APPLIED THERMODYNAMICS
(AME007)

MECHANICAL ENGINEERING

B. Tech IV Semester

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UNIT I

Internal Combustion Engines

Introduction :

- **Heat engine :** It can be defined as any engine that converts thermal energy to mechanical work output. Examples of heat engines include: steam engine, diesel engine, and gasoline (petrol) engine.

- On the basis of how thermal energy is being delivered to working fluid of the heat engine, heat engine can be classified as an internal combustion engine and external combustion engine.

- In an **Internal combustion engine**, combustion takes place within working fluid of the engine, thus fluid gets contaminated with combustion products.
  - Petrol engine is an example of internal combustion engine, where the working fluid is a mixture of air and fuel .

- In an **External combustion engine**, working fluid gets energy using boilers by burning fossil fuels or any other fuel, thus the working fluid does not come in contact with combustion products.
  - Steam engine is an example of external combustion engine, where the working fluid is steam.

Internal combustion engines may be classified as :

- Spark Ignition engines.
- Compression Ignition engines.

- **Spark ignition engine (SI engine):** An engine in which the combustion process in each cycle is started by use of an external spark.
- **Compression ignition engine (CI engine):** An engine in which the combustion process starts when the air-fuel mixture self ignites due to high temperature in the combustion chamber caused by high compression.
    - Spark ignition and Compression Ignition engine operate on either a four stroke cycle or a two stroke cycle.

- Four stroke cycle : It has four piston strokes over two revolutions for each cycle.
- Two stroke cycle : It has two piston strokes over one revolution for each cycle.
- We will be dealing with Spark Ignition engine and Compression Ignition engine operating on a four stroke cycle.

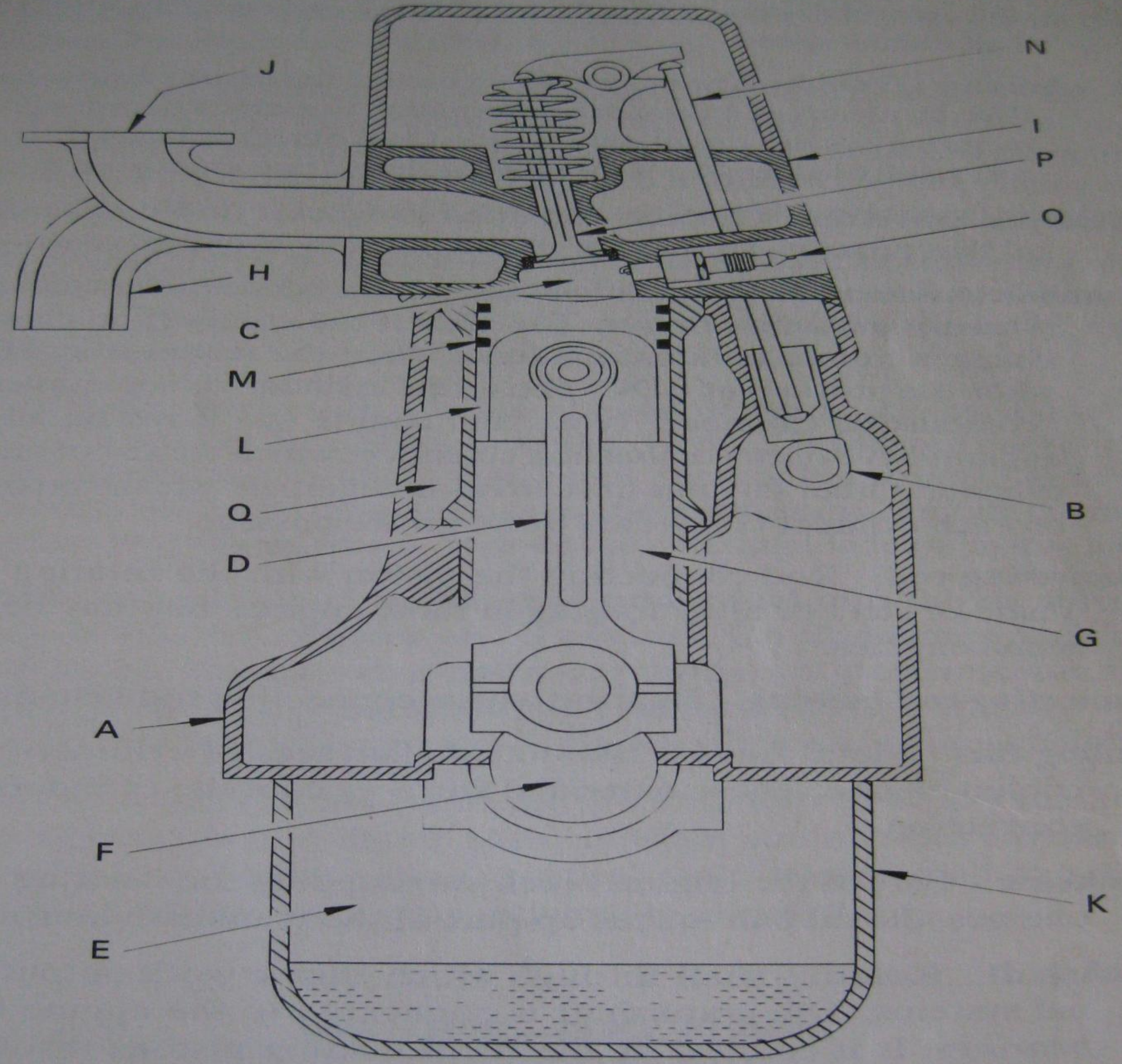
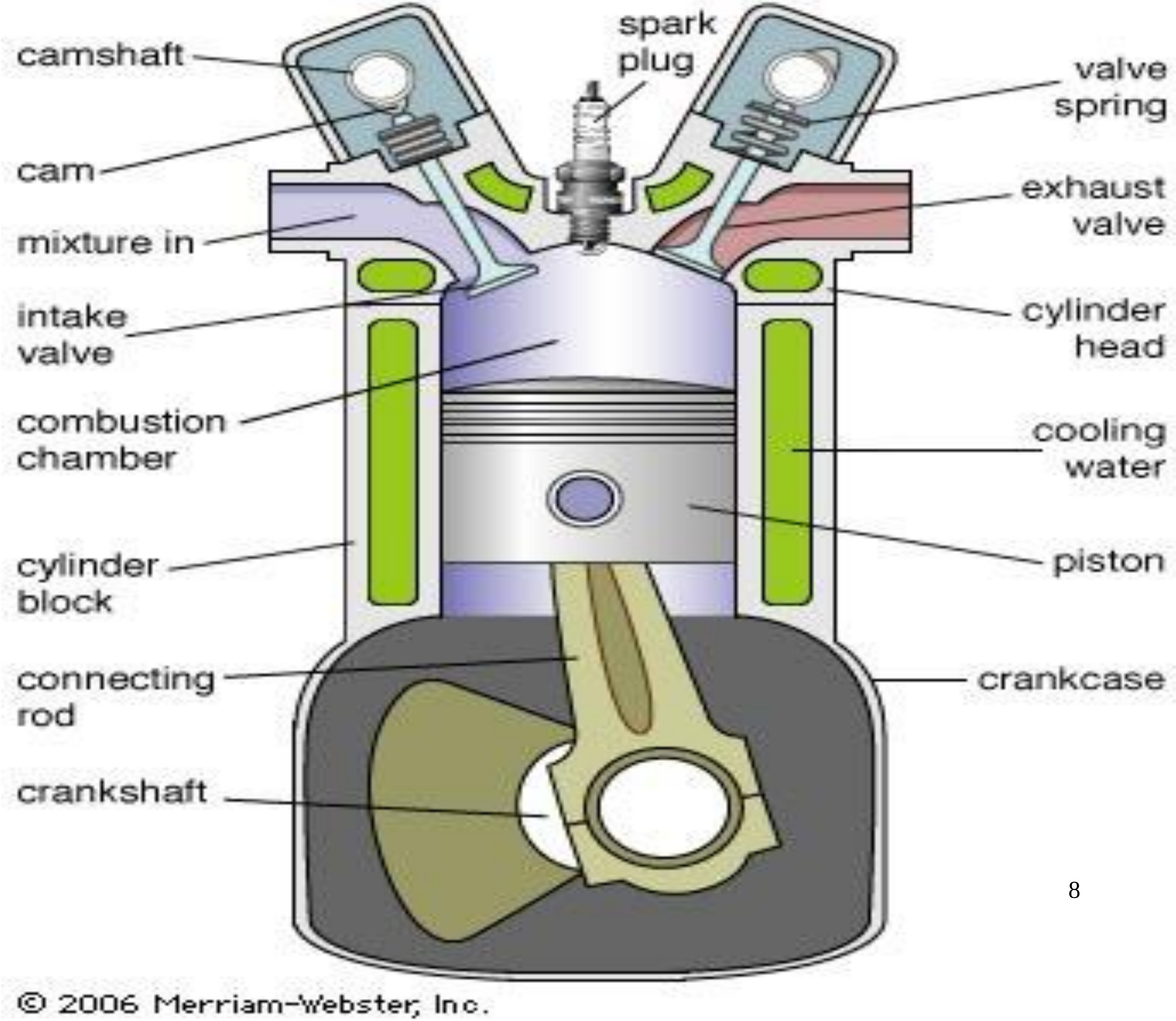


