of a fluid in a container.

1.30 Conservation of Mass Principle

- The conservation of mass principle for a control volume can be expressed as: The net mass transfer to or from a control volume during a time interval Δt is equal to the net change (increase or decrease) of the total mass within the control volume during Δt. That is,

$$\begin{pmatrix} Total\ mass\ entering \\ the\ CV\ during\ \Delta t \end{pmatrix} - \begin{pmatrix} Total\ mass\ leaving \\ the\ CV\ during\ \Delta t \end{pmatrix} = \begin{pmatrix} Net\ change\ of\ mass \\ within\ the\ CV\ during\ \Delta t \end{pmatrix}$$

$$m_{in} - m_{out} = \Delta m_{CV} \quad kg$$

$$OR$$

$$\dot{m}_{in} - \dot{m}_{out} = \Delta \dot{m}_{CV} \quad kg/s$$

1.31 Mass Balance for Steady-Flow Processes

- During a steady-flow process, the total amount of mass contained within a control volume does not change with time (m_{CV} = constant).
- When dealing with steady-flow processes, we are not interested in the amount of mass that flows in or out of a device over time; instead, we are interested in the amount of mass flowing per unit time, that is, the mass flow rate$\dot{m}$. The conservation of mass principle for a general steady flow system with multiple inlets and outlets is expressed in rate form as

$$\sum_{in} \dot{m} = \sum_{out} \dot{m} \quad \text{(kg/s)}$$

- It states that the total rate of mass entering a control volume is equal to the total rate of mass leaving it. Many engineering devices such as nozzles, diffusers, turbines, compressors, and pumps involve a single stream (only one inlet and one outlet).
- For single-stream steady-flow systems,

$$\dot{m}_1 = \dot{m}_2 \quad \rightarrow \quad \rho_1 V_1 A_1 = \rho_2 V_2 A_2$$

1.32 Flow Work and The Energy of a Flowing Fluid

- Unlike closed systems, control volumes involve mass flow across theirboundaries, and some work is required to push the mass into or out of thecontrol volume. This work is known as the flow work, or flow energy, andis necessary for maintaining a continuous flow through a control volume.

1.33 Total Energy of a Flowing Fluid

- the total energy of a simple compressiblesystem consists of three parts: internal, kinetic, and potential energies. On a unit-mass basis, it is expressed as

$$e = u + ke + pe = u + \frac{V^2}{2} + g\,z \quad , \quad kJ/kg$$

- Where V is the velocity and z is the elevation of the system relative to someexternal reference point.
- The fluid entering or leaving a control volume possesses an additional form of energy,the flow energy Pv. Then the totalenergy of a flowing fluid on a unit-mass basis (denoted by u) becomes

$$\theta = Pv + e = Pv + u + ke + pe$$

- But the combination Pv+ u has been previously defined as the enthalpy h.

$$\theta = h + ke + pe = h + \frac{V^2}{2} + g\,z \quad , \quad kJ/kg$$

- By using the enthalpy instead of the internal energy to represent theenergy of a flowing fluid, one does not need to be concerned about theflow work. The energy associated with pushing the fluid into or out ofthe control volume is automatically taken care of by enthalpy.

1.34 Energy Analysis of Steady-Flow Systems

- A large number of engineering devices such as turbines, compressors, andnozzles operate for long periods of time under the same conditions once thetransient start-up period is completed and steady operation is established,and they are classified as **steady-flow devices**
- During a steady-flow process, no intensive or extensive properties withinthe control volume change with time. Thus, the volume V, the mass m, andthe total energy content E of the control volume remain constant
- The fluid properties at an inlet or exit remain constant during a steadyflowprocess.
- Also, the heat and work interactionsbetween a steady-flow system and its surroundings do not change with time.
- Thus, the power delivered by a system and the rate of heat transfer to or from a system remains constant during a steady-flow process.
- The mass balance for a single-stream (one-inlet and one-outlet) steady-flowsystem is given as

$$\dot{m}_1 = \dot{m}_2 \quad \rightarrow \quad \rho_1 V_1 A_1 = \rho_2 V_2 A_2$$

- Where the subscripts 1 and 2 denote the inlet and the exit states, respectively, ρ is density, V is the average flow velocity in the flow direction, andA is the cross-sectional area normal to flow direction.
- During a steady-flow process, the total energy content of a control volumeremains constant (E_{CV}= constant), and thus the change in the total energyof the control volume is zero (ΔE_{CV}= 0).
- Therefore, the amount of energyentering a control volume in all forms (by heat, work, and mass) must beequal to the amount of energy leaving it.
- Then the rate form of the generalenergy balance reduces for a steady-flow process to

$$E_{in} - E_{out} = \Delta E_{CV} = 0 \quad for\ steady\ flow\ process$$

$$\therefore \quad E_{in} = E_{out}$$

- for a general steady-flow system can also bewritten more explicitly as

$$\dot{Q}_{in} + \dot{W}_{in} + \sum_{in} \dot{m} \left(h + \frac{V^2}{2} + g\,z \right) = \dot{Q}_{out} + \dot{W}_{out} + \sum_{out} \dot{m} \left(h + \frac{V^2}{2} + g\,z \right)$$

Based on the first law expression for a process

$$\dot{Q} - \dot{W} = \sum_{out} \dot{m} \left(h + \frac{V^2}{2} + g\,z \right) - \sum_{in} \dot{m} \left(h + \frac{V^2}{2} + g\,z \right)$$

For a single stream steady flow process

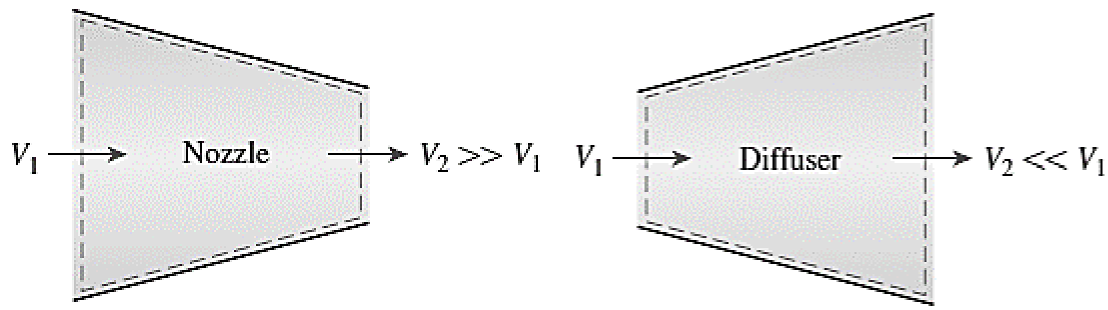
$$\dot{Q} - \dot{W} = \dot{m} \left\{ \left(h_2 + \frac{{V_2}^2}{2} + g\,z_2 \right) - \left(h_1 + \frac{{V_1}^2}{2} + g\,z_1 \right) \right\}$$

1.35 Steady-Flow Engineering Devices

- Some common steady-flow devices are described, and thethermodynamic aspects of the flow through them are analyzed. The conservationof mass and the conservation of energy principles for these devicesare illustrated with examples.

1.35.1 Nozzles and Diffusers

- Nozzles and diffusers are commonly utilized in jet engines, rockets, spacecraft,and even garden hoses.
- A nozzle is a device that increases the velocityof a fluid at the expense of pressure.
- A diffuser is a device that increasesthe pressure of a fluid by slowing it down.
- That is, nozzles and diffusersperform opposite tasks.



- The rate of heat transfer between the fluid flowing through a nozzle or a diffuser and the surroundings is usually very small ($\dot{Q}$< 0) since the fluid has high velocities, and thus it does not spend enough time in the device for any significant heat transfer to take place.
- Nozzles and diffusers typically involve no work ($\dot{W}$ = 0) and any change in potential energy is negligible (Δpe ≅ 0).
- as a fluid passes through a nozzle or diffuser, it experiences large changes in its velocity and hence the change in kinetic energy is not equal to zero (Δke≠0).

$$\dot{m}\left(h_1 + \frac{{V_1}^2}{2} + g\,z_1\right) = \dot{m}\left(h_2 + \frac{{V_2}^2}{2} + g\,z_2\right)$$

$$h_1 + \frac{{V_1}^2}{2} = h_2 + \frac{{V_2}^2}{2}$$

1.35.2 Turbines and Compressors

- In steam, gas, or hydroelectric power plants, the device that drives the electricgenerator is the **turbine**. As the fluid passes through the turbine, workis done against the blades, which are attached to the shaft. As a result, theshaft rotates, and the turbine produces work.
- **Compressors**, as well as pumps and fans, are devices used to increasethe pressure of a fluid. Work is supplied to these devices from an externalsource through a rotating shaft. Therefore, compressors involve workinputs.
- Even though these three devices function similarly, they do differ inthe tasks they perform.
- A **fan** increases the pressure of a gas slightly and ismainly used to mobilize a gas.
- A **compressor** is capable of compressing thegas to very high pressures.
- **Pumps** work very much like compressors exceptthat they handle liquids instead of gases.

- Note that turbines produce power output whereas compressors, pumps, and fans require power input. ($\dot{W} \neq 0$)
- Heat transfer from turbines is usually negligible ($\dot{Q} \cong 0$) since they are typically well insulated.
- Heat transfer is also negligible for compressors unless there is intentional cooling.
- Potential energy changes are negligible for all of these devices (Δpe $\cong$ 0).
- The velocities involved in these devices, with the exception of turbines and fans, are usually too low to cause any significant change in the kinetic energy (Δke $\cong$ 0).
- The fluid velocities encountered in most turbines are very high, and the fluid experiences a significant change in its kinetic energy. However, this change is usually very small relative to the change in enthalpy, and thus it is often disregarded.
- For a compressor, the energy balance equation becomes

$$\dot{W}_{in} + \dot{m}\left(h_1 + \frac{{V_1}^2}{2} + g\, z_1\right) = \dot{Q}_{out} + \dot{m}\left(h_2 + \frac{{V_2}^2}{2} + g\, z_2\right)$$

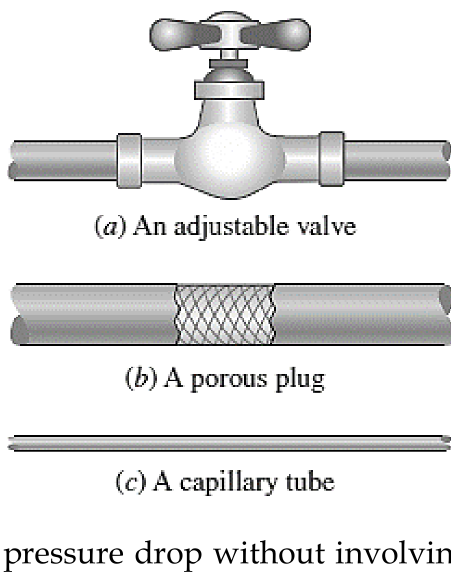
- For a turbine, the energy balance equation becomes

$$\dot{m}\left(h_1 + \frac{{V_1}^2}{2} + g\, z_1\right) = \dot{W}_{out} + \dot{Q}_{out} + \dot{m}\left(h_2 + \frac{{V_2}^2}{2} + g\, z_2\right)$$

$$\dot{m}\left(h_1 + \frac{{V_1}^2}{2} + g\, z_1\right) = \dot{W}_{out} + \dot{m}\left(h_2 + \frac{{V_2}^2}{2} + g\, z_2\right) \quad if\ \dot{Q} = 0$$

1.35.3 Throttling Valves

- Throttling valves are any kind of flow-restricting devices that cause a significant pressure drop in the fluid. Some familiar examples are ordinary adjustable valves, capillary tubes, and porous plugs.



(*a*) An adjustable valve

(*b*) A porous plug

(*c*) A capillary tube

- Unlike turbines, they produce a pressure drop without involving any work. The pressure drop in the fluid is often accompanied by a large drop in temperature, and for that reason throttling devices are commonly used in refrigeration and air-conditioning applications.
- Throttling valves are usually small devices, and the flow through them may be assumed to be adiabatic ($\dot{q} \cong 0$) since there is neither sufficient time nor large enough area for any effective heat

transfer to take place. Also, there is no work done ($\dot{w}$ = 0), and the change in potential energy, if any, is very small (Δpe ≅ 0).

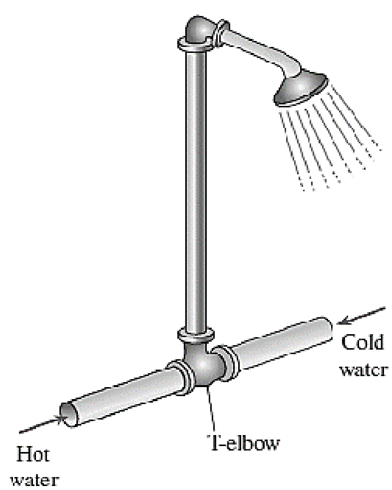
- Even though the exit velocity is often considerably higher than the inlet velocity, in many cases, the increase in kinetic energy is insignificant (Δke ≅ 0).
- Then the conservation of energy equation for this single-stream steady-flow device reduces to

$$h_1 = h_2$$

1.35.4 Mixing Chambers

- In engineering applications, mixing two streams of fluids is not a rare occurrence. The section where the mixing process takes place is commonly referred to as a mixing chamber. The mixing chamber does not have to be a distinct "chamber." An ordinary T-elbow or a Y-elbow in a shower, for example, serves as the mixing chamber for the cold- and hot-water streams (Fig. 5–35).
- The conservation of mass principle for a mixing chamber requires that the sum of the incoming mass flow rates equal the mass flow rate of the outgoing mixture.
- Mixing chambers are usually well insulated ($\dot{q}$ ≅ 0) and usually do not involve any kind of work ($\dot{w}$ = 0).
- Also, the kinetic and potential energies of the fluid streams are usually negligible (ke ≅ 0, pe ≅ 0).
- Then all there is left in the energy equation is the total energies of the incoming streams and the outgoing mixture.
- The conservation of energy principle requires that these two equals each other.
- Therefore, the conservation of energy equation becomes analogous to the conservation of mass equation for this case.

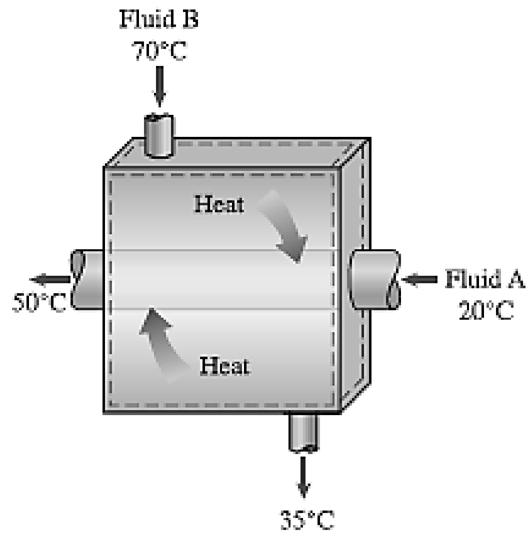
$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3$$



1.35.5 Heat Exchangers

- heat exchangers are devices where two moving fluidstreams exchange heat without mixing. Heat exchangers are widely used invarious industries, and they come in various designs.
- The simplest form of a heat exchanger is a double-tube (also calledtube-and-shell) heat exchanger.

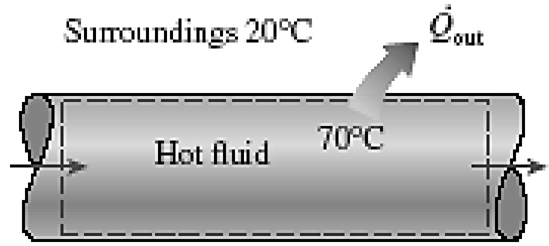
- The conservation of mass principle for a heat exchanger in steady operation requires that the sum of the inbound mass flow rates equal the sum of the outbound mass flow rates. This principle can also be expressed as follows:



- Under steady operation, the mass flow rate of each fluid stream flowingthrough a heat exchanger remains constant.
- Heat exchangers typically involve no work interactions ($\dot{w}$= 0) andnegligible kinetic and potential energy changes (Δke ≅ 0, Δpe ≅ 0) foreach fluid stream.

1.35.6 Pipe and Duct Flow

- The transport of liquids or gases in pipes and ducts is of great importance in many engineering applications. Flow through a pipe or a duct usually satisfies the steady-flow conditions and thus can be analyzed as a steady flow process.



PROBLEMS:

1. The internal energy of a certain substance is given by the following equation u= 3.56pv+84, where u is given in kJ/kg, p is in kPa, and v is in m^3/kg. A system composed of 3kg of this substance expands from an initial pressure of 500kPa and a volume of 0.22 m^3 to a final pressure 100kPa in a process in which pressure and volume are related by $pv^{1.2}$=constant.If the expansion is quasi-static, find Q, ΔU, and W for the process.