Figure 1-15 Cross-section of four-stroke cycle SI engine showing engine components: (A) block, (B) camshaft, (C) combustion chamber, (D) connecting rod, (E) crankcase, (F) crankshaft, (G) cylinder, (H) exhaust manifold, (I) head, (J) intake manifold, (K) oil pan, (L) piston, (M) piston rings, (N) push rod, (O) spark plug, (P) valve, (Q) water jacket.

Figure1 : Engine components [W.W.Pulkrabek]


spark plug
camshaft
valve spring
cam
exhaust valve
mixture in
intake valve
cylinder head
combustion chamber
cooling water
piston
cylinder block
connecting rod
crankcase
crankshaft
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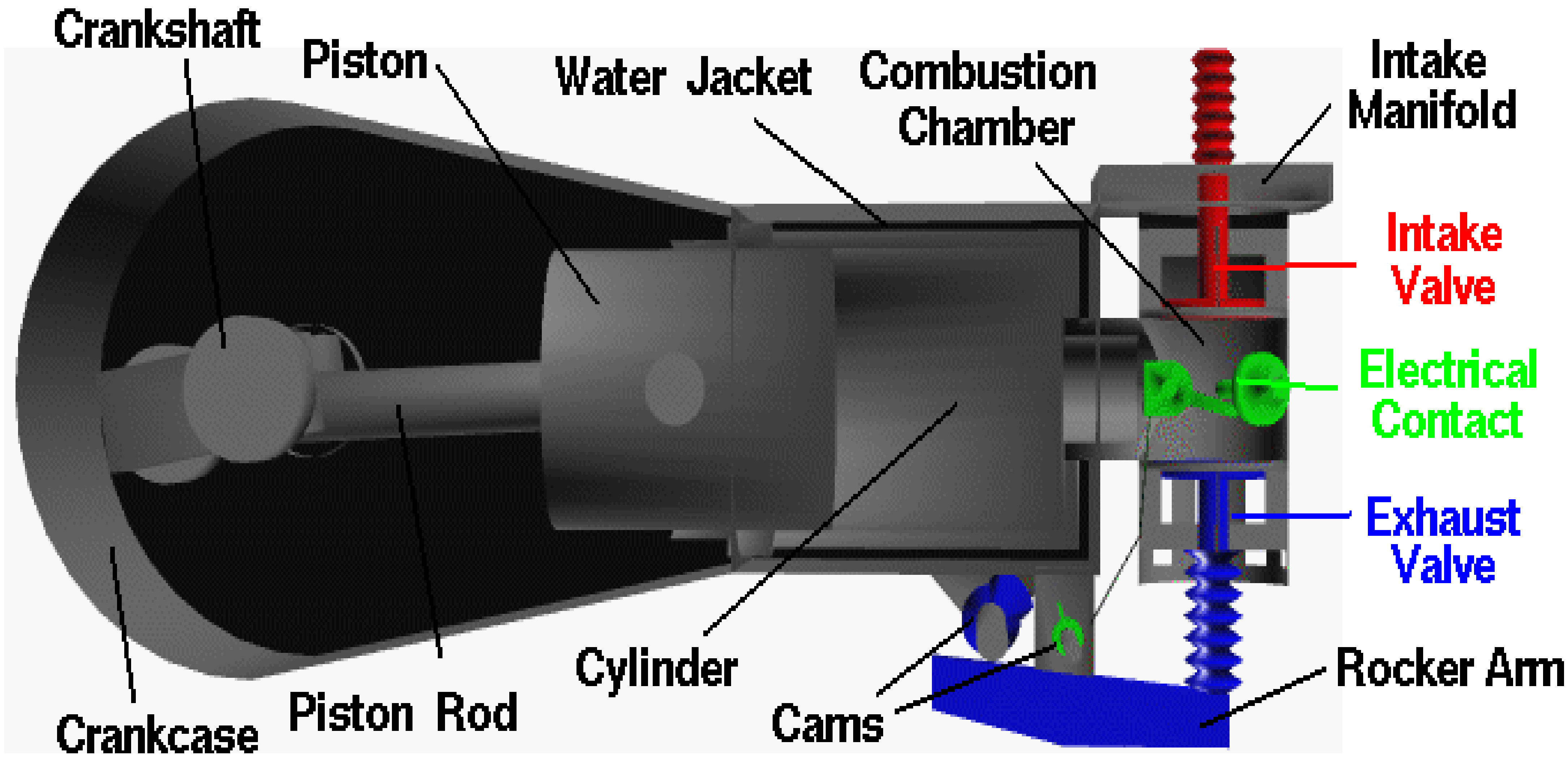


Figure2: Engine components

Internal combustion Engine Components:

I.C. Engine components shown in figure1 and figure2 are defined as follows:

- **Block :** Body of the engine containing cylinders, made of cast iron or aluminium.
- **Cylinder :** The circular cylinders in the engine block in which the pistons reciprocate back and forth.
- **Head :** The piece which closes the end of the cylinders, usually containing part of the clearance volume of the combustion chamber.
- **Combustion chamber:** The end of the cylinder between the head and the piston face where combustion occurs.
  - The size of combustion chamber continuously changes from minimum volume when the piston is at TDC to a maximum volume when the piston at BDC.