   Solution:

   According to the first law of thermodynamics, for a closed system undergoing a process

$$Q = \Delta U + W$$

   Where

$$\Delta U = U_2 - U_1 = 3.56(P_2V_2 - P_1V_1)$$

   We know that for a polytropic process with n = 1.2

$$\frac{P_1}{P_2} = \left(\frac{V_2}{V_1}\right)^n$$

   On solving

$$V_2 = 0.056\, m^3$$

   Therefore,

$$\Delta U = U_2 - U_1 = 3.56(100 \times 0.056 - 500 \times 0.22) = -371.66\, kJ$$

   The work done during a polytropic process is given as

$$W = \frac{P_1V_1 - P_2V_2}{n-1} = \frac{500 \times 0.22 - 100 \times 0.056}{1.2 - 1} = 522\, kJ$$

   Therefore,

$$Q = \Delta U + W$$
$$Q = -371.66 + 522 = 150.34\, kJ$$

2. A piston and cylinder machine contains a fluid system which passes through a complete cycle of four processes. During a cycle, the sum of all heat transfers is -170 kJ. The system completes 100 cycles per minute. Complete the following table showing the method for each item and compute the net rate of work output in kW.

Process	Q (kJ/min)	W (kJ/min)	ΔE (kJ/min)
a-b	0	2170	-------
b-c	21000	0	-------
c-d	-2100	-------	-36600
d-a	-------	-------	-------

   Solution:

   According to the first law of thermodynamics, for a closed system undergoing a process

$$Q = \Delta E + W$$

   Therefore, for process 1-2

$$Q_{1-2} = \Delta E_{1-2} + W_{1-2}$$
$$\Delta E_{1-2} = -2170\, kJ/min$$

   For process 2-3

$$Q_{2-3} = \Delta E_{2-3} + W_{2-3}$$
$$\Delta E_{2-3} = 21000\, kJ/min$$

For process, 3-4

$$Q_{3-4} = \Delta E_{3-4} + W_{3-4}$$
$$W_{3-4} = 35500\ kJ/min$$

We know that, according to first law of thermodynamics for a closed system undergoing a cyclic process,

$$\sum Q = \sum W = -170 \times 100 = -17000\ kJ/min$$

Therefore,

$$Q_{1-2} + Q_{2-3} + Q_{3-4} + Q_{4-1} = -17000$$
$$Q_{4-1} = -35900\ kJ/min$$

Also

$$W_{1-2} + W_{2-3} + W_{3-4} + W_{4-1} = -17000$$
$$W_{4-1} = -54670\ kJ/min$$

We also know that

$$\oint \Delta E = 0$$

Therefore,

$$\Delta E_{1-2} + \Delta E_{2-3} + \Delta E_{3-4} + \Delta E_{4-1} = 0$$
$$\Delta E_{4-1} = 17770\ kJ/min$$

The net work done during the cycle in Kw is

$$W = -\frac{17000}{60} = 283.33\ kW$$

3. A fluid is confined in a cylinder by a spring loaded frictionless piston. Show the pressure in the fluid is a linear function of the volume (p = a+bV). The internal energy of the fluid is given by the following equation U = 34 + 3.15pV where U is in kJ, p is in kPa and V in m^3. If the fluid changes from an initial state of 170 kPa, 0.03 m^3 to a final state of 4000 kPa, 0.06 m^3 with no work other than that done on the piston, find the direction and magnitude of the work and heat transfer.

Solution:

According to the first law of thermodynamics, for a closed system undergoing a process

$$Q = \Delta U + W$$

Where

$$\Delta U = U_2 - U_1 = 3.15(P_2V_2 - P_1V_1)$$
$$\Delta U = U_2 - U_1 = 3.15(4000 \times 0.06 - 170 \times 0.03) = 740\ kJ$$

The work done during this process is only PdV work, therefore

$$W = \int_1^2 PdV = \int_1^2 (a + bV)dV$$

On integrating the above equation, we get

$$W = a(V_2 - V_1) + b\left(\frac{{V_2}^2 - {V_1}^2}{2}\right)$$

To find the constants a & b

$$P = a + b\,V$$

For state 1

$$170 = a + 0.03\,b$$
$$4000 = a + 0.06\,b$$

On solving the above simultaneous equation, we get

$$a = -3660$$

$$b = 127666.67$$

On substituting a & b values in the integrated equation, we get

$$W = -3660\,(0.03) + 127666.67\left(\frac{0.06^2 - 0.03^2}{2}\right)$$

$$W = 62.55\ kJ$$

Therefore,

$$Q = 740 + 62.55 = 802.55\ kJ$$

4. A fluid undergoes a reversible adiabatic compression from 0.5 MPa, 0.2 m^3 to 0.05 m^3 according to the law, $PV^{1.3} = C$. Determine the change in enthalpy, internal energy, the heat transfer and work transfer during the process.Assume R= 0.287KJ/kg K and c_p = 1kJ/kg K, c_v = 0.72 kJ/kg K.

Solution:

To find the final pressure for the given process,

$$\frac{P_2}{P_1} = \left(\frac{V_2}{V_1}\right)^n$$

$$P_2 = 0.83\ MPa$$

To find work done,

$$W_{1-2} = \frac{P_1V_1 - P_2V_2}{n-1}$$

$$W_{1-2} = \frac{500 \times 0.2 - 830 \times 0.05}{1.3 - 1}$$

$$W_{1-2} = 195\ kJ$$

In order to find the other data's, we should find the initial and final temperature

we can use PVT relation

$$\frac{P_1}{P_2} = \left(\frac{T_2}{T_1}\right)^{n/n-1}$$

$$T_2 = \left(\frac{P_1}{P_2}\right)^{\frac{n-1}{n}} \times T_1$$

$$T_2 = \left(\frac{0.5}{0.83}\right)^{\frac{1.3-1}{1.3}} \times T_1$$

$$T_2 = 0.89\,T_1$$

We know that the heat transfer is given as

$$Q_{1-2} = W \times \left(\frac{\gamma - n}{\gamma - 1}\right) = 195 \times \frac{1.4 - 1.3}{1.4 - 1} = 48.75\ kJ$$

From the first law of thermodynamics for a process

$$Q_{1-2} = W_{1-2} + \Delta U_{1-2}$$

Therefore, the change internal energy

$$\Delta U_{1-2} = Q_{1-2} - W_{1-2} = 48.75 - 195 = -146.25\ kJ$$

We also know that

$$\Delta U_{1-2} = m\,c_v \Delta T$$

Therefore,

$$m\Delta T = \frac{146.25}{0.72} = 203.13\ kg.K$$

We know that, the change in enthalpy is given as

$$\Delta H_{1-2} = m\ c_p \Delta T = 1 \times 203.13 = 203.15\ kJ$$

5. A gas undergoes a thermodynamic cycle consisting of three processes beginning at an initial state where p_1= 1bar, V_1 = 1.5 m^3 and U_1 = 512 kJ. The processes are as follows:
    - Process 1-2: Compression with PV = constant to P_2= 2 bar, U_2 = 690 kJ
    - Process 2-3: W_{23} = 0, Q_{23} = -150 kJ
    - Process 3 -1: W_{31} = + 50 kJ. Neglecting KE and PE changes determine the heat interactions Q_{12} and Q_{31}.

Solution:

According to the first law of thermodynamics, for a closed system undergoing a process

$$Q = \Delta U + W$$

Therefore, for process 1-2

$$Q_{1-2} = \Delta U_{1-2} + W_{1-2}$$

Where

$$\Delta U_{1-2} = U_2 - U_1 = 690 - 512 = 178\ kJ$$

For a process with PV = constant,

$$P_1V_1 = P_2V_2$$

$$V_2 = \frac{P_1V_1}{P_2} = \frac{1 \times 1.5}{2} = 0.75\ m^3$$

the work done is given as

$$W_{1-2} = P_1V_1 \ln\left(\frac{V_2}{V_1}\right) = 1 \times 10^2 \times \ln\left(\frac{0.75}{1.5}\right) = -69.32\ kJ$$

Therefore,

$$Q_{1-2} = 178 - 69.32 = 108.68\ kJ$$

We know that for a cyclic process

$$\sum Q = \sum W$$

$$\sum W = W_{1-2} + W_{2-3} + W_{3-1} = -69.32 + 0 + 50 = -19.32\ kJ$$

$$\sum Q = Q_{1-2} + Q_{2-3} + Q_{3-1} = -19.32$$

$$Q_{3-1} = -19.32 - 108.68 + 150 = 22\ kJ$$

6. In a Gas turbine installation, the gases enter the turbine at the rate of 5 kg/sec with a velocity of 50 m/sec and enthalpy of 900 kJ/kg and leave the turbine with 150 m/sec and enthalpy of 400 kJ/kg. The loss of heat from the gases to the surroundings is 25 kJ/kg. Assume R= 0.285 kJ/kgK, c_p = 1.004 kJ/kg K and inlet conditions to be at 100 kPa and 27°C. Determine the work done and diameter of the inlet pipe.

Solution:

According to the first law of thermodynamics for an open system undergoing steady flow process, the steady flow energy equation is

$$E_{in} = E_{out}$$

$$\dot{m}\left(h_1 + \frac{{V_1}^2}{2} + gz_1\right) = \dot{m}\left(h_2 + \frac{{V_2}^2}{2} + gz_2\right) + \dot{Q} + \dot{W}$$

Neglecting P.E. changes and rearranging the equation, we get

$$\dot{W} = \dot{m}\left([h_1 - h_2] + \frac{\left({V_1}^2 - {V_2}^2\right)}{2}\right) - \dot{Q}$$

$$\dot{W} = 5\left([900 - 400] \times 10^3 + \frac{(50^2 - 150^2)}{2}\right) - 25 \times 10^3$$

$$\dot{W} = 465\ kW$$

According to the continuity equation, we have

$$\dot{m} = \frac{A_1 V_1}{v_1}$$

We know that according to equation of state

$$P_1 v_1 = RT_1$$

Therefore,

$$v_1 = \frac{RT_1}{P_1} = \frac{0.287 \times 300}{100} = 0.861\ m^3/kg$$

Hence,

$$A_1 = \frac{\dot{m} \times v_1}{V_1} = \frac{5 \times 0.861}{50} = 0.0861\ m^2$$

$$A_1 = \frac{\pi}{4}{d_1}^2 = 0.0861$$

$$d_1 = 0.331\ m$$

7. Air flows steadily at the rate of 0.5 Kg/s through an air compressor, entering at 7m/s velocity, 100Kpa pressure, and 0.95 m^3/kg volume, and leaving at 5m/s, 700Kpa, and 0.19 m^3/kg. the internal energy of the air leaving is 90 KJ/kg greater than that of air entering. Cooling water in the compressor jackets absorbs heat from the air at the rate of 58 KW. (a) compute the rate of shaft work input to the air in KW. (b) find the ratio of the inlet pipe diameter to outlet pipe diameter.

Solution:

According to the first law of thermodynamics for an open system undergoing steady flow process, the steady flow energy equation is

$$e_{in} = e_{out}$$

$$\dot{m}\left(h_1 + \frac{{V_1}^2}{2} + gz_1\right) + \dot{W} = \dot{m}\left(h_2 + \frac{{V_2}^2}{2} + gz_2\right) + \dot{Q}$$

We know that, h = u + Pv

$$\dot{m}\left([u_1 + P_1 v_1] + \frac{{V_1}^2}{2} + gz_1\right) + \dot{W} = \dot{m}\left([u_2 + P_2 v_2] + \frac{{V_2}^2}{2} + gz_2\right) + \dot{Q}$$

Neglecting P.E. changes and rearranging the equation, we get

$$\dot{W} = \dot{m}\left([(u_2 - u_1) + (P_2 v_2 - P_1 v_1)] + \frac{\left({V_2}^2 - {V_1}^2\right)}{2}\right) + \dot{Q}$$

$$\dot{W} = 0.5\left([(90) + (700 \times 0.19 - 100 \times 0.95)] \times 10^3 + \frac{(5^2 - 7^2)}{2}\right) + 58 \times 10^3$$

$$\dot{W} = 122\ kW$$

According to the continuity equation, we have

$$\frac{A_1V_1}{v_1} = \frac{A_2V_2}{v_2}$$

$$\frac{A_1}{A_2} = \frac{v_1V_2}{v_2V_1} = \frac{0.95 \times 5}{0.19 \times 7} = 3.571$$

$$\frac{\frac{\pi}{4}{d_1}^2}{\frac{\pi}{4}{d_2}^2} = 3.571$$

$$\frac{d_1}{d_2} = \sqrt{3.571} = 1.89$$

8. A nozzle is a device for increasing the velocity of the steadily flowing steam. At the inlet of the nozzle the enthalpy of the fluid passing is 3000KJ/kg and velocity is 60m/s at the discharge end the enthalpy is 2762 KJ/kg. The nozzle is horizontal and there is negligible heat loss from it. (a) Find the velocity at the exit of the nozzle. (b) If the inlet area is $0.1m^2$ and specific volume at the inlet is $0.187m^3/kg$. Find the mass flow rate. (c) If the specific volume at the nozzle exit is $0.498m^3/kg$, find the exit area of the nozzle.

Solution:

According to the first law of thermodynamics for an open system undergoing steady flow process, the steady flow energy equation is

$$E_{in} = E_{out}$$

$$\dot{m}\left(h_1 + \frac{{V_1}^2}{2} + gz_1\right) = \dot{m}\left(h_2 + \frac{{V_2}^2}{2} + gz_2\right) + \dot{Q} + \dot{W}$$

Neglecting K.E &P.E. changes and rearranging the equation, we get

$$h_1 + \frac{{V_1}^2}{2} = h_2 + \frac{{V_2}^2}{2}$$

$$3000 \times 10^3 + \frac{60^2}{2} = 2762 \times 10^3 + \frac{{V_2}^2}{2}$$

On solving

$$V_2 = 692.53\ m/s$$

Mass flow rate,

$$\dot{m} = \frac{A_1V_1}{v_1} = \frac{0.1 \times 60}{0.187} = 32.09\ kg/s$$

Exit area of the nozzle

$$A_2 = \frac{\dot{m} \times v_2}{V_2} = \frac{32.09 \times 0.498}{692.53} = 0.023\ m^2$$

9. A turbine operates under steady flow conditions, receiving steam at the flowing state: pressure 1.2 MPa, temperature 188°C, enthalpy 2785 KJ/kg, velocity 33.3 m/s and elevation 3 m. the steam leaves the turbine at the flowing state: pressure 20 kPa, enthalpy 2512 KJ/kg, velocity 100m/s andelevation 0 m. heat is lost to the surroundings at the rate of 0.29 KJ/s. if the rate of steam flow through the turbine is 0.42 kg/s, what is the power output of the turbine in KW.

Solution:
According to the first law of thermodynamics for an open system undergoing steady flow process, the steady flow energy equation is

$$E_{in} = E_{out}$$

$$\dot{m}\left(h_1 + \frac{{V_1}^2}{2} + gz_1\right) = \dot{m}\left(h_2 + \frac{{V_2}^2}{2} + gz_2\right) + \dot{Q} + \dot{W}$$

Neglecting P.E. changes and rearranging the equation, we get

$$\dot{W} = \dot{m}\left([h_1 - h_2] + \frac{\left({V_1}^2 - {V_2}^2\right)}{2} + g(z_1 - z_2)\right) - \dot{Q}$$

$$\dot{W} = 0.42\left([2785 - 2512] \times 10^3 + \frac{(33.3^2 - 100^2)}{2} + g(3 - 0\,)\right) - 0.29 \times 10^3$$

$$\dot{W} = 112.52\ kW$$

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POSSIBLE QUESTIONS

UNIT II AIR CYCLES

PART - A

1. **What is meant by mean effective pressure (MEP)?**
   Mean effective pressure is defined as the constant pressure acting on the piston during the working stroking. It is also defined as the ratio of work done to the stroke volume or piston displacement volume.

2. **What is an air standard efficiency?**
   Air standard efficiency is defined as the ratio of work done by the cycle to heat supplied to the cycle.

3. **Define a) compression ratio b) cut off ratio**
   Compression ratio is defined as the ratio between total cylinder volumes to clearance volume.
   Cut off ratio is defined as the ratio of volume after the heat addition to volume before the heat addition.

4. **For a given compression ratio the Otto cycle is more efficient than the Diesel cycle. Justify?**
   The Otto air standard cycle is more efficient because the area under the PV diagram is larger. This is due to the heat addition being done at constant volume (analogous to the piston being at TDC compression), while the diesel heat addition is at constant pressure, being analogous to the heat being added while the piston is moving down in the expansion stroke. So some of the potential heat energy of the fuel is not fully utilized in the expansion stroke on a diesel.

5. **Mention the ranges of compression ratios for SI and CI engines.**
   For petrol of SI engine 6 to 8
   For diesel of CI engine 12 to 18

6. **What is relative efficiency?**
   It is also known as efficiency ratio. The relative efficiency of an I. C. engine is the ratio of the indicated thermal efficiency to the air standard efficiency.

7. **Draw the p-V and T-s diagrams for dual cycle and name the processes.**
   (i) Isentropic compression.
   (ii) Constant volume heat supplied
   (iii) Constant pressure heat supplied.
   (iv) Isentropic expansion, and
   (v) Constant volume heat rejection.

8. **What is meant by valve overlapping period?**
   Overlap period is the period in crank angle degrees during which both inlet and exhaust valves are open to assist in clearing the products of combustion from the cylinder.

9. **What is a carburetor? State any two functions of carburetor**.
   To atomize the fuel and mix it homogeneously with the air.