- **Crankshaft :** Rotating shaft through which engine work output is supplied to external systems.
  - The crankshaft is connected to the engine block with the main bearings.
  - It is rotated by the reciprocating pistons through the connecting rods connected to the crankshaft, offset from the axis of rotation. This offset is sometimes called crank throw or crank radius.
- **Connecting rod :** Rod connecting the piston with the rotating crankshaft, usually made of steel or alloy forging in most engines but may be aluminum in some small engines.
- **Piston rings:** Metal rings that fit into circumferential grooves around the piston and form a sliding surface against the cylinder walls.

- **Camshaft :** Rotating shaft used to push open valves at the proper time in the engine cycle, either directly or through mechanical or hydraulic linkage (push rods, rocker arms, tappets) .
- **Push rods :** The mechanical linkage between the camshaft and valves on overhead valve engines with the camshaft in the crankcase.
- **Crankcase :** Part of the engine block surrounding the crankshaft.
  - In many engines the oil pan makes up part of the crankcase housing.
- **Exhaust manifold :** Piping system which carries exhaust gases away from the engine cylinders, usually made of cast iron .

- **Intake manifold :**Piping system which delivers incoming air to the cylinders, usually made of cast metal, plastic, or composite material.
  - In most SI engines, fuel is added to the air in the intake manifold system either by fuel injectors or with a carburetor.
  - The individual pipe to a single cylinder is called runner.
- **Carburetor :** A device which meters the proper amount of fuel into the air flow by means of pressure differential.
  - For many decades it was the basic fuel metering system on all automobile (and other) engines.
- **Spark plug :** Electrical device used to initiate combustion in an SI engine by creating high voltage discharge across an electrode gap.

I.C. Engine components apart from components shown in the figure:

- **Exhaust System:** Flow system for removing exhaust gases from the cylinders, treating them, and exhausting them to the surroundings.
  - It consists of an exhaust manifold which carries the exhaust gases away from the engine, a thermal or catalytic converter to reduce emissions, a muffler to reduce engine noise, and a tailpipe to carry the exhaust gases away from the passenger compartment.
- **Flywheel :** Rotating mass with a large moment of inertia connected to the crank shaft of the engine.
  - The purpose of the flywheel is to store energy and furnish large angular momentum that keeps the engine rotating between power strokes and smooths out engine operation.

- **Fuel injector :** A pressurized nozzle that sprays fuel into the incoming air (SI engines)or into the cylinder (CI engines).
- **Fuel pump :** Electrically or mechanically driven pump to supply fuel from the fuel tank (reservoir) to the engine.
- **Glow plug :** Small electrical resistance heater mounted inside the combustion chamber of many CI engines, used to preheat the chamber enough so that combustion will occur when first starting a cold engine.
  - The glow plug is turn off after the engine is started.
- **Starter :** Several methods are used to start IC engines. Most are started by use of an electric motor (starter) geared to the engine flywheel. Energy is supplied from an electric battery.

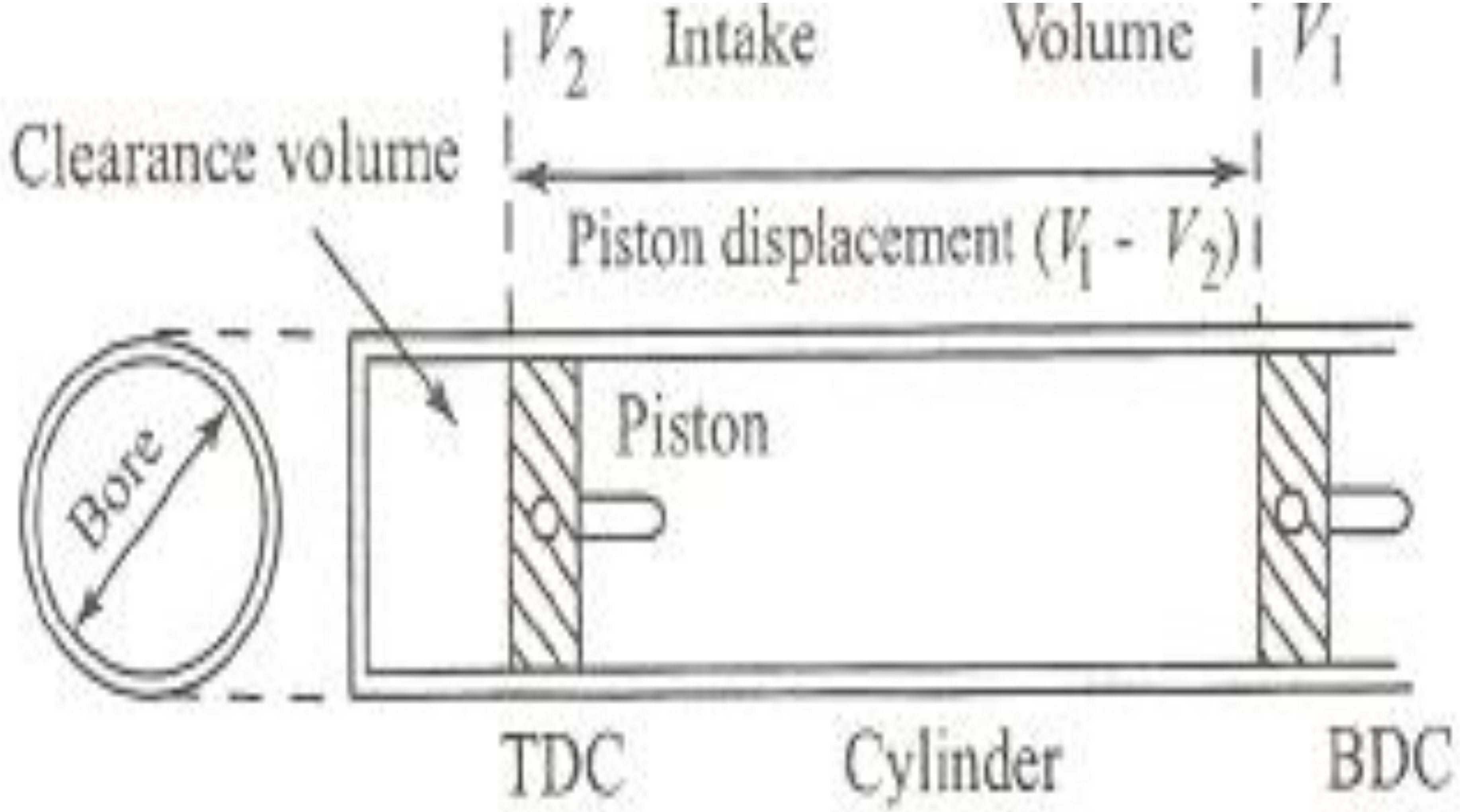


Figure3 : Engine Terminology

Engine Terminology :

Figure 3, shows the pressure volume diagram of ideal engine cycle along with engine terminology as follows:

- **Top Dead Center (TDC):** Position of the piston when it stops at the furthest point away from the crankshaft.
  - Top because this position is at the top of the engines (not always), and dead because the piston stops as this point. Because in some engines **TDC** is not at the top of the engines(e.g: horizontally opposed engines, radial engines,etc,.) Some sources call this position **Head End Dead Center (HEDC).**
  - Some source call this point **TOP Center (TC).**
  - When the piston is at TDC, the volume in the cylinder is a minimum called the clearance volume.