To run the engine smoothly without hunting of fuel wastage.
To provide rich mixture during starting and idling and also for quick acceleration.
To provide a constant air fuel ratio at various loads.
To start the engine even in cold weather conditions.

10. What is meant by lean and rich mixture?

Ratios lower than stoichiometric are considered "rich". Rich mixtures are less efficient, but may produce more power and burn cooler, which is kinder on the engine. Ratios higher than stoichiometric are considered "lean." Lean mixtures are more efficient but may cause engine damage or premature wear and produce higher levels of nitrogen oxides.

11. Why the two stroke engines are not widely used in two wheelers?

2 stroke engines are rarely used because in this engine the problem of scavenging occurs.Scavenging is termed as incomplete combustion of fuel and air mixture i.e. some of the fuel doesn't gets burnt out, it goes into the exhaust without getting in combustion. So,the fuel required to burn the air is also more, this reduces the fuel efficiency. Also 2 stroke engines produces black smoke which in term increases the pollution which is very harmful for the environment.

PART – B

1. The minimum pressure and temperature in an Otto cycle are 100 kPa and 27^{O}C. The amount of heat added to the air per cycle is 1500 kJ/kg. i) Determine the pressures and temperatures at all points of the air standard Otto cycle, ii) Also calculate the specific work and thermal efficiency of the cycle for a compression ratio of 8:1. Take for air, C_V = 0.72 kJ/kgK and γ = 1.4 **(Refer Class Notes)**

2. An engine working on Otto cycle has a volume of 0.45m^3, pressure 1 bar and temperature 30^{O}C at the beginning of compression stroke. At the end of compression stroke, the pressure is 11 bar. 210 kJ of heat is added at constant volume. Determine: i) pressures, temperatures and volumes at salient points in the cycle, ii) efficiency, iii) mean effective pressure. **(Refer Class Notes)**

3. An engine with 200mm cylinder diameter and 300mm stroke works on theoretical diesel cycle. The initial pressure and temperature of air used are 1 bar and 27^{O}C. The cut off is 8% of the stroke. Determine i) pressures and temperatures at all salient points, ii) theoretical air standard efficiency, iii) mean effective pressure. Assume that compression ratio is 15 and working fluid is air. **(Refer Class Notes)**

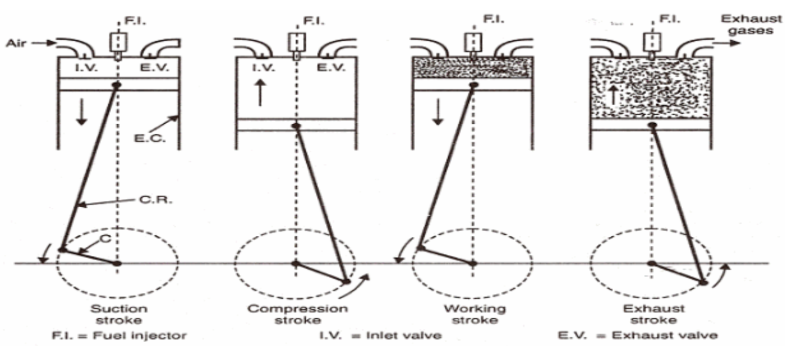
4. In an engine working on a dual cycle, the temperature and pressure at the beginning of the cycle are 90^{O}C and 1 bar. The compression ratio is 9. The maximum pressure is limited to 68 bar and total heat supplied per kg of air is 1750 kJ. Determine the air standard efficiency and mean effective pressure. **(Refer Class Notes)**

5. Consider an air standard cycle in which the air enters the compressor at 1 bar and 25^{O}C. The pressure of air leaving the compressor is 3 bar and temperature at turbine inlet is 650^{O}C. Determine per kg of air: i) cycle efficiency, ii) heat supplied to air, iii) work output, iv) heat rejected in the cooler, v) temperature of air leaving the turbine. **(Refer Class Notes)**

6. Discuss the construction and working principle of a four stroke engine with neat sketch.

A four-stroke engine:

- Is an internal combustion engine
- Converts gasoline into motion
- Is the most common car engine type
- Is relatively efficient
- Is relatively inexpensive



Basic Components of Four-Stroke

Engines:

Intake Valve- opens at the proper time to let in air and fuel

Valve Cover- Protects the valves and the valve springs. Keeps dirt out and lubricating oil in.

Intake Port- the passageway in a cylinder head for the fuel and air to pass through.

Head- a platform containing most of the parts of the combustion chamber.

Coolant- circulating water and antifreeze to keep the temperature regulated.

Engine Block- cast in one piece. The basis for most of the parts of the engine.

Oil Pan- where the oil is collected and recirculated.

Oil Sump- the collected oil primarily for lubricating the crankshaft and rod bearing

Camshaft- a round shaft with lobes, that rotates to open and close the fuel and exhaust valves.

Exhaust Valve- open at the proper time to release the exhaust

Spark Plug- a device, inserted into the combustion chamber for firing an electrical spark to ignite air-fuel mixture

Exhaust Port- the passageway in a cylinder head, for the exhaust to pass through

Piston- the part of the engine that moves up and down in the cylinder converting the gasoline into motion

Connecting Rod- links the piston to the crankshaft

Rod Bearing- used to reduce friction to the rod and crankshaft

Crankshaft- converts the up and down motion of the piston into a turning, or rotating motion

Working:

- Intake- process of filling the cylinder with the proper air-fuel mixture through the intake valve.
- Compression- the process of compressing the air-fuel mixture in the cylinder to make it more combustible
- Combustion-the process of igniting the compressed air-fuel mixture to create motion and the over all power of the engine.
- Exhaust- the process of releasing the exhaust out of the cylinder through the exhaust valve.

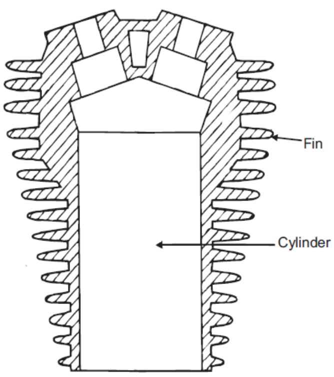
7. a) Explain the method of air cooling of IC engine.

Air Cooled System

Air cooled system is generally used in small engines say up to 15-20 Kw and in aero plane engines. In this system fins or extended surfaces are provided on the cylinder walls, cylinder head, etc. Heat generated due to combustion in the engine cylinder will be conducted to the fins and when the air flows over the fins, heat will be dissipated to air.

The amount of heat dissipated to air depends upon :

(a) Amount of air flowing through the fins.
(b) Fin surface area.
(c) Thermal conductivity of metal used for fins.



Advantages of Air Cooled System

(a) Radiator/pump is absent hence the system is light.

(b) In case of water cooling system there are leakages, but in this case there are no leakages.

c) Coolant and antifreeze solutions are not required.

(d) This system can be used in cold climates, where if water is used it may freeze.

Disadvantages of Air Cooled System

(a) Comparatively it is less efficient.

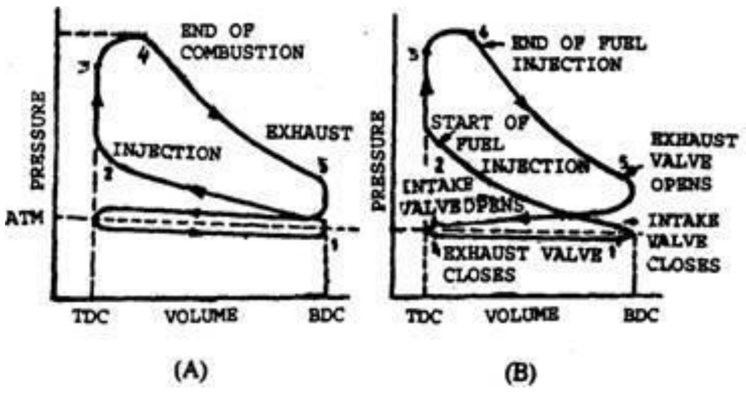
(b) It is used only in aero planes and motorcycle engines where the engines are exposed to air directly

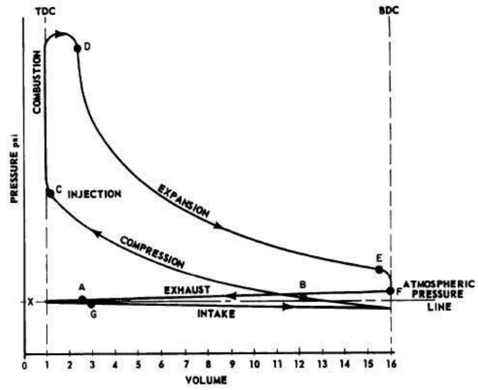
7. b) Compare between petrol engine and diesel engine.

SI. No.	Petrol Engine	Diesel Engine
1	The exhaust is less noisy.	The exhaust is noisy due to short time available for exhaust.
2	Intake (Petrol) and air is admitted into the cylinder during suction stroke.	Air alone is admitted into the cylinder during suction stroke.
3	Fuel Ignition: - By spark plug -Spark Ignition (SI) engine.	By the compressed hot air Compression Ignition (CI) Engine.
4	Cycle of operation: - Otto cycle (constant volume cycle)	Diesel Cycle.
5	Compression Ratio Low (7 to 8).	High (16 to 17).
6	Fuel admission Through carburetor.	Through fuel injector.
7	Engine speed: - high speed; can run up to 5000 rpm since petrol ' engine is lighter.	Low speed; about up to 3500 rpm
8	Weight:- Because of low compression ratio, the engine cylinder undergoes less pressure. It weights about 0.5 to 3 kg per KW (kilo watt) of power produced.	Higher compression ratio in diesel engines result in higher pressure, therefore diesel engines are sturdier and heavier. Diesel engine weights about 2 to 10 kg per KW of power produced
9	Lubricating Property: - Petrol does not have lubricating properties	Diesel has lubricating properties.
10	Engine starting in cold condition is easy	Greater cranking effort is required to overcome the higher compression ratio, due to the cold air in the combustion chamber.
11	Fire hazard: - Petrol is highly volatile and there is a greater risk of fire.	Diesel 'is less volatile and has a reduced risk of fire.
12	Engine cost: - Less costly since the fuel systems used are not expensive.	More costly since the fuel injection system used are expensive.
13	Fuel Consumption: - more	Less
14	Fuel cost: - More	Less
15	Maintenance cost: - Less skill is required. Spark plugs are not expensive.	More skill is required for repair of injection equipment. Fuel injectors are very expansive.
16	Space:- For the same power output, Petrol engine occupies lesser space.	For the same output, more space is required for diesel engine.
17	Engine life: - Less than 60000 KM	More than 1,50,000 km
18	Vibration and noise: - Very less	More due to high operation pressure (compression ratio).

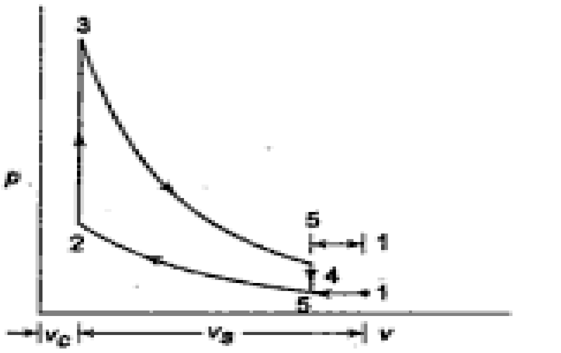
8. Explain actual and theoretical p-V diagrams of two stroke engine and four stroke engine.

Actual PV diagram of four stroke engine **Theoretical PV diagram for four stroke engine**

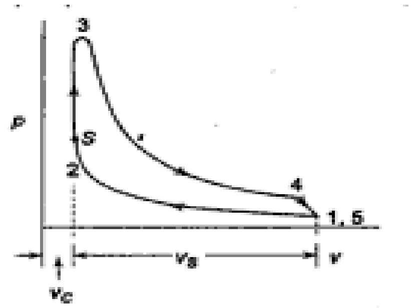




Theoretical and Actual PV diagram of two stroke Petrol Engine:



Theoretical p-v diagram for two-stroke



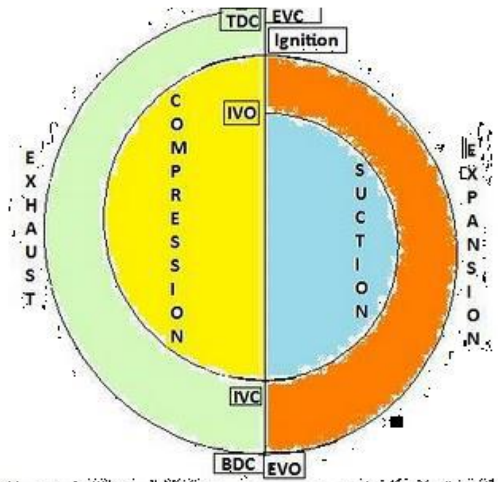
Actual p-v diagram for a two stroke petrol engine

9. With the help of suitable sketch, briefly explain the valve timing and port timing diagrams.

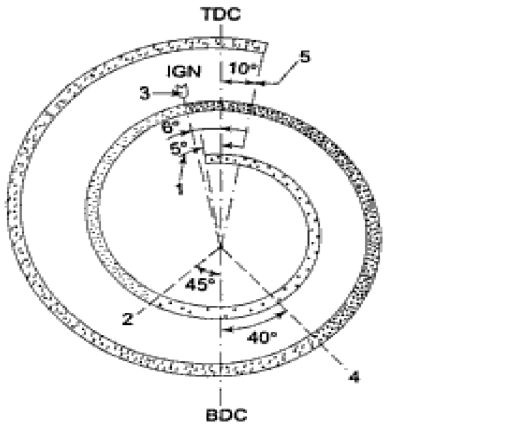
Theoretical valve timing diagram of four stroke engine:

Actual valve timing diagram of four stroke engine:

1
1
1
1
1
1
1
1
1
1
2
2
2
2
2
2
2

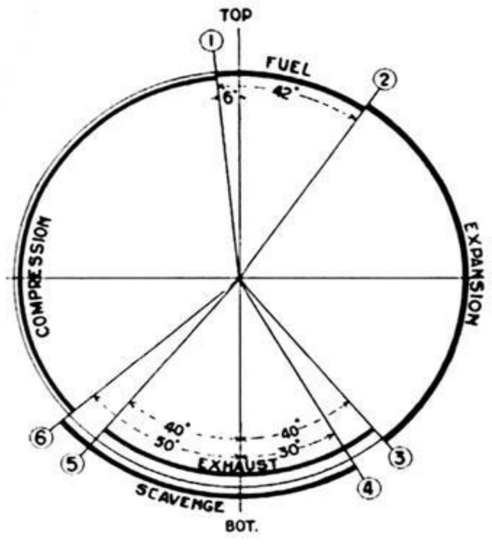


Valve Timing Diagram-4stroke engine/otto cycle (Theoretical)



Valve timing 1. Inlet valve open at 5° before TDC; 2. Inlet valve closed at 45° after BDC; 3. Ignition at 6° before TDC; 4. Exhaust valve open at 40° before BDC; 5. Exhaust valve closed at 10° after TDC

Port timing diagram of two stroke engine:


TOP
1
FUEL
6°
42°
2
COMPRESSION
EXPANSION
6
5
40°
30°
40°
30°
3
4
EXHAUST
SCAVENGE
BOT.

UNIT III THERMODYNAMICS OF ONE DIMENSIONAL FLUID FLOW

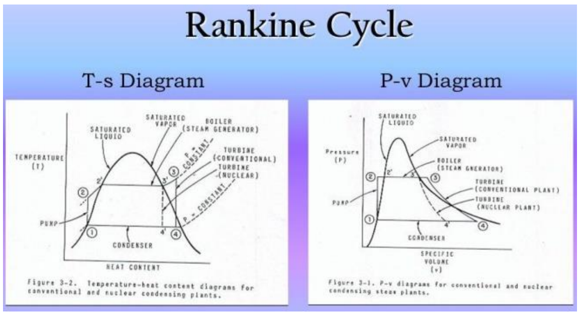
1. Define a boiler.

A boiler is a closed vessel in which water or other fluid is heated.

2. What is Rankine cycle?

The Rankine cycle is an idealized thermodynamic cycle of a heat engine that converts heat into mechanical work while undergoing phase change.

3. Draw the Rankine cycle on p-V and T-s diagram.



4. State the uses of steam produced by the boilers.

Steam is mainly used for food cooking, printing and dyeing industry, the pharmaceutical industry, the ironing of clothing, road maintenance, but also supply production steam to medical institutions supply disinfection steam, for other enterprises, hotels Heat the water supply through the tank.

5. How are boilers classified?

a) Horizontal, Vertical or Inclined Boiler
b) Fire Tube and Water Tube
c) Externally Fired and Internally Fired
d) Forced circulation and Natural Circulation
e) Higher Pressure and Low Pressure Boilers
f) Stationary and Portable
g) Single Tube and Multi Tube Boiler

6. List the methods of increasing the thermal efficiency of a Rankine cycle.

a) Lowering the condenser pressure and temperature of heat rejection
b) Superheating the steam to high temperature
c) Increasing the boiler pressure

7. State the advantages of reheat cycle.

The advantage claimed by the reheat cycle are higher thermal efficiency, reduced feed water pump power, smaller condenser, smaller boiler, long life of the turbine and less handling of the fuel and firing requirement.