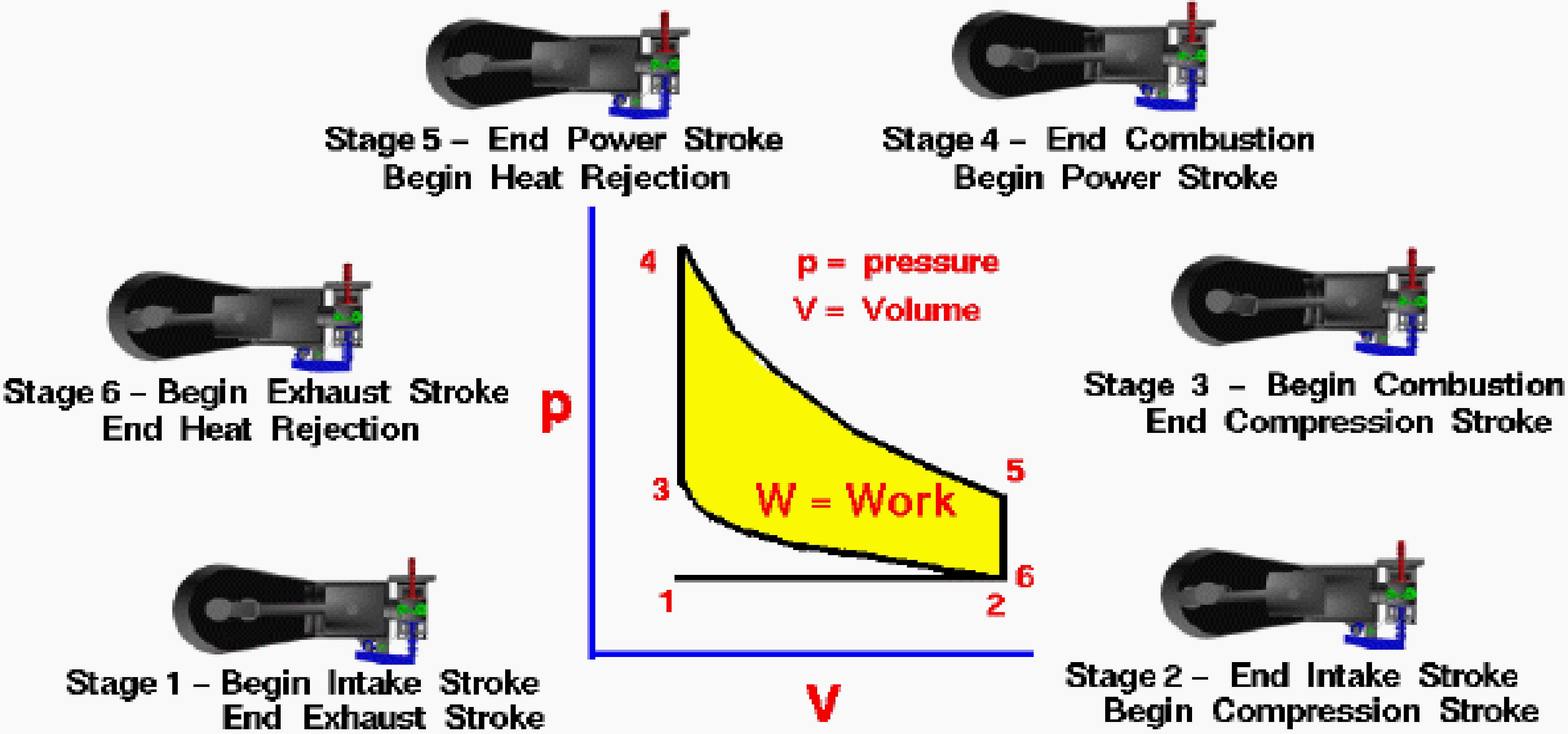
- **Bottom Dead Center (BDC):** Position of the piston when it stops at the point closest to the crankshaft.
  - Some sources call this **Crank End Dead Center (CEDC)** because it is not always at the bottom of the engine.Some source call this point **Bottom Center (BC).**
- **Stroke :** Distance traveled by the piston from one extreme position to the other : TDC to BDC or BDC to TDC.
- **Bore :**It is defined as **c**ylinder diameter or piston face diameter; piston face diameter is same as cylinder diameter(minus small clearance).
- **Swept volume/Displacement volume :** Volume displaced by the piston as it travels through one stroke.
  - Swept volume is defined as stroke times bore.
  - Displacement can be given for one cylinder or entire engine (one cylinder times number of cylinders).

- **Clearance volume :** It is the minimum volume of the cylinder available for the charge (air or air fuel mixture) when the piston reaches at its outermost point (top dead center or outer dead center) during compression stroke of the cycle.
  - Minimum volume of combustion chamber with piston at TDC.
- **Compression ratio :** The ratio of total volume to clearance volume of the cylinder is the compression ratio of the engine.
  - Typically compression ratio for SI engines varies form 8 to 12 and for CI engines it varies from 12 to 24

SI Engine Ideal Otto Cycle

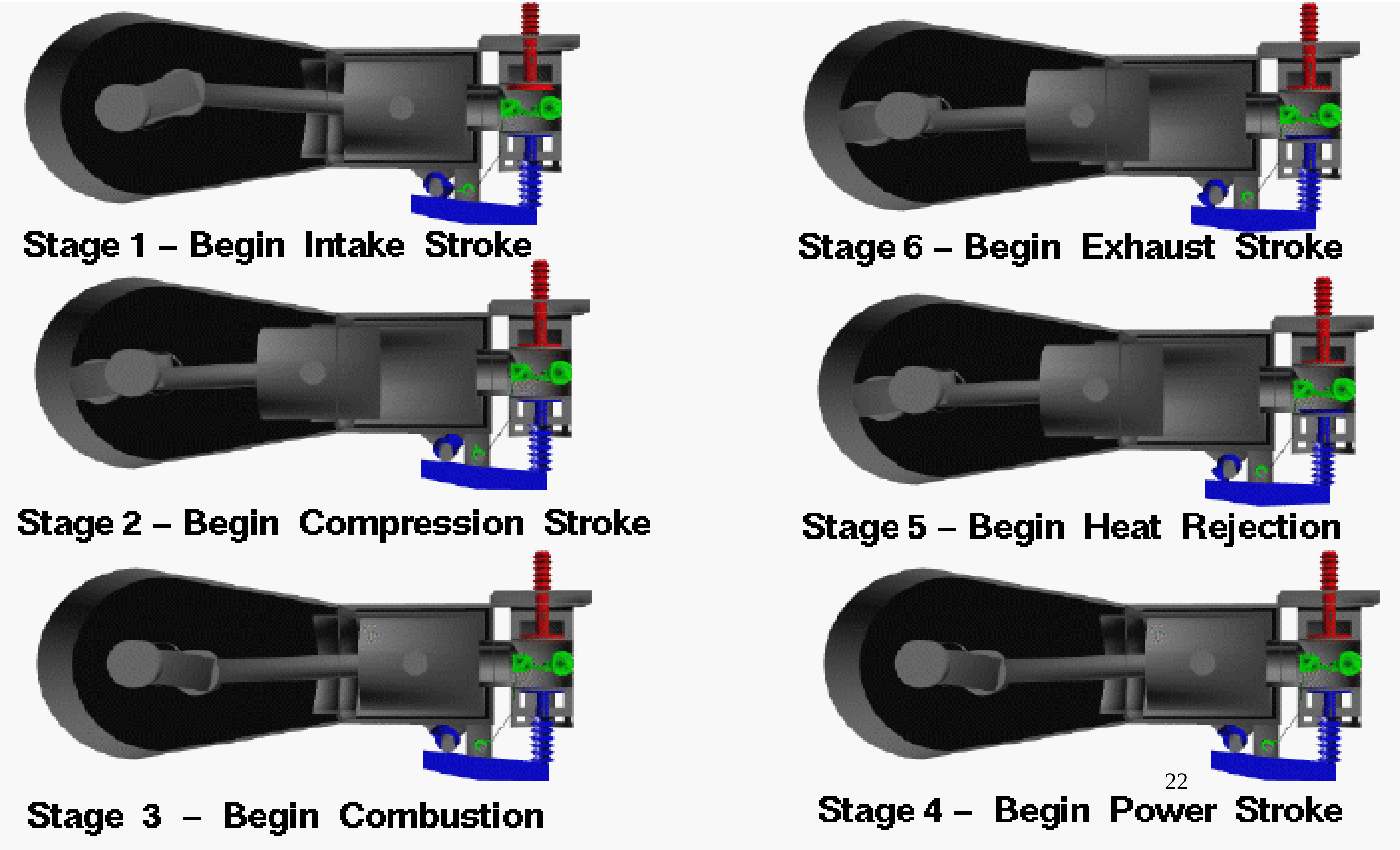
- We will be dealing with four stroke SI engine, the following figure shows the PV diagram of Ideal Otto cycle.

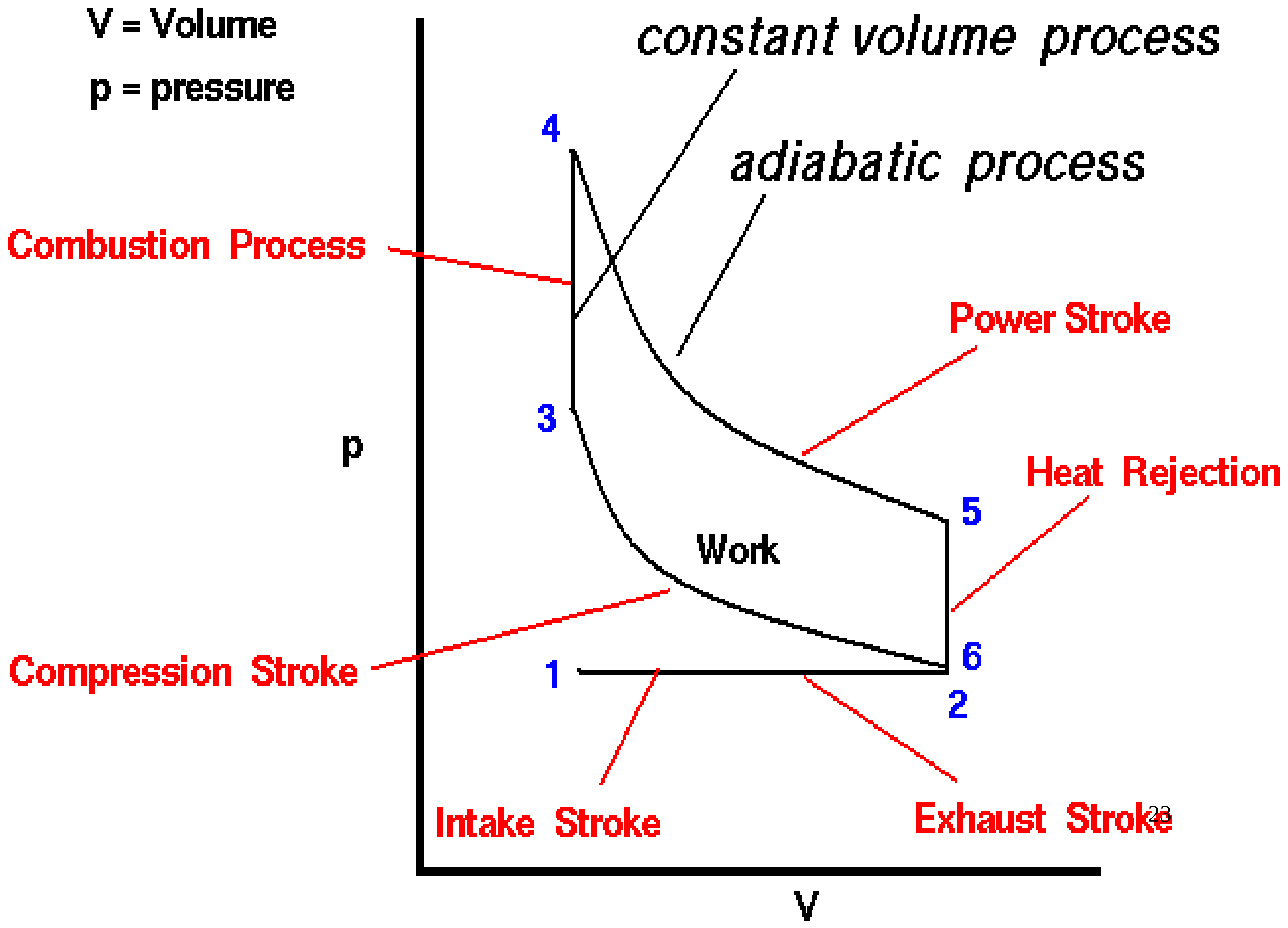
Ideal Otto Cycle



Work available from the cycle equals enclosed area of p–V diagram.

Power equals work times cycle per second.


Stage 1 – Begin Intake Stroke
Stage 2 – Begin Compression Stroke
Stage 3 – Begin Combustion
Stage 4 – Begin Power Stroke
Stage 5 – Begin Heat Rejection
Stage 6 – Begin Exhaust Stroke


V = Volume
p = pressure
constant volume process
adiabatic process
4
Combustion Process
Power Stroke
3
p
Heat Rejection
5
Work
6
Compression Stroke
1
2
Intake Stroke
Exhaust Stroke
V