8. State the various accessories used in a boiler.

a) Air Preheater, b) Economizer, c) Super heater, d) Feed Pump, e) Injector

9. Define equivalent evaporation.

The rate at which water would be vaporized in a given steam boiler if supplied and evaporated at the normal boiling point and normal atmospheric pressure is termed as equivalent evaporation

10. How do you determine the dryness fraction of steam? Why it is needed?

The dryness fraction of steam is determined by using Separating calorimeter, throttling calorimeter.

The use of dryness fraction allows us to know both the mass of dry steam and mass of water vapour.

11. What is the function of boiler mountings?

These are the fittings, which are mounted or installed on the boiler for its appropriate and safe working.

12. Define dryness fraction.

It is defined as the ratio of mass of the dry steam to the mass of the total steam.

PART – B

UNIT-2

1. **i) Compare between fire-tube and water-tube boilers**.

Comparison between Fire-tube & water-tube boilers

S no.	Particulars	Fire tube boilers	Water tube boilers
1.	Mode of firing	Internally fired	Externally fired
2.	Rate of steam production	lower	Higher
3.	construction	Difficult	Simple
4.	transportation	Difficult	Simple
5.	Treatment of water	Not so necessary	More necessary
6.	Operating pressure	Limited to 16 bar	Under high pressure as 100 bar
7.	Floor area	More floor area	Less floor area
8.	Shell diameter	Large for same power	Small same power
9.	explosion	Less	More
10.	Risk of bursting	lesser	More risk

ii) What are the methods for improving the performance of Rankine cycle?

Increasing the Efficiency of Rankine Cycle

- We know that the efficiency is proportional to: $1-T_L/T_H$
- 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.

Different methods

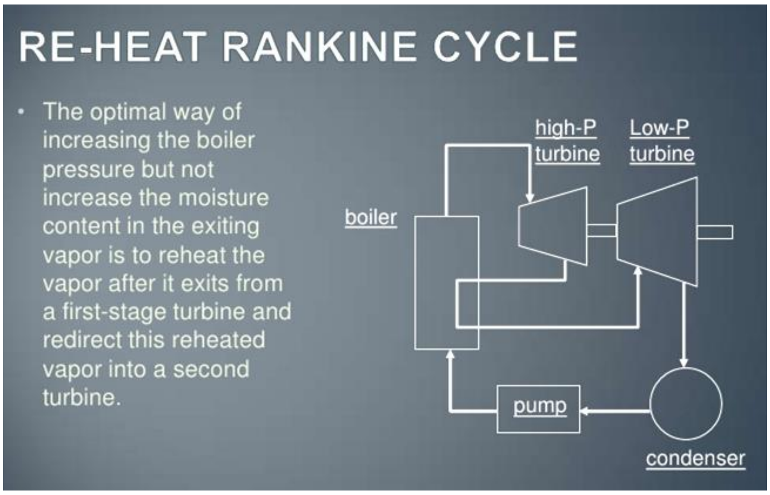
Decreasing the of Condenser Pressure (Lower TL)

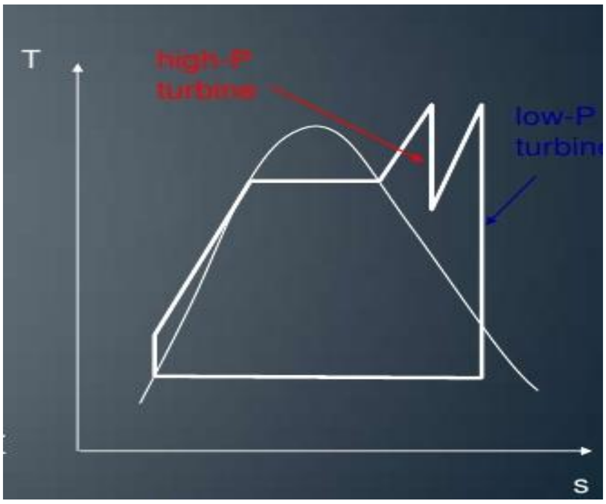
Superheating the Steam to High Temperatures (Increase TH)

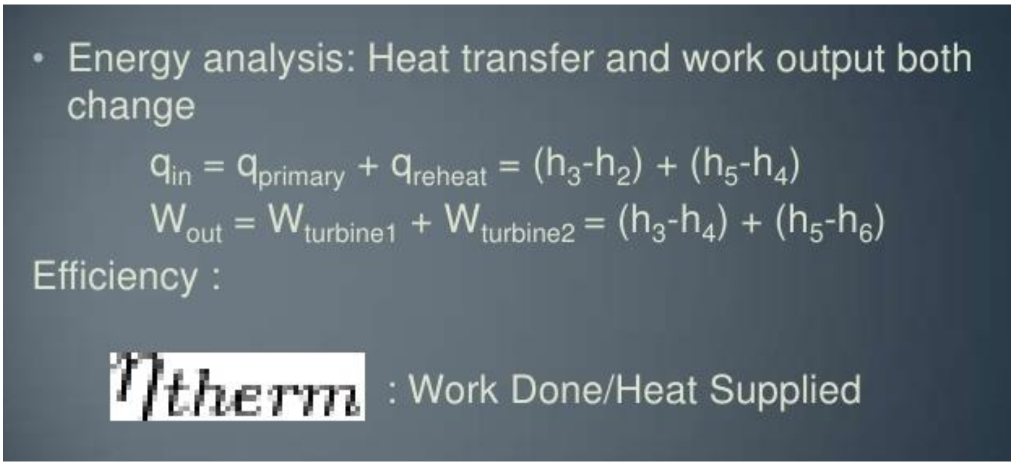
Increasing the Boiler Pressure (Increase TH)

2. In a Rankine cycle, the steam at inlet to turbine is saturated at a pressure of 35 bar and the exhaust pressure is 0.2 bar. Determine: i) the pump work, ii) the turbine work, iii) the Rankine efficiency, iv) the condenser heat flow, v) the dryness at the end of expansion. Assume flow rate of 9.5 kg/s. **(Refer Class Notes)**
3. In a boiler test 1250 kg of coal are consumed in 24 hours. The mass of water evaporated is 13000 kg and the mean effective pressure is 7 bar. The feed water temperature was $40^{O}C$, heating value of coal is 30000 kJ/kg. The enthalpy of 1 kg of steam at 7 bar is 2570.7 kJ. Determine:
    i. Equivalent evaporation per kg of coal
    ii. Efficiency of the boiler **(Refer Class Notes)**

4. **Explain the process of reheating with the help of T-s diagram in the Rankine cycle.**







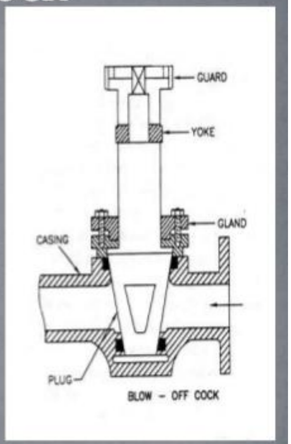
One of the ways to reduce the wetness of exhaust steam at the turbine exit is to superheat the steam in the boiler. Superheating leads to an increase in the thermal efficiency of the cycle realized, and at the same time, on the T-s diagram it shifts the point corresponding to the conditions of exhaust steam to the right, into the region of greater dryness fractions.

5. **With the neat sketch, explain any three boiler mountings in detail.**

Blow-Off Cock

Function:

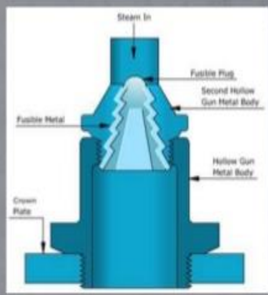
The function of blow-off cock is to discharge mud and other sediments deposited in the bottom most part of the water space in the boiler, while boiler is in operation. It can also be used to drain-off boiler water. Hence it is mounted at the lowest part of the boiler. When it is open, water under the pressure rushes out, thus carrying sediments and mud.



Fusible plug

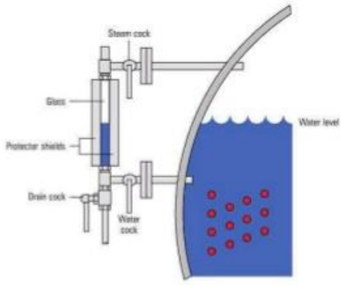
- Function :

It is use to protect the boil against damage due to overheating caused by low water level in the boiler.



Water level Indicator

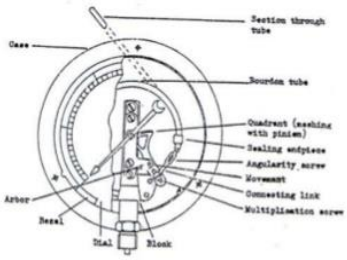
Water level indicator is located in front of boiler in such a position that the level of water can easily be seen by attendant. Two water level indicators are used on all boilers.



Pressure Gauge

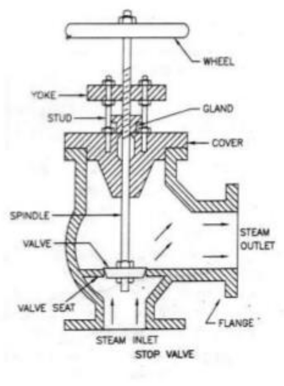
A pressure gauge is fitted in front of boiler in such a position that the operator can conveniently read it. It reads the pressure of steam in the boiler and is connected to steam space by a siphon tube.

The most commonly, the Bourdon pressure gauge is used.



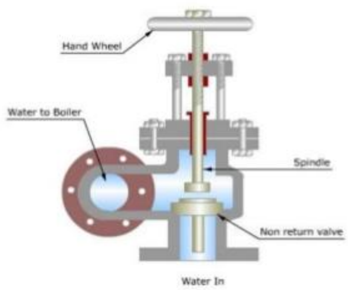
Steam Stop Valve

The steam stop valve is located on the highest part of the steam space. It regulates the steam supply to use. The steam stop valve can be operated manually or automatically.



Feed Check Valve

The feed check valve is fitted to the boiler, slightly below the working level in the boiler. It is used to supply high pressure feed water to boiler. It also prevents the returning of feed water from the boiler if feed pump fails to work.

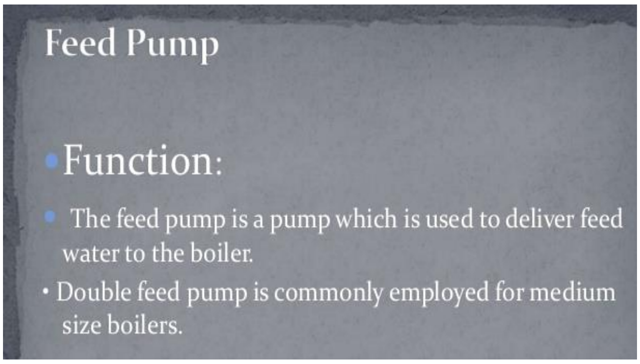


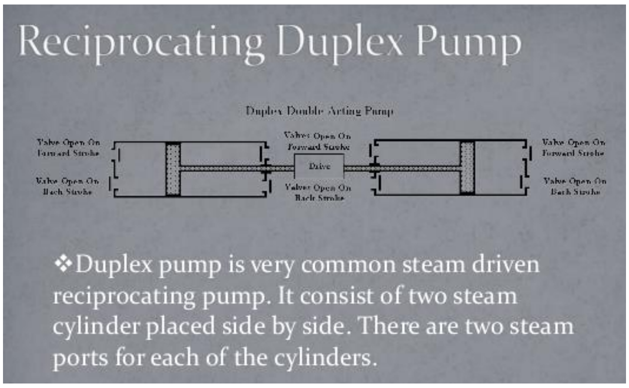
6. A steam power plant operates on a theoretical reheat cycle. Steam at boiler at 150 bar, 550^{O}C expands through the high pressure turbine. It is reheated at a constant pressure of 40 bar to 550^{O}C and expands through the low

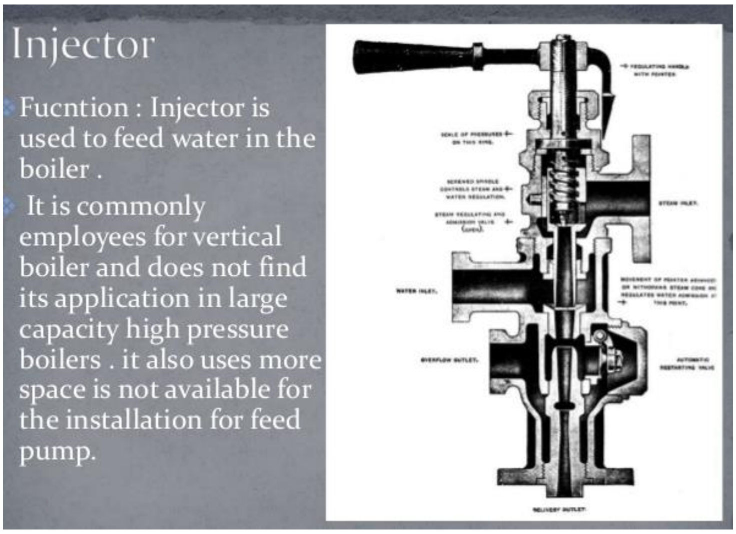
pressure turbine to a condenser at 0.1 bar. Draw T-s and h-s diagrams. Find: i) quality of steam at turbine exhaust, ii) cycle efficiency, iii) steam rate in kg/kW hr. **(Refer Class Notes)**

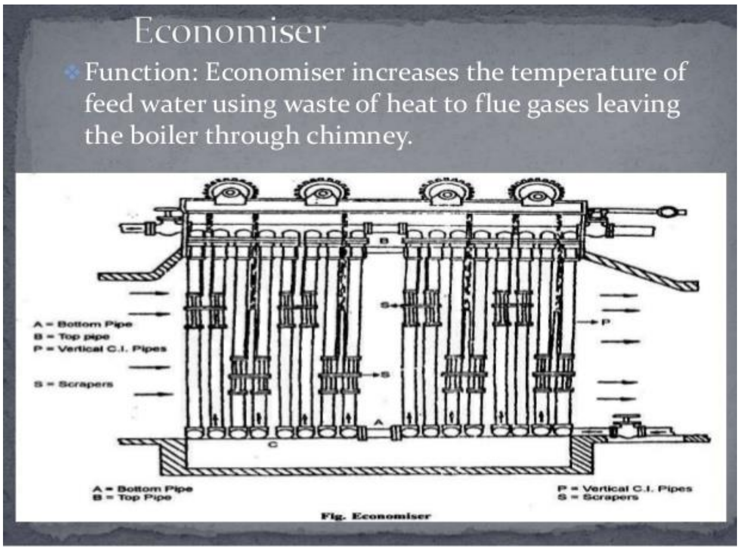
7. A steam generator evaporates 18000 kg/hr of steam at 12.5 bar and a quality of 0.97 from feed water at 105^{O}C, when coal is fired at the rate of 2040 kg/h. If the higher calorific value of the coal is 27400 kJ/kg, find:
   i. The heat rate of boiler in kJ/hr
   ii. The equivalent evaporation
   iii. The thermal efficiency **(Refer Class Notes)**

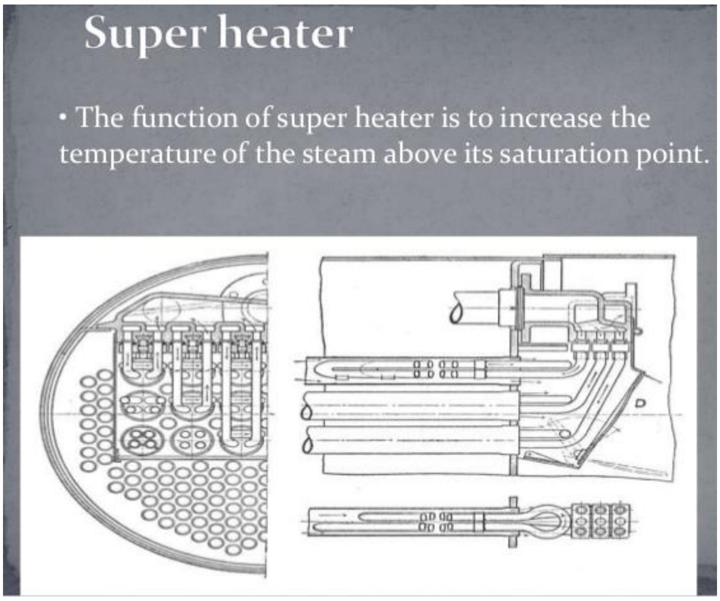
8. **With the neat sketch, explain any three boiler accessories in detail.**