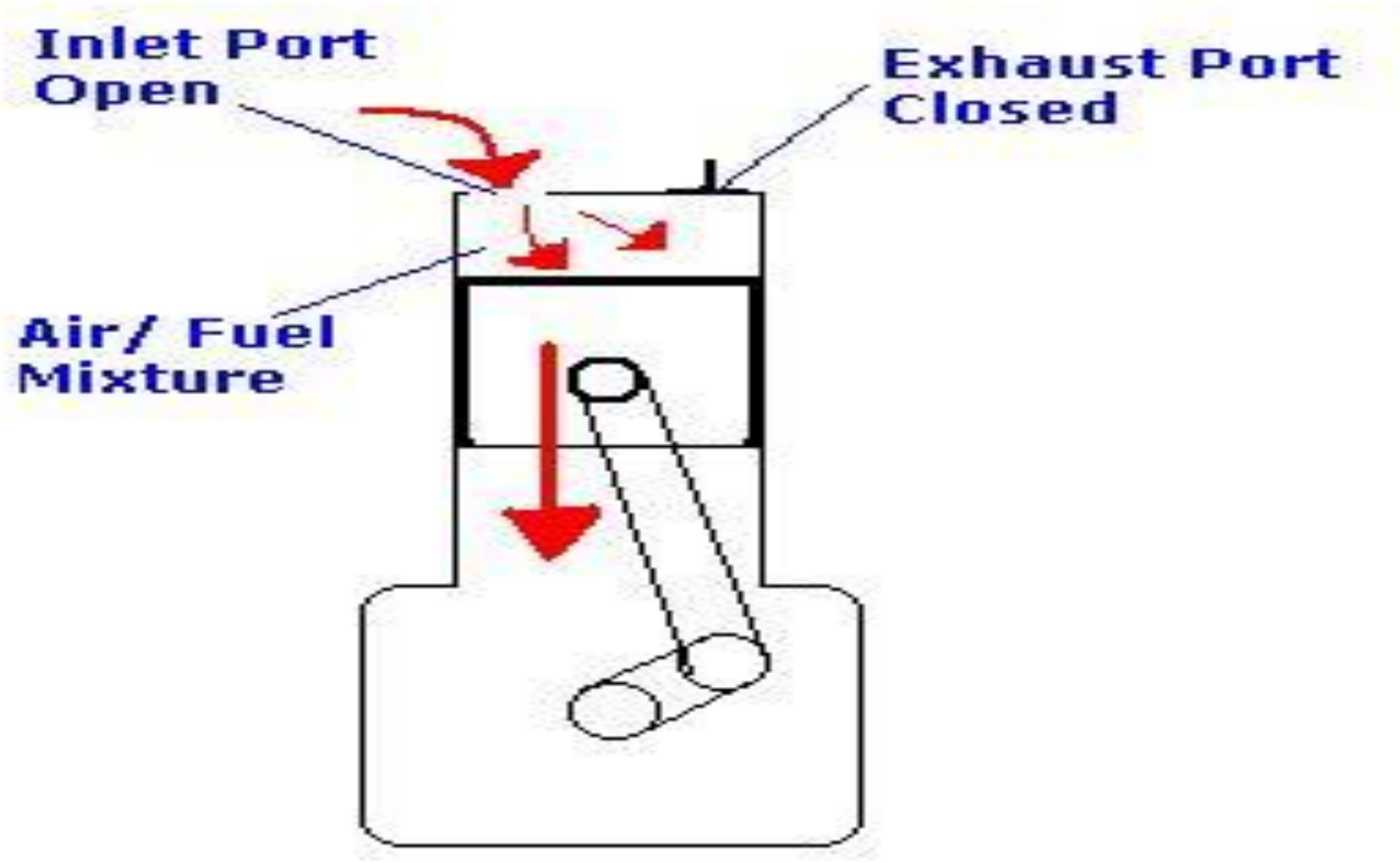


Figure4: Suction stroke

Four strokes of SI Engine Cycle :

- **Suction/Intake stroke:** Intake of air fuel mixture in cylinder through intake manifold.
  - The piston travel from TDC to BDC with the intake valve open and exhaust valve closed.
  - This creates an increasing volume in the combustion chamber, which in turns creates a vacuum.
  - The resulting pressure differential through the intake system from atmospheric pressure on the outside to the vacuum on the inside causes air to be pushed into the cylinder.
  - As the air passes through the intake system fuel is added to it in the desired amount by means of fuel injectors or a carburettor.

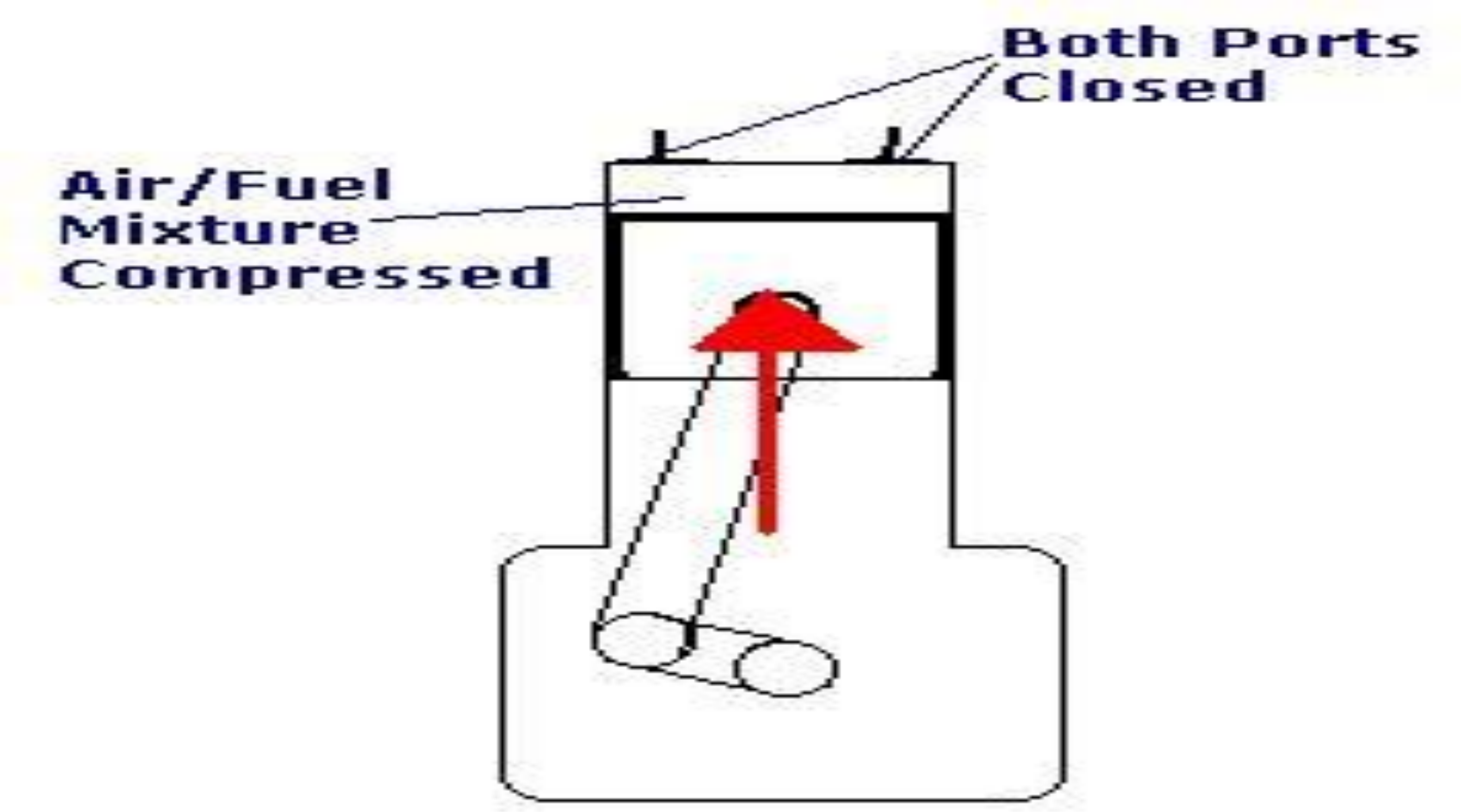


Figure5: Compression Stroke

- **Compression stroke:** When the piston reaches BDC, the intake valve closes and the piston travels back to TDC with all valves closed.
  - This compresses air fuel mixture, raising both the pressure and temperature in the cylinder.
  - Near the end of the compression stroke the spark plug is fired and the combustion is initiated.