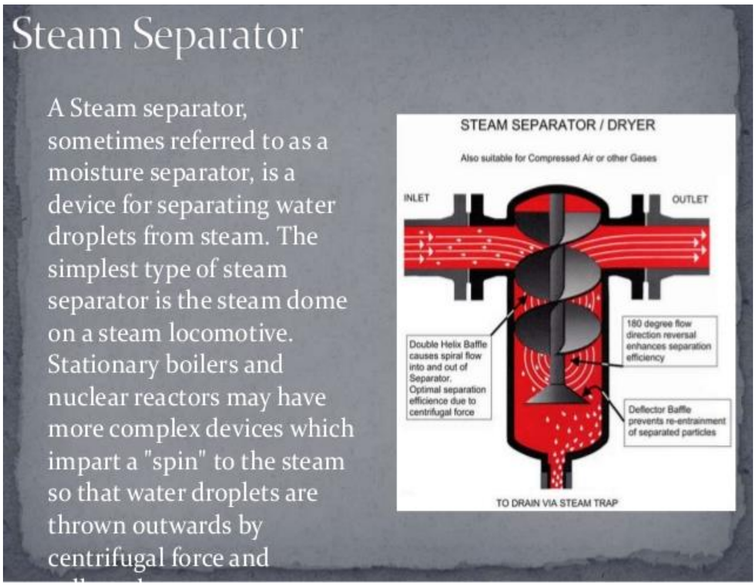








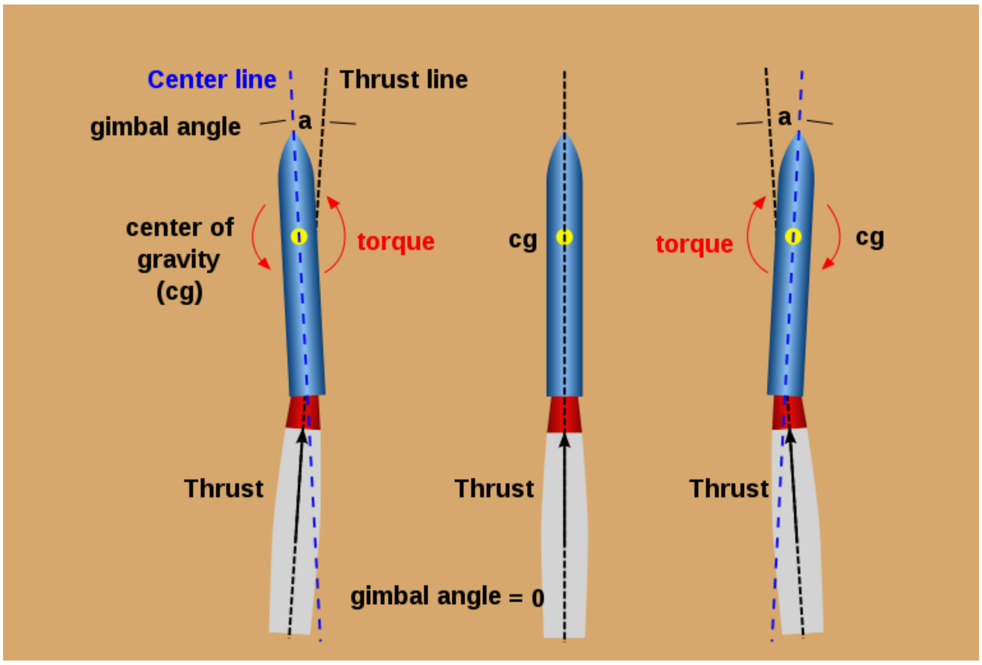




Thrust Vector Control :

Thrust vector control is effective only while the propulsion system is creating thrust. At other stages of flight, separate mechanisms are required for attitude and flight path control. Nominally, the line of action of the thrust vector of a rocket nozzle passes through the vehicle's center of mass, generating zero net moment about the mass center. It is possible to generate pitch and yaw moments by deflecting the main rocket thrust vector so that it does not pass through the mass center. Because the line of action is generally oriented nearly parallel to the roll axis, roll control usually requires the use of two or more separately hinged nozzles or a separate system altogether, such as fins, or vanes in the exhaust plume of the rocket engine, deflecting the main thrust. Thrust vectoring for many liquid rockets is achieved by gimballing the rocket engine. This often involves moving the entire combustion chamber and outer engine bell as on the Titan II's twin first stage motors, or even the entire engine assembly including the related fuel and oxidizer pumps. Such a system was used on the Saturn V and the Space Shuttle.

Another method of thrust vectoring used on early solid propellant ballistic missiles was liquid injection, in which the rocket nozzle is fixed, but a fluid is introduced into the exhaust flow from injectors mounted around the aft end of the missile. If the liquid is injected on only one side of the missile, it modifies that side of the exhaust plume, resulting in different thrust on that side and an asymmetric net force on the missile. This was the control system used on the Minuteman II and the early SLBMs of the United States Navy. A later method developed for solid propellant ballistic missiles achieves thrust vectoring by deflecting the rocket nozzle using electric servo mechanisms or hydraulic cylinders. The nozzle is attached to the missile via a ball joint with a hole in the center, or a flexible seal made of a thermally resistant material, the latter generally requiring more torque and a higher power actuation system. The Trident C4 and D5 systems are controlled via hydraulically actuated nozzle.



Specific impulse.

Specific impulse is the change in momentum per unit mass for rocket fuels, or rather how much more push accumulates as you use that fuel. The speed of a rocket depends on thrust (which is roughly the amount of propellant that is thrown out of the back of the rocket and the speed at which that propellant is thrown out) compared to the rocket's weight.

The faster the speed at which propellant is thrown out the back of the rocket, the faster the rocket can travel or the more cargo it can carry. The specific impulse of a rocket propellant is a rough measure of how fast the propellant is ejected out of the back of the rocket. A rocket with a high specific impulse doesn't need as much fuel as a rocket with low specific impulse. The higher the specific impulse, the more push you get for the fuel that rushes out. Or, put another way, specific impulse determines how much fuel you have to use to get a good-sized push.

UNIT IV

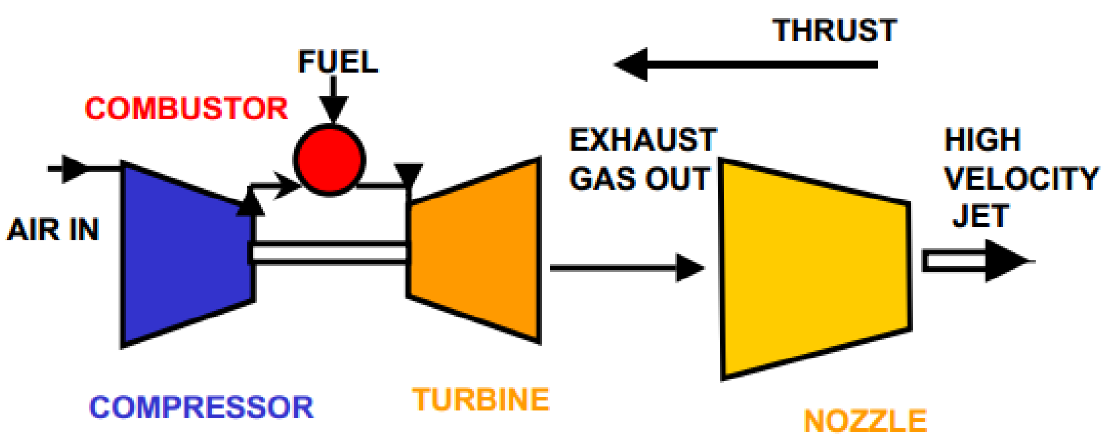
BASIC OF PROPULSION AND HEAT TRANSFER

GAS TURBINE ENGINE

A gas turbine, also called a combustion turbine, is a type of internal combustion engine. It has an upstream rotating compressor coupled to a downstream turbine, and a combustion chamber in between.

The basic operation of the gas turbine is similar to that of the steam power plant except that air is used instead of water. Fresh atmospheric air flows through a compressor that brings it to higher pressure. Energy is then added by spraying fuel into the air and igniting it so the combustion generates a high-temperature flow. This high-temperature high-pressure gas enters a turbine, where it expands down to the exhaust pressure, producing a shaft work output in the process.

The turbine shaft work is used to drive the compressor and other devices such as an electric generator that may be coupled to the shaft. The energy that is not used for shaft work comes out in the exhaust gases, so these have either a high temperature or a high velocity. The purpose of the gas turbine determines the design so that the most desirable energy form is maximized. Gas turbines are used to power aircraft, trains, ships, electrical, or even tanks.



Working

In an ideal gas turbine, gases undergo three thermodynamic processes:

An isentropic compression, an isobaric (constant pressure) combustion and an isentropic expansion. Together, these make up the Brayton cycle.

In a practical gas turbine, mechanical energy is irreversibly transformed into heat when gases are compressed (in either a centrifugal or axial compressor), due to internal friction and turbulence. Passage through the combustion chamber, where heat is added and the specific volume of the gases increases is accompanied by a slight loss in pressure. During expansion amidst the stator and rotor blades of the turbine, irreversible energy transformation once again occurs.

If the device has been designed to power a shaft as with an industrial generator or a turboprop, the exit pressure will be as close to the entry pressure as possible. In practice it is necessary that some pressure remains at the outlet in order to fully expel the exhaust gases. In the case of a jet engine only enough pressure and energy is extracted from the flow to drive the compressor and other components. The remaining high pressure gases are accelerated to provide a jet that can, for example, be used to propel an aircraft.

As with all cyclic heat engines, higher combustion temperatures can allow for greater efficiencies. However, temperatures are limited by ability of the steel, nickel, ceramic, or other materials that make up the engine to withstand high temperatures and stresses. To combat this many turbines feature complex blade cooling systems.

As a general rule, the smaller the engine, the higher the rotation rate of the shaft(s) must be to maintain tip speed. Blade-tip speed determines the maximum pressure ratios that can be obtained by the turbine and the compressor. This, in turn, limits the maximum power and efficiency that can be obtained by the engine. In order for tip speed to remain constant, if the diameter of a rotor is reduced by half, the rotational speed must double. For example, large jet engines operate around 10,000 rpm, while micro turbines spin as fast as 500,000 rpm.

Mechanically, gas turbines can be considerably less complex than internal combustion piston engines. Simple turbines might have one moving part: the shaft/compressor/turbine/alternative-rotor assembly (see image above), not counting the fuel system. However, the required precision manufacturings for components and temperature resistant alloys necessary for high efficiency often make the construction of a simple turbine more complicated than piston engines.

More sophisticated turbines (such as those found in modern jet engines) may have multiple shafts (spools), hundreds of turbine blades, movable stator blades, and a vast system of complex piping, combustors and heat exchangers.

Thrust bearings and journal bearings are a critical part of design. Traditionally, they have been hydrodynamic oil bearings, or oil-cooled ball bearings. These bearings are being surpassed by foil bearings, which have been successfully used in micro turbines and auxiliary power units.

THRUST

Thrust is the force which moves an aircraft through the air. Thrust is generated by the propulsion system of the airplane.

Thrust is a mechanical force which is generated through the reaction of accelerating a mass of gas, as explained by Newton's third law of motion. A gas or working fluid is accelerated to the rear and the engine and aircraft are accelerated in the opposite direction. To accelerate the gas, we need some kind of propulsion system.

THRUST EQUATION:

$$m_j c_j - m_i c_i = F + (p_i - p_a) Ai - (p_j - p_a) A_j$$

Mass balance;

$$m_j = m_i + m_f$$

Fuel air ratio;

$$m_j = m_i (1+f)$$

$$\text{Thrust } (F) = m_i (1+f) c_j - c_i + (p_j - p_a) A_j - (p_i - p_a) A_i$$

Thrust (F) =Momentum thrust + Pressure Thrust

Pressure thrust developed is too small so neglect it,

Therefore;

Thrust (F) =Momentum thrust

$$F = m_i (1+f) c_j - c_i$$

Fuel-air ratio(f) is very small

$$F = m_i (c_j - c_i)$$

SPEED RATIO:

$\propto = c_i / c_j$

Therefore;

$$\boxed{F = m_i c_i (1/\propto - 1)}$$

FACTORS AFFECTING THRUST

The factors that affect the thrust of a gas turbine engine include air density, airspeed/ram effect and engine RPM. The effect of these factors is not restricted to any particular gas turbine engine; although a certain engine may be able to compensate for an effect better than another.

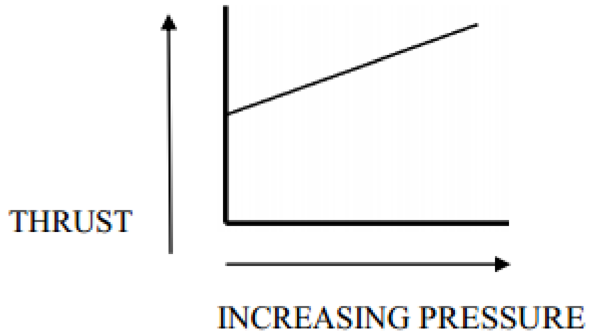
AIR DENSITY

Density is the mass of a substance per unit of its volume. According to the thrust equation, if the mass of airflow increases, thrust will increase. If the density of air increases, mass will increase, and therefore thrust will increase. As an aircraft operates at various altitudes and climates, the ambient air temperature and pressure will vary. These factors will affect the density of the air entering the engine, and as a result, will affect thrust.

As air temperature increases, air molecules tend to move apart. This results in a density decrease, and a resultant decrease in thrust . An engine operating in the warm temperatures near the equator will produce less thrust than an engine operating in the cold of Alaska.

Thrust may vary as much as 20 percent from standard rated thrust on a hot or cold day.

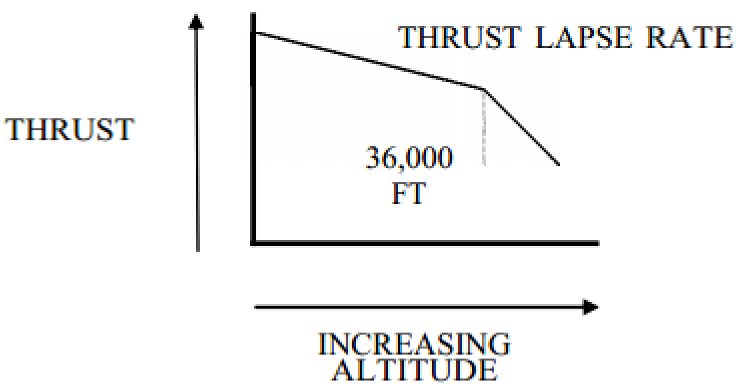
As air pressure increases, air molecules tend to move closer together. This results in an increase in density, and therefore, thrust increases.



ALTITUDE

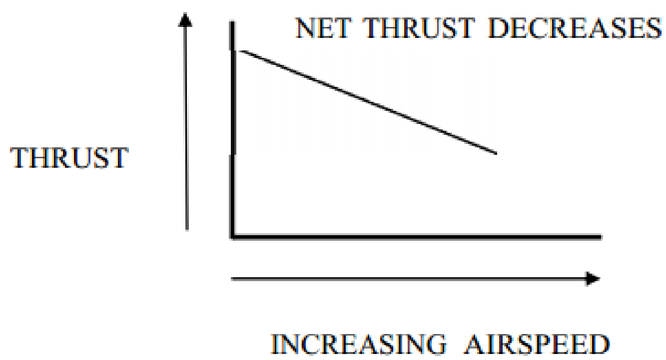
As an aircraft climbs, pressure and temperature will normally drop. Thrust will decrease with a pressure decrease, and thrust will increase with a temperature decrease. With an increase in altitude, however, the rate of thrust decreases because a pressure drop is greater than the thrust increase resulting from a temperature drop. This means an engine will produce less thrust as it increases in altitude.

At approximately 36,000 feet (beginning of the isothermal layer), temperature stabilizes. As a result, temperature will no longer offset the density decrease due to pressure. Therefore, thrust decreases more rapidly. This altitude is also known as the optimum cruise level. At this altitude, thrust available plus low fuel flow and diminished drag combine to provide optimum performance for many engines.



AIRSPEED

In the thrust equation, the difference between the inlet and exhaust velocities plays a major role in determining thrust available. As the inlet velocity (v initial) approaches the magnitude of the exhaust velocity (v final), thrust is reduced. Therefore, if the mass of air and fuel is held constant, thrust will decrease as airspeed increases .This decrease in thrust due to an increase in airspeed is theoretical.



RAM EFFECT

If we only consider the change in airflow velocity in the thrust equation, then thrust decreases with an increase in airspeed. Remember, that the thrust equation consists of two variables: mass (m) and acceleration (V final – V initial). As mentioned, the difference between inlet and exhaust velocities decreases as the aircraft increases speed. However, more and more air is being rammed into the inlet, increasing the mass and pressure of inlet air. This offsets the decrease in acceleration and results in a neutral effect or slight increase in thrust at subsonic airspeeds.
This is due to the compressibility of airflow as velocity increases toward supersonic. As airflow becomes compressible, mass due to ram effect increases at an increasing rate. Ram effect is especially important to high performance aircraft due to the exceptionally high- mass airflow that occur at supersonic speeds. This results in a significant increase in overall thrust due to ram effect at supersonic speeds (Figure 3.1-13). For many high-performance fighter aircraft, ram effect allows excellent high altitude performance, although air density is low.

ENGINE REVOLUTIONS PER MINUTE (RPM)
One of the most obvious factors that affect the thrust output is the rotational speed of the engine. With an increase in RPM, there is an increase in thrust. However, at low RPM there is very little increase in thrust with an increase in throttle. At higher rates of revolution, a small increase in throttle setting will produce a large increase in thrust. At the lower settings, fuel consumption is high for the amount of thrust produced. For this reason, gas turbine engines are normally operated at near their maximum RPM.

THRUST AUGMENTATION

Increasing the thrust is called Thrust augmentation.

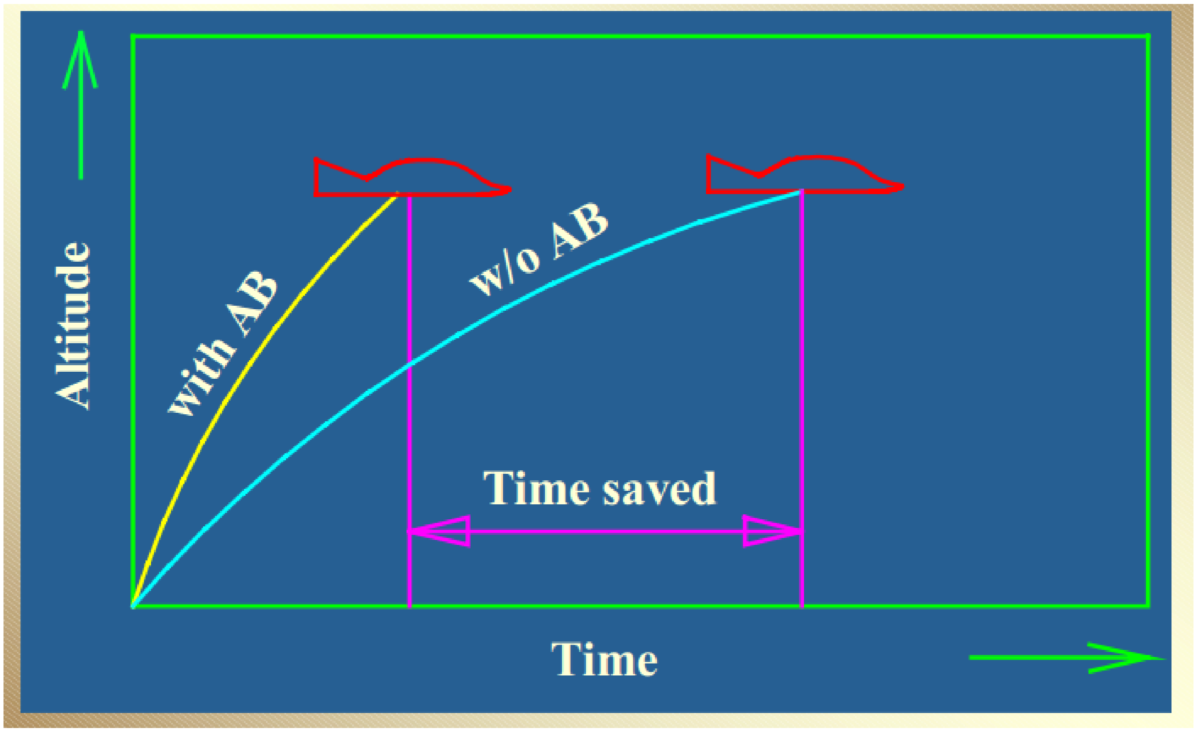
METHODS OF THRUST GENERATION:

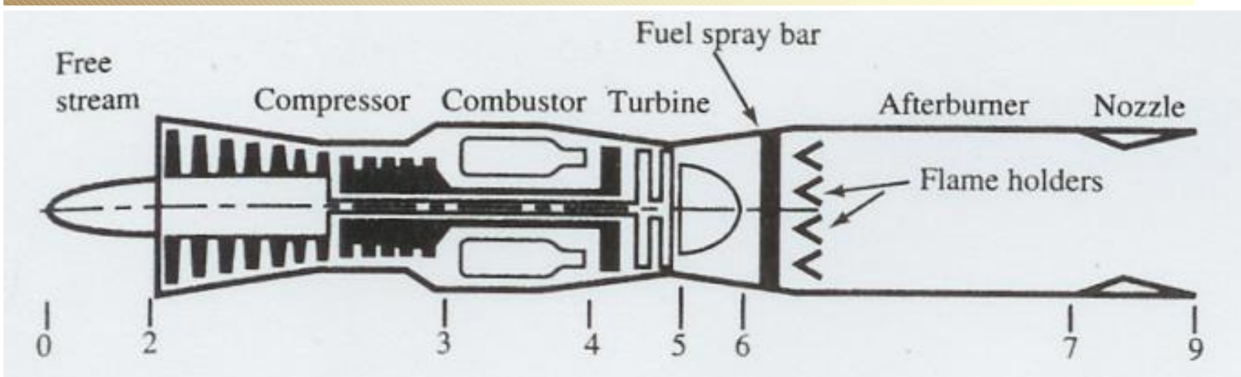
- After Burner
- Liquid injection
- Bleed burn cycle

Jet thrust can be increased by injecting additional fluids and it is then called wet thrust. Early engines and some current non-afterburning engines use **water injection** to temporarily increase thrust. Water is injected at the air compressor inlet or the diffuser to cool the compressing air which permits an increase in pressure for higher burning. A 10 to 30% additional thrust can thus be gained. Methyl or ethyl alcohol (or a mixture of one or both of these with water) has been used in the past for injection. However, water has a higher heat of evaporation, and is therefore the only liquid generally used for thrust augmentation today. ***Today's military combat engines use an afterburner for increased thrust.***

An **afterburner** (or a reheat) is an additional component present on some jet engines, mostly military supersonic aircraft. Its purpose is to provide an increase in thrust, usually for supersonic flight, takeoff and for combat situations. Afterburning is achieved by injecting additional fuel into the jet pipe downstream of (i.e. after) the turbine. The advantage of afterburning is significantly increased thrust; the disadvantage is its very high fuel consumption and inefficiency, though this is often regarded as acceptable for the short periods during which it is usually used.

Pilots can activate and deactivate afterburners in-flight, and jet engines are referred to as operating wet when afterburning is being used and dry when not. An engine producing maximum thrust wet is at maximum power, while an engine producing maximum thrust dry is at military power.





0-2 – Inlet 2-3 Compressor 3-4 Combustor 4-5 Turbine 5-7 Afterburner 7-9 Nozzles

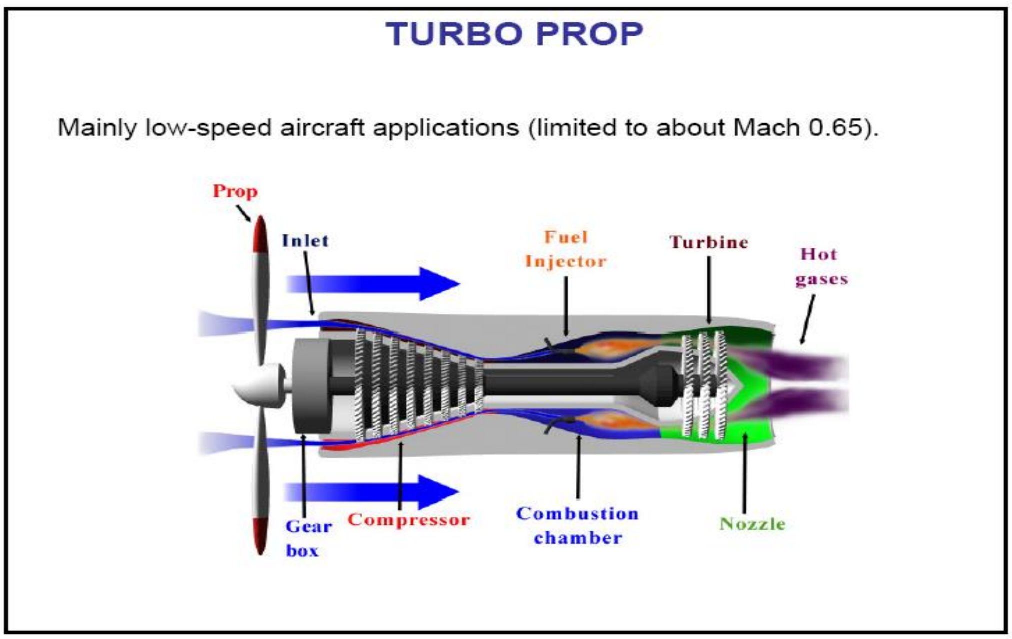
TURBOPROP ENGINE:

Turboprop Engine consist of;

- Propeller
- an air inlet
- an air compressor
- a combustion chamber
- a gas turbine (that drives the air compressor) and
- a nozzle.

Working:

- Propeller is used to extract more air into the engine.
- Propeller rotation is controlled using gear mechanism connected in a shaft.
- Inlet/diffuser is used to minimize the loss and increase the pressure initially.
- Compressor is used to increase the pressure to maximum level, using stator and rotor blades.
- Stator is a stationary blade and rotor is a rotating blade.
- The high pressure air from compressor is sent into the combustor, where air and fuel are burned and ignited.
- After the combustion process the combustion product (gas) with maximum temperature is received in the Turbine.
- The turbine entry temperature should be minimum or to level accepted by the turbine in order to avoid turbine blade damage.
- The gas pressure is reduced and velocity is increased in the nozzle and sent outside.
- By Newton's third law, thrust is obtained in the forward direction.

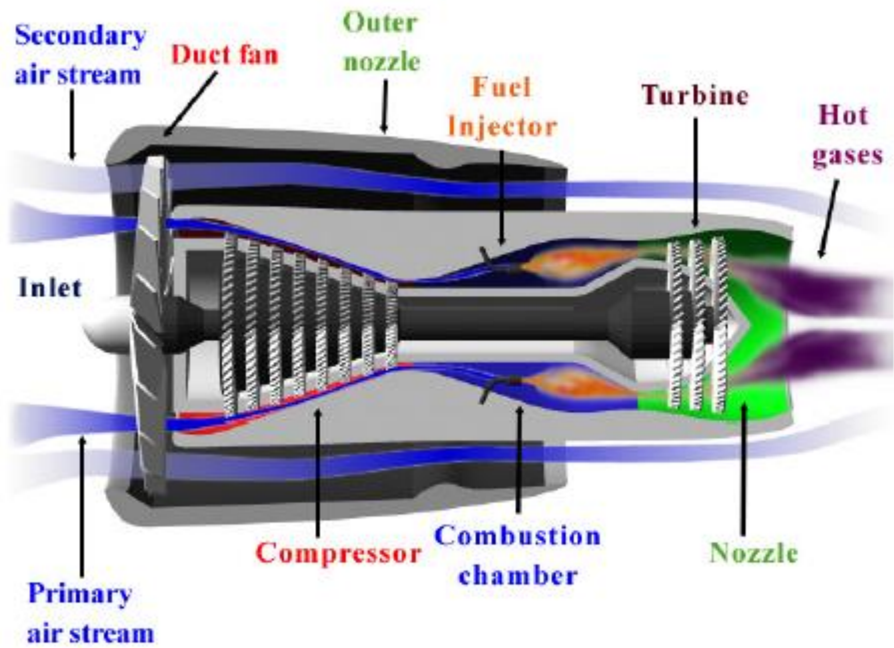


Characteristics of a Turboprop

Advantages	Disadvantages
1. Develops very high thrust at low airspeeds	1. Heavier and more complicated aircraft
2. Excellent take-off, slow speed, and low altitude characteristics	2. Limited speeds (approx. 400-450 kts.)
3. Superior for lifting heavy loads off short and medium length runways	

TURBOFAN ENGINE:

- A turbofan engine is a gas turbine engine that is very similar to a turbojet. Like a turbojet, it uses the gas generator core (compressor, combustor, turbine) to convert internal energy in fuel to kinetic energy in the exhaust.
- The fan and Inlet is used to capture possible amount of air. To utilize it for production of thrust.
- The compressor is driven by the turbine. The compressor rotates at very high speed, adding energy to the airflow and at the same time squeezing (compressing) it into a smaller space. Compressing the air increases its pressure and temperature.
- Combustor mixes the air and fuel in required ratio and fuel is sprayed through igniter to produce combustion process.
- The high burnt gases from combustor expands in the turbine, where power is developed.
- Turbofans differ from turbojets in that they have an additional component, a fan. Like the compressor, the fan is powered by the turbine section of the engine. Unlike the turbojet, some of the flow accelerated by the fan bypasses the gas generator core of the engine and is exhausted through a nozzle.
- The ratio of the mass-flow of air bypassing the engine core compared to the mass-flow of air passing through the core is referred to as the **bypass ratio**.



Characteristics of a Turbofan

Advantages

1. Higher thrust at low airspeeds
2. Lower TSFC
3. Shorter takeoff distance
4. Considerable noise reduction, 10 to 20 percent over the turbojet

Disadvantages

1. Higher specific weight
2. Larger frontal area
3. Inefficient at higher altitudes

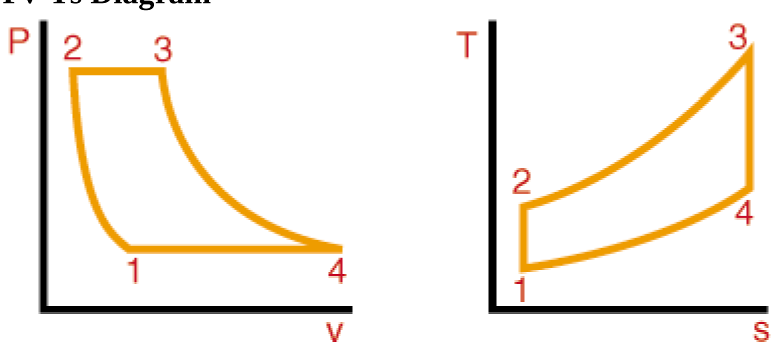
TURBOJET ENGINE:

- Turbojets consist of;
  - an air inlet
  - an air compressor
  - a combustion chamber
  - a gas turbine (that drives the air compressor) and
  - a nozzle.
- The air is compressed into the chamber, heated and expanded by the fuel combustion and then allowed to expand out through the turbine into the nozzle where it is accelerated to high speed to provide propulsion.

Working:

- Inlet/diffuser is used to minimize the loss and increase the pressure initially.
- Compressor is used to increase the pressure to maximum level, using stator and rotor blades.
- Stator is a stationary blade and rotor is a rotating blade.
- The high pressure air from compressor is sent into the combustor, where air and fuel are burned and ignited.
- After the combustion process the combustion product (gas) with maximum temperature is received in the Turbine.
- The turbine entry temperature should be minimum or to level accepted by the turbine in order to avoid turbine blade damage.
- The gas pressure is reduced and velocity is increased in the nozzle and sent outside.
- By Newton's third law, thrust is obtained in the forward direction.

Pv-Ts Diagram



1-2 Compression 2-3 Combustion 3-4 Expansion 4-1 Exhaust

Characteristics of a Turbojet

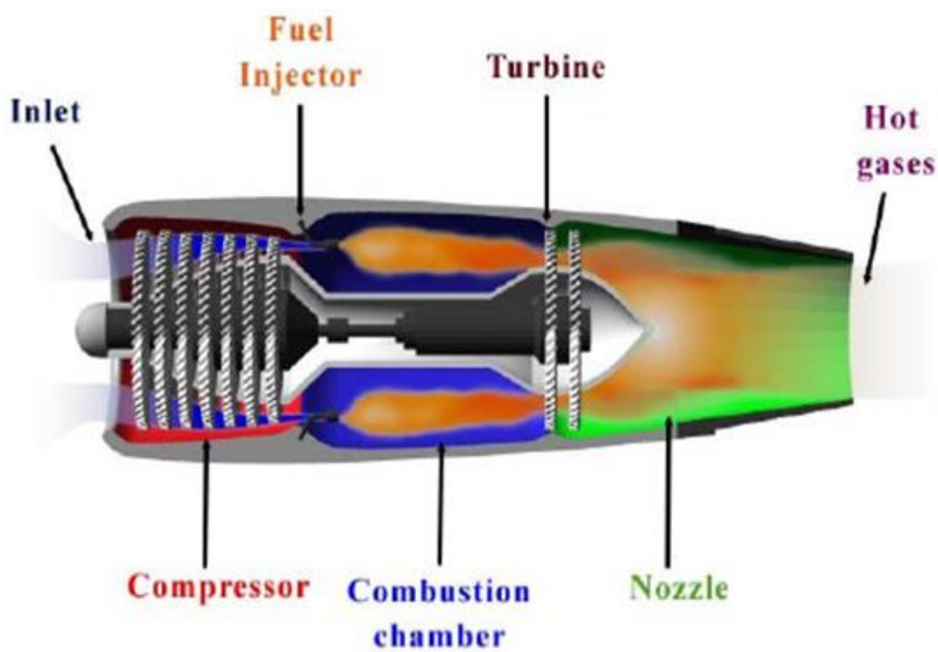
Advantages

1. Lightest specific weight (weight per pound of thrust produced
2. Higher and faster than any other engine

Disadvantages

1. Low propulsive efficiency at low forward speeds
2. Relatively high TSFC at low altitude and low airspeeds
3. Long takeoff roll required

These characteristics indicate that the turbojet engine is best suited for high-speed and/or high-altitude flights.