- **Combustion** of the air-fuel mixture occurs in a very short but finite length of time with the piston near TDC (i.e., nearly constant volume combustion).
  - It starts near the end of the compression stroke slightly before TDC and lasts into the power stroke slightly after TDC.
  - Combustion changes the composition of the gas mixture to that of exhaust products and increases the temperature in the cylinder to a high value.
  - This in turn increases the pressure in the cylinder to a high value.

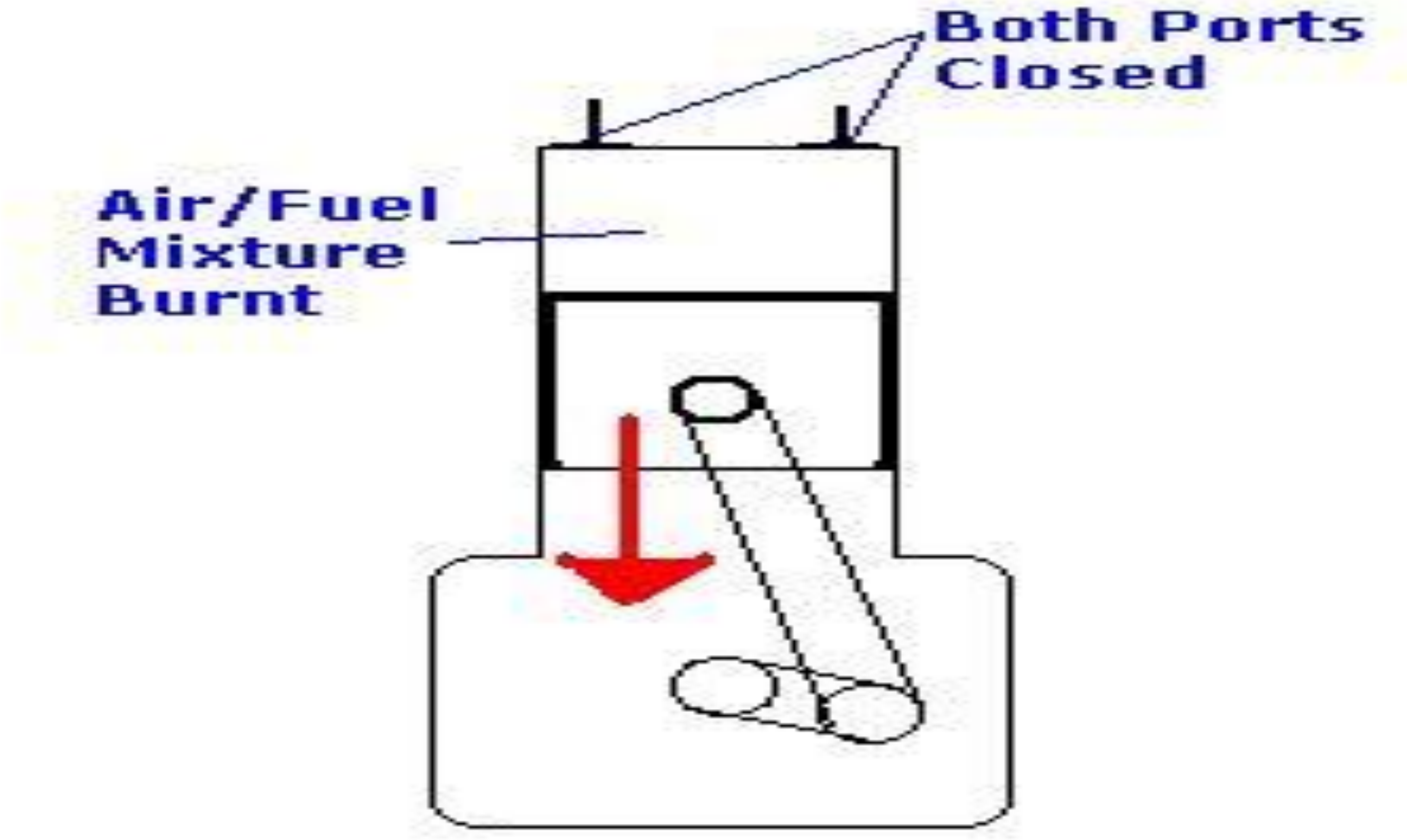


Figure6: Combustion followed by Expansion stroke.

- **Expansion stroke/Power stroke :** With all valves closed the high pressure created by the combustion process pushes the piston away from the TDC.
  - This is the stroke which produces work output of the engine cycle.
  - As the piston travels from TDC to BDC, cylinder volume is increased, causing pressure and temperature to drop.

- **Exhaust Blowdown** : Late in the power stroke, the exhaust valve is opened and exhaust blowdown occurs.
  - Pressure and temperature in the cylinder are still high relative to the surroundings at this point, and a pressure differential is created through the exhaust system which is open to atmospheric pressure.
  - This pressure differential causes much of the hot exhaust gas to be pushed out of the cylinder and through the exhaust system when the piston is near BDC.
  - This exhaust gas carries away a high amount of enthalpy, which lowers the cycle thermal efficiency.
  - Opening the exhaust valve before BDC reduces the work obtained but is required because of the finite time needed for exhaust blowdown.