COMPARATIVE STUDY OF TURBOJET VS TURBOFAN VS TURBOPROP

TURBOJET	TURBOFAN	TURBOPROP
Parts: Intake, compressor, combustors, turbine and nozzle.	Parts: Intake, compressor, combustors, turbine, nozzle and fan.	Parts: Intake, compressor, combustors, turbine, nozzle and Propeller.
The turbojet is the simplest jet engine in terms of construction.	The turbofan engine was designed in order to permit higher turbine temperatures without increasing gas velocity dramatically because this would decrease efficiency in subsonic flight.	The turboprop is similar to the turbojet, except that the turbine drives a propeller.
It is widely used in military aviation.	Bypass ducts are available.	Gear mechanism is used to control the propeller rotation.
No need of bypass ratios	The ratio of the mass-flow of air bypassing the engine core compared to the mass-flow of air passing through the core is referred to as the bypass ratio	It is coupled to the turbine through a reduction gear that converts the high RPM, low torque output to low RPM, high torque.
High exhaust speed.	Higher velocity engine exhaust.	This engine's exhaust gases contain little energy compared to a jet engine.
It is used in medium range cruise missiles, due to their high exhaust speed.	It is efficient in the range of speeds from about 500 to 1000 km/h (310 to 620 mph), the speed at which most commercial aircraft operate	It reaches a very high fuel-efficiency at the expense of airspeed.
low frontal area and relative simplicity	Frontal area is greater than turbojet.	Frontal area is greater than turbojet.
Torque is not developed.	Torque is not developed.	Torque is developed because of reduction gears.

UNIT V AIR COMPRESSORS

Syllabus: Classification and working principle, work of compression with clearance, Isothermal and Isentropic efficiency of reciprocating air compressors, multistage compression and inter cooling. Various types of compressors

Types of Air Compressors

Reciprocating, rotary screw and rotary centrifugal air compressors

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The three basic types of air compressors are

- Reciprocating
- Rotary screw
- Rotary centrifugal

Reciprocating Air Compressors

Reciprocating air compressors are positive displacement machines, meaning that they increase the pressure of the air by reducing its volume. This means they are taking in successive volumes of air which is confined within a closed space and elevating this air to a higher pressure. The reciprocating air compressor accomplishes this by a piston within a cylinder as the compressing and displacing element.

The reciprocating air compressor is single acting when the compressing is accomplished using only one side of the piston. A compressor using both sides of the piston is considered double acting. Load reduction is achieved by unloading individual cylinders. Typically this is accomplished by throttling the suction pressure to the cylinder or bypassing air either within or outside the compressor. Capacity control is achieved by varying speed in engine-driven units through fuel flow control. Reciprocating air compressors are available either as air-cooled or water-cooled in lubricated and non-lubricated configurations and provide a wide range of pressure and capacity selections.

Rotary Screw Compressors

Rotary air compressors are positive displacement compressors. The most common rotary air compressor is the single stage helical or spiral lobe oil flooded screw air compressor. These compressors consist of two rotors within a casing where the rotors compress the air internally. There are no valves. These units are basically oil cooled (with air cooled or water cooled oil coolers) where the oil seals the internal clearances. Since the cooling takes place right inside the compressor, the working parts never experience extreme operating temperatures. The rotary compressor, therefore, is a continuous duty, air cooled or water cooled compressor package.

Rotary screw air compressors are easy to maintain and operate. Capacity control for these compressors is accomplished by variable speed and variable compressor displacement. For the latter control technique, a slide valve is positioned in the casing. As the compressor capacity is reduced, the slide valve opens, bypassing a portion of the compressed air back to the suction. Advantages of the rotary screw compressor include smooth, pulse-free air output in a compact size with high output volume over a long life. The oil free rotary screw air compressor utilizes specially designed air ends to compress air without oil in the compression chamber yielding true oil free air. Oil free rotary screw air compressors are available air cooled and water cooled and provide the same flexibility as oil flooded rotaries when oil free air is required.

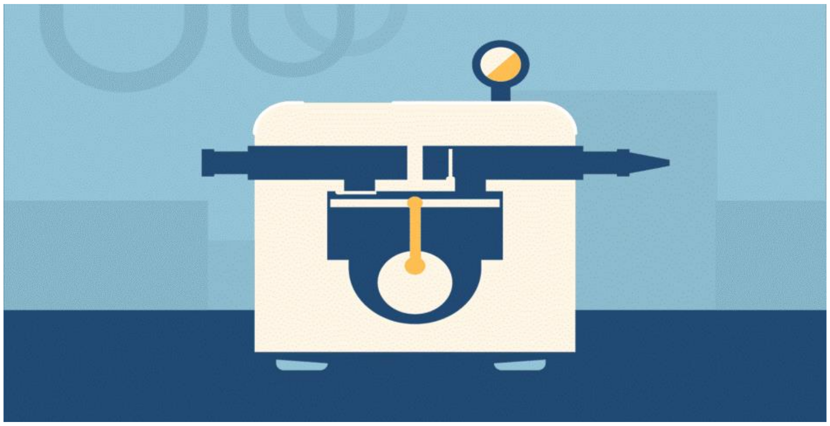
Centrifugal Compressors

The centrifugal air compressor is a dynamic compressor which depends on transfer of energy from a rotating impeller to the air. Centrifugal compressors produce high-pressure discharge by converting angular momentum imparted by the rotating impeller (dynamic displacement). In order to do this efficiently, centrifugal compressors rotate at higher speeds than the other types of compressors. These types of compressors are also designed for higher capacity because flow through the compressor is continuous. Adjusting the inlet guide vanes is the most common method to control capacity of a centrifugal compressor. By closing the guide vanes, volumetric flows and capacity are reduced. The centrifugal air compressor is an oil free compressor by design. The oil lubricated running gear is separated from the air by shaft seals and atmospheric vents.

Working principles of Air Compressors

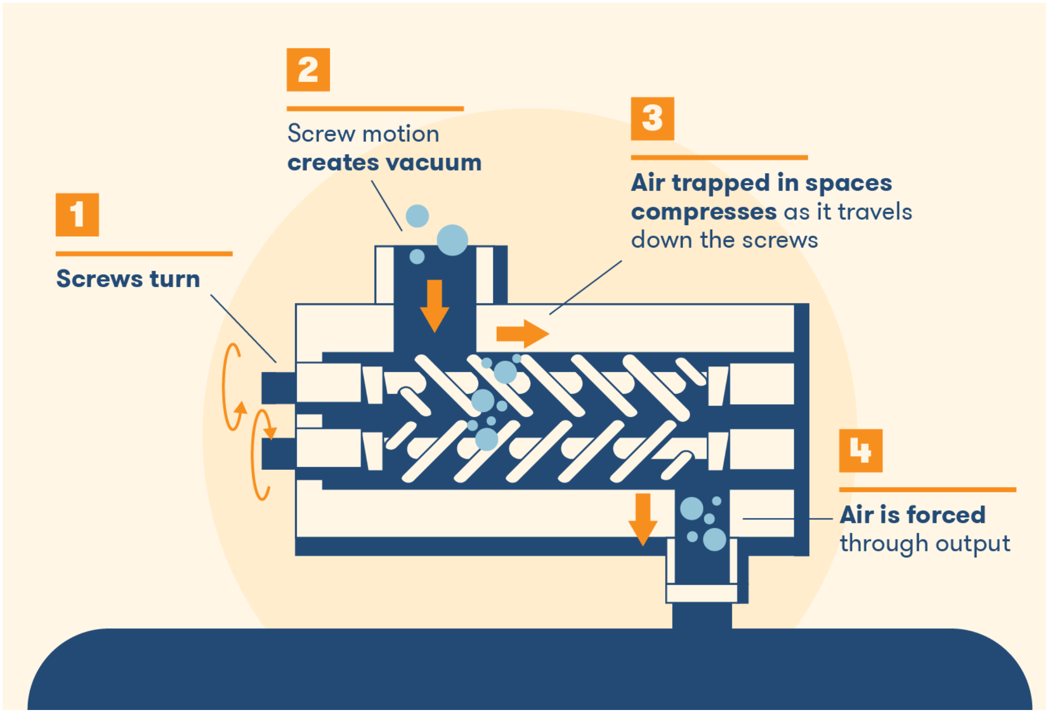
The main advantage of air compressors is that they’re much more powerful than regular tools, and they don’t require their own bulky motors. Since the only real maintenance that’s required of them is a little bit of oiling, a variety of tools can be powered by a single engine that utilizes air pressure for maximum potential.

Their versatility doesn't just stop at the workbench for drills or sanders; they can be used for anything from inflating a tire (like the ones at your local gas station) to unclogging the sink at home. Air compressors are a testament to human ingenuity. It's important to understand how they work so you can choose the right air compressor for your project.



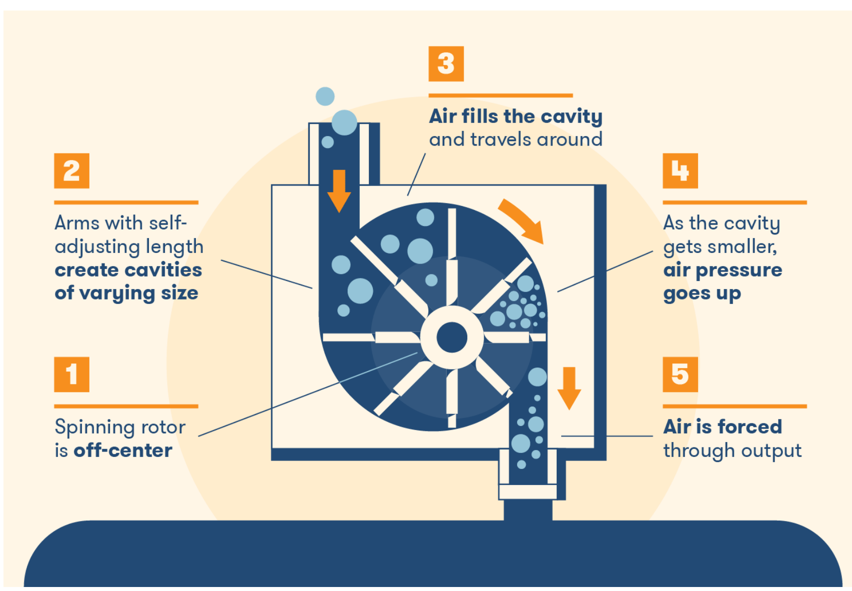
There are two methods of achieving air compression: positive and dynamic displacement. Each method has several sub-categories which we cover below. The outcomes are relatively similar, but the processes to achieve them vary. Positive displacement air compressors force air in a chamber where the volume is decreased to compress the air. Positive displacement is an umbrella term that describes different air compressors that are power through positive air displacement. Although the internal systems vary among different machines, the method of providing the power is the same. Some types of positive displacement compressors are better equipped for industrial workloads while others are better for hobbyists or private projects. Here are the three main types of air compressors that use positive displacement:

Rotary Screw



Rotary screw compressors have two internal "screws" that rotate in opposite directions, trapping and compressing air between them. The two screws also generate constant movement as they rotate around. This is a common type of air compressor and is one of the easiest to take care of. The engines are typically industrial-sized and are great for continuous use.

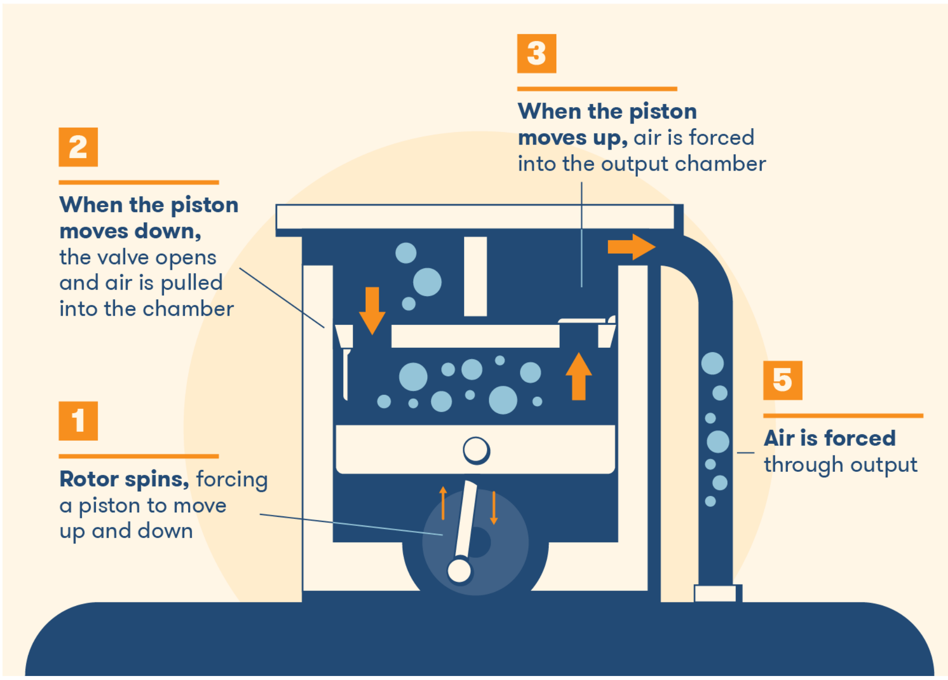
Rotary Vane



Rotary vane compressors are like rotary screw compressors, but instead of screws, vanes are mounted on a rotor and rotated inside the cavity. The air compresses between the vane and its casing and is then pushed out at a different exhaust port. Rotary vane compressors are very easy to use, making them very popular for private projects.

There are two types of piston compressors: single stage and two stage.

1. **Single Stage**



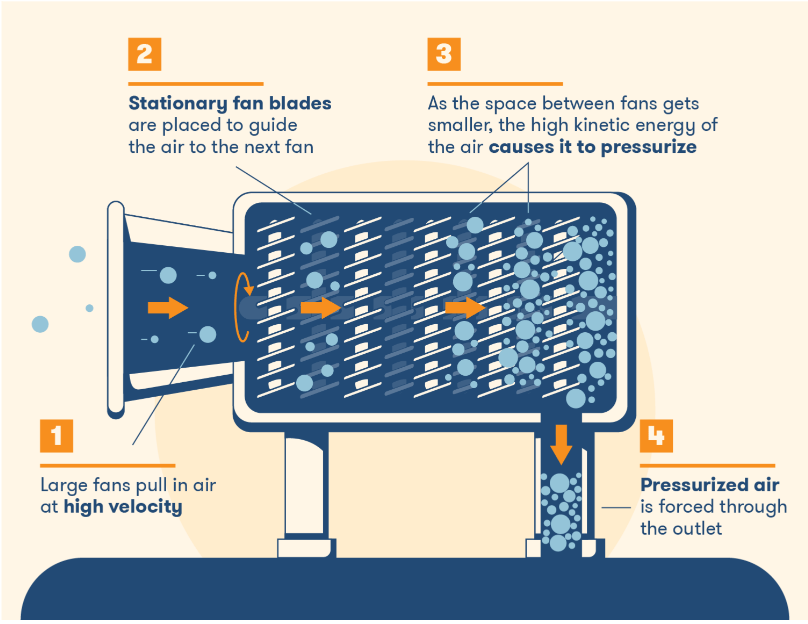
In the single stage compressors, the air is compressed on one side of the piston, while the other side deals with the functionality of it: as the piston moves down, the air is drawn in, and when it moves up, the air is compressed. Single stage compressors are relatively affordable compared to the other compressors and are typically easy to acquire; they can be found in almost any mechanic shop.

2. Two Stage

Two stage compressors have two compression chambers on either side of a piston. Double-acting compressors are typically water-cooled by a continuous stream of water through the engine. This provides a better cooling system than other compressors. Due to their high cost, two stage compressors are better for factories and workshops versus private projects.

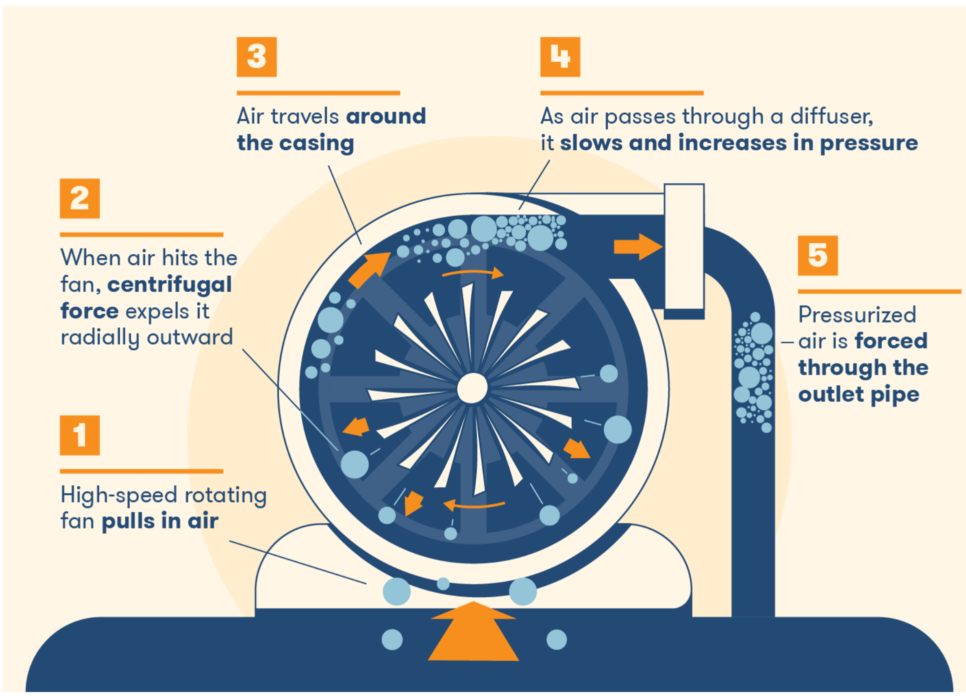
Just like with positive displacement compressors, there are two distinct types of dynamic displacement: axial and centrifugal.

1. **Axial Compressors**



Axial compressors use a series of turbine blades to generate air, forcing it through a small area. Although similar to other bladed compressors, axial compressors operate with stationary blades which slow airflow, increasing pressure. These types of air compressors aren't very common and have limited functionality. They're used mainly in aircraft engines and in large air separation plants.

2. Centrifugal Compressors



Centrifugal, or radial compressors, work by bringing air into the center through a rotating impeller, which is then pushed forward through centrifugal, or outward, force. By slowing the flow of air through a diffuser, more kinetic energy is generated. Electric high-speed motors are typically used for these kinds of compressors. One of the more common uses of centrifugal compressors is through HVAC systems.

An air compressor is a mechanical device which produces the compressed air i.e. which increases the pressure of air above the atmospheric pressure as per the requirement and stores it in a high pressure vessel. In air compressor, normal atmospheric air is sucked and compressed continuously. It can be run or derived by an electric motor, IC engine or steam engine etc. The high pressure air or compressed air has numerous applications in industry as well as in our daily life.

Some of the applications of compressed air are given as below:

- **(i)** Dusting/cleaning in home, shops etc.
- **(ii)** Inflation of tires.
- **(iii)** Operating tools in factories.
- **(iv)** Operating heavy drills, execrators etc.
- **(v)** Boring and developing of tube wells.
- **(vi)** Starting Diesel engines with air starter motor.
- **(vii)** Operating brakes of buses, trucks or other heavy vehicles.
- **(viii)** Operation of pneumatic valves in automated processing industries
- **(ix)** Drying industry.
- **(x)** Air conditioning.

31.2 Use of Air Compressor in Dairy Industry

Dairy Industry is a type of food processing industry, where milk is processed to produce a number of milk products. The process control is carried out by keeping the operating parameters like pressure, temperature, concentration etc., in optimum range by automatically controlling the flow rate of milk/ milk product, steam and cooling water or refrigerant etc. through pneumatic (air operated) valves. Many a times, some other type of automated mechanical movements are required to be carried out in a processing or packaging machine automatically for the purpose of process control. These movements are carried out precisely with the help of air-motors run by compressed air for example in a pouch filling and packing machine. Compressed air is also used in general dusting and cleaning purpose in a plant. Compressed air is also required in cleaning and drying of milk storage and processing equipment. Thus compressed air finds very important application in modern dairy processing plants and is an important utility

31.3 Classification of Air Compressor

Air compressor is actually an air pump just like a water pump, which pumps the air continuously from low pressure to high pressure. Air compressors may be classified on various basis as mentioned below.

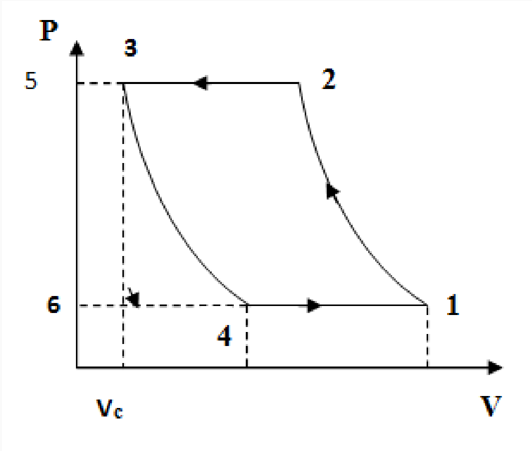


Fig. 31.2 P-V diagram of single stage reciprocating air-compressor

31.6.2 Working

1-2: Pure-compression

This process is most important in the overall working of a compressor. During this process, both suction and discharge valve remain closed and compressor acts as a closed system. On the upwards movement of piston from BDC volume of air inside the cylinder shrinks and so pressure rises. The compression may happen theoretically as any of the isentropic, isothermal or polytropic processes. In actual compressor it is always a polytropic process and try is made to keep it as close to isothermal process as possible by external cooling. Piston work is least in case of isothermal compression.

2-3: Compressed air discharge

When the pressure in the cylinder reaches to a value of pressure in compressed air vessel, somewhere in between the stroke of piston, discharge valve opens and compression becomes an open system. On further upward movement of piston, compressed air is simply discharged to compressed air tank through the discharge valve. This process ends when the piston reaches to the top end position, TDC and stroke is completed. During this process compressor acts like a pump which discharges the compressed air but does not compress it further.

3-4: Expansion of air trapped in clearance volume

This process starts as soon as the piston starts moving down towards BDC and cylinder volume starts increasing. Due to increase in volume pressure falls down and discharge valve close but some high pressure air remains in the clearance volume which could not be discharged. On downward movement of piston, this clearance volume air expands polytropically or isothermally or isentropically doing some work on the piston. When somewhere in between the downward stroke of piston during expansion, pressure falls below the outside normal air pressure, suction valve opens and expansion process ends. During this process compressor acts as a closed system. This process is reverse of compression process 1-2 and it also takes place for a part of the stroke of piston. Due to this process the effective suction of air is reduced and volumetric efficiency becomes less than 1.

4-1: Suction of air

On further downward movement of piston after opening of suction valve, atmospheric air is sucked in the cylinder until the piston reaches to bottom dead centre (BDC). In this process, compressor acts as an open system and fresh mass of air is sucked from atmosphere. At the end of this stroke cycle completes. The theoretical work consumed by compressor during one cycle is given by area of enclosed cycle 1-2-3-4.

In this way, when the piston is reciprocated continuously in the cylinder by rotating the crankshaft with the help of an electric motor, it completes one working cycle in two strokes of piston or one revolution of crankshaft. The expansion of high pressure air, trapped in the clearance volume (C.V.) in the previous stroke, and suction of fresh air from atmosphere takes place during downward stroke of piston from TDC to BDC, Then compression of air and its discharge to air tank take place during upward stroke of piston from BDC to TDC.

With the running of compressor, normal atmospheric air is continuously compressed and accumulated in high pressure air tank. The construction of suction valve and discharge valve is geometrically similar but they act in the opposite direction under the action of two forces, one is spring force and other is force due to pressure difference. Normally the spring keeps the suction valve pressed on its seat in upward direction in closed position and it opens against spring force only when vacuum is created inside the cylinder during suction stroke. Conversely the spring keep the discharge valve pressed on its seat in downward direction in closed position and it opens against spring force only when pressure in cylinder is higher than that in discharge port or air tank. Suction valve opening is connected to an air filter placed in open atmosphere. Discharge valve opening is connected to closed discharge port connected to air tank on other side. Reciprocating air compressor is a similar but simpler machine than an I.C. engine. Similarity exists only in basic design and construction but purpose of both are altogether different

31.3.2 On the basis of number of stages

31.3.2.1 Single stage

When the compressor compresses the air straightway from atmospheric pressure to discharge pressure in a single stage is called a single stage compressor.

31.3.2.2 Multi stage

When the compressor compresses the air from atmospheric pressure to final discharge pressure in more than one step by using more than one single stages of compressor is called Multi-stage compressor. Here the discharge of first stage enters the suction side of next stage and so on until the air is discharged to required pressure of final stage.

31.4 Positive Displacement Type Compressor

In positive displacement type compressor, a moving mechanical component, displaces or compresses the air positively against high pressure. These are further of two types as discussed below:

31.4.1 Reciprocating compressor

It is called so because here an air tight component i.e. piston reciprocates continuously in its counterpart closed component i.e. cylinder. With the help of operation of automatic valves, piston sucks fresh air inside cylinder in one stroke called suction stroke and pushes or discharges it to high pressure air tank in the next discharge stroke. Thus piston is made to reciprocate with the help of a connecting rod and crankshaft rotated by an electric motor. The construction of a reciprocating air compressor is basically similar to an IC engine. Here also the basic components are same i.e. cylinder piston, connecting rod, crankshaft, cylinder head valves etc. One main difference is that the engine produces power but air compressor consumes power. A reciprocating air compressor is further classified as single acting or double acting based on that piston sucks and compress the air from one side only or from both the sides of piston like IC engine, compressor may also be single cylinder type or multi cylinder type. Multi cylinder compressor may also further be having many type of arrangements or designs like In-line or V-type etc.

31.4.2 Rotary compressor

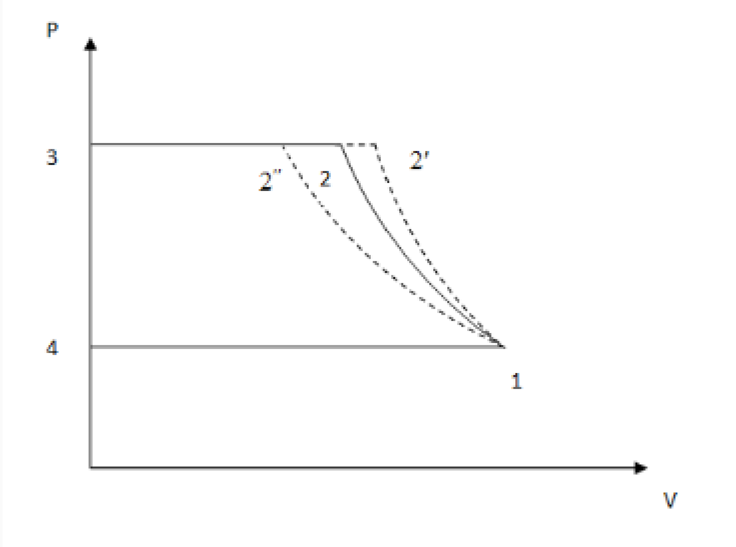
In this compressor a rotating mechanical component displaces the air positively and continuously through the casing of air compressor in which it is rotating. By this rotating movement, air cavities are formed which move from one place to another place or which shrink continuously and compress the air. Based on the construction of casing, rotating part and principle of cavity movement, these are further classified as:

- **a)** Roots Blower Compressor or Lobe Type Compressor
- **b)** Sliding Vane Compressor
- **c)** Screw Compressor
- **d)** Spiral Compressor

31.5 Centrifugal Compressor

Centrifugal compressor is one which imparts rotational energy to air. This rotational energy is converted to centrifugal force by which the air flows against pressure in the discharge side. The rotating mechanical component which imparts rotational energy to air is called impeller. The impeller consists of curved vanes which facilitate the flow of air through it. The fixed vanes of diffuser in the centrifugal casing convert a part of this rotational energy of air into pressure energy and air is discharged against high pressure. The main components of centrifugal compressor are centrifugal casing, impeller, main shaft, diffuser, suction and discharge ports etc.

In a centrifugal compressor, the flow of air takes place through compressor in a direction normal to the axis of rotating shaft. But if the flow takes place parallel to the axis of main shaft, it is called axial flow compressor. Construction wise, centrifugal compressor can also be named as rotary compressor or a rotary compressor can be of both types as positive displacement type and centrifugal type.



1 – 2 : Polytropic Compression

1 – 2′: Adiabatic Compression

1 – 2′′: Isothermal Compression

Fig. 31.3 Single stage Air Compressor with zero clearance volume

In another way, it can be concluded that, in case of an isothermal compression i.e. compression without any rise in temperature, compressor has to work against the rise in pressure of air or gas due to shrinkage of volume only and so work is least. In case of isentropic compression, compressor has to work against the rise in pressure due to shrinkage of volume of air or gas and also due to rise in temperature thus more work is required. If some cooling is done, temperature rise will be less and so pressure rise will also be less thus lesser work will be required. In all these three cases, we are talking about the work required against compression of gas only without considering any internal or external friction and other losses. Considering all these losses, the actual work requirement will further increase. Overall, it can be concluded that work required in compression can be minimized by choosing such design of compressor, where friction and other losses are least and cooling is more and more effective.

31.8.2 Volumetric efficiency

It is the ratio of volume of free air delivered per stroke to the swept volume of compressor. As some part of swept volume is used up in the expansion of clearance volume gas, volumetric efficiency is always less than one. Volumetric efficiency is also reduced due to resistance offered by suction valve and heating up of suction air in the compressor.

31.8.3 Isothermal efficiency

It is the ratio of work required by compressor in case of isothermal compression in an air compressor to the actual indicated work of compression. Indicated work of compression means the work represented by indicator P-V diagram of compressor.

31.8.4 Isentropic efficiency

It is the ratio of isentropic work of a compressor i.e. work consumed considering isentropic compressor to the actual work required by compression. This term is mostly used in refrigerant compressor.

31.8.5 Mechanical efficiency

It is the ratio of indicated power of compressor to the actual shaft power of compressor. Shaft power of compressor means power required to be given to its driving shaft. It accounts for the loss of power due to friction in moving parts.

31.8.6 Overall isothermal efficiency

It is the ratio of compression work in case of isothermal compression to the actual work required by the compressor.

31.8.7 Clearance ratio

It is the ratio of clearance volume to the total swept volume of an air compressor. It is denoted as K or C.

$$K = \frac{V_c}{V_s}$$

31.9 Multistage Compression

As mentioned upto now is the single stage compression i.e. the pressure is raised from atmosphere to the required value in one stage. But when the requirement is of very high pressure, single stage compression has some disadvantages as mentioned below:

1) With the increase in delivery pressure, the high pressure air remained in clearance volume takes more part of piston stroke to expand upto suction pressure thus decreasing the effective swept volume and hence the mass flow rate through compressor. It is clear from figure 31.4 that if the delivery pressure is too high, there may not be any discharge of air and the compression and expansion processes 1-2 or 2-1 may takes place in full strokes of piston. In that case valve will not operate and delivery of air would become zero.

2) With the increase in delivery pressure delivery temperature also increases which if not required is a dual energy loss.

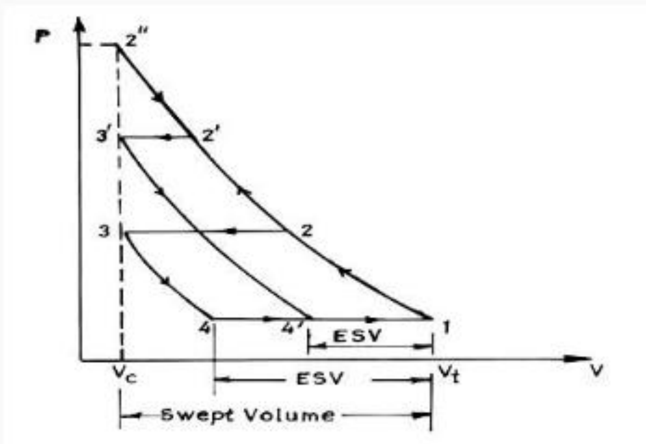


Fig. 31.4 Compression cycles with different values of delivery pressure

The only solution to this problem is to increase the delivery pressure not in single stage but in multistage. First, the atmosphere air is compressed to a reasonable intermediate pressure level in the first stage and is delivered as suction of 2nd stage where the pressure is further increased reasonably and so on until the final pressure is reached. There may be two, three or more stages depending on the delivery pressure required. Between the stages, the air may be cooled so as to keep the overall compression curve close to isothermal curve thus to decrease the compression work also. The combined compression cycle of multistage compressor is shown in

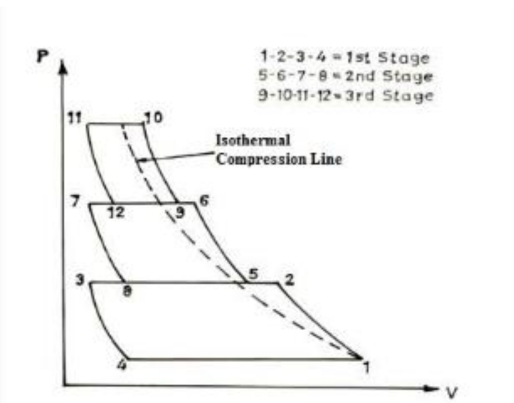


Fig. 31.5 Three stage compression cycle

fig 31.5

Advantages of multistage compression

- The air can be cooled at intermediate pressure between the stages of compression, thus decreasing the work required for next stage. Hence, the power required to drive a multistage compressor is less than that required for a single stage compressor delivering the same quantity of air at the same delivery pressure.
- Multistage compressors have better mechanical balance. So lighter flywheel is required.
- The pressure and temperature range may be kept within desirable limits which results in
  - i). Reduced losses due to air leakage
  - ii). Improved lubrication
  - iii). Improved volumetric efficiency
- For higher delivery pressure, in a single stage compressor, cylinder, piston and other moving parts must be robust enough to withstand the higher load. However in multistage compressor, the low pressure cylinder may be lighter in construction.
- The size of different stages of compressor may be adjusted and designed independently depending on volume of air handled in different pressure range.

Disadvantages

The multistage compressor with intercoolers is more expensive in initial cost than a single stage, compressor of same capacity, but its running cost is less.