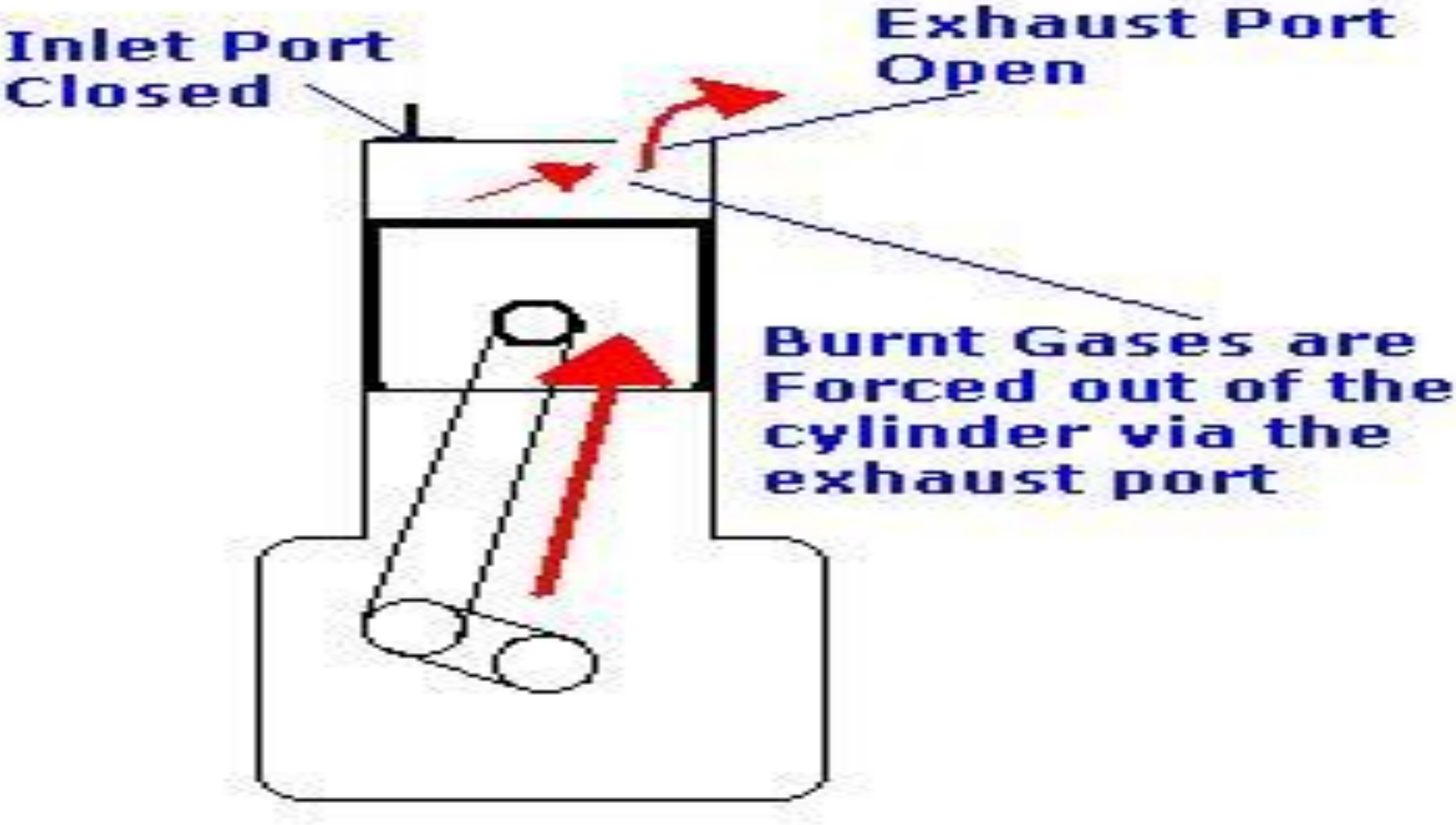
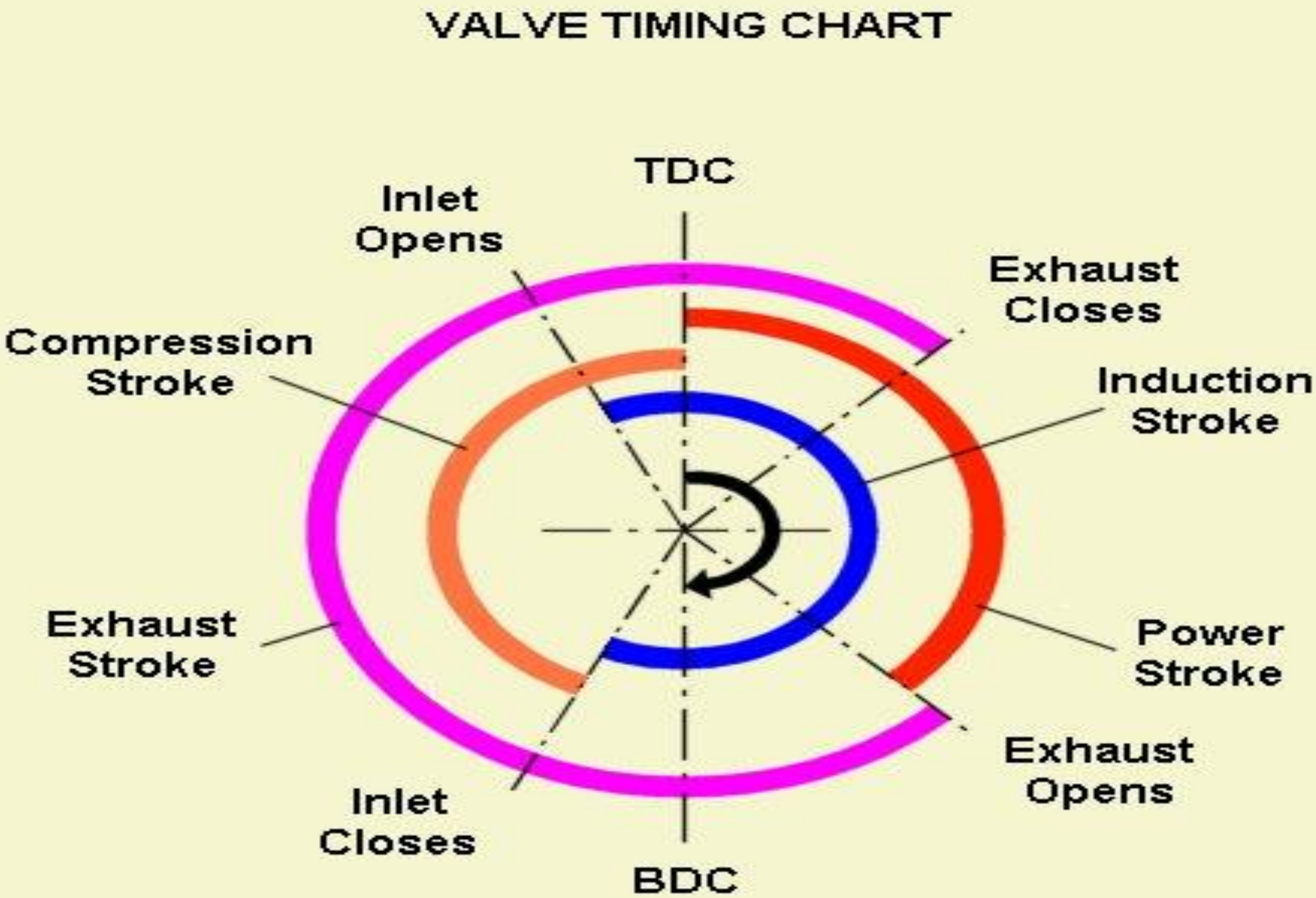


Figure7: Exhaust blowdown followed by Exhaust stroke

- **Exhaust stroke:** By the time piston reaches BDC, exhaust blowdown is complete, but the cylinder is still full of exhaust gases at approximately atmospheric pressure.
  - With the exhaust valve remaining open, the piston travels from BDC to TDC in the exhaust stroke.
  - This pushes most of the remaining exhaust gases out of the cylinder into the exhaust system at about atmospheric pressure, leaving only that trapped in the clearance volume when the piston reaches TDC.

- Near the end of the exhaust stroke before TDC, the intake valve starts to open, so that it is fully open by TDC when the new intake stroke starts the next cycle.
- Near TDC the exhaust valve starts to close and finally is fully closed sometime after TDC.
- This period when both the intake valve and exhaust valve are open is called **valve overlap,** it can be clearly seen in valve timing chart given below.


VALVE TIMING CHART
TDC
Inlet Opens
Exhaust Closes
Compression Stroke
Induction Stroke
Exhaust Stroke
Power Stroke
Exhaust Opens
Inlet Closes
BDC

Compression Ignition Engine :

- We will deal with Compression Ignition engine.
- The ideal diesel cycle PV diagram is shown in following figure 8.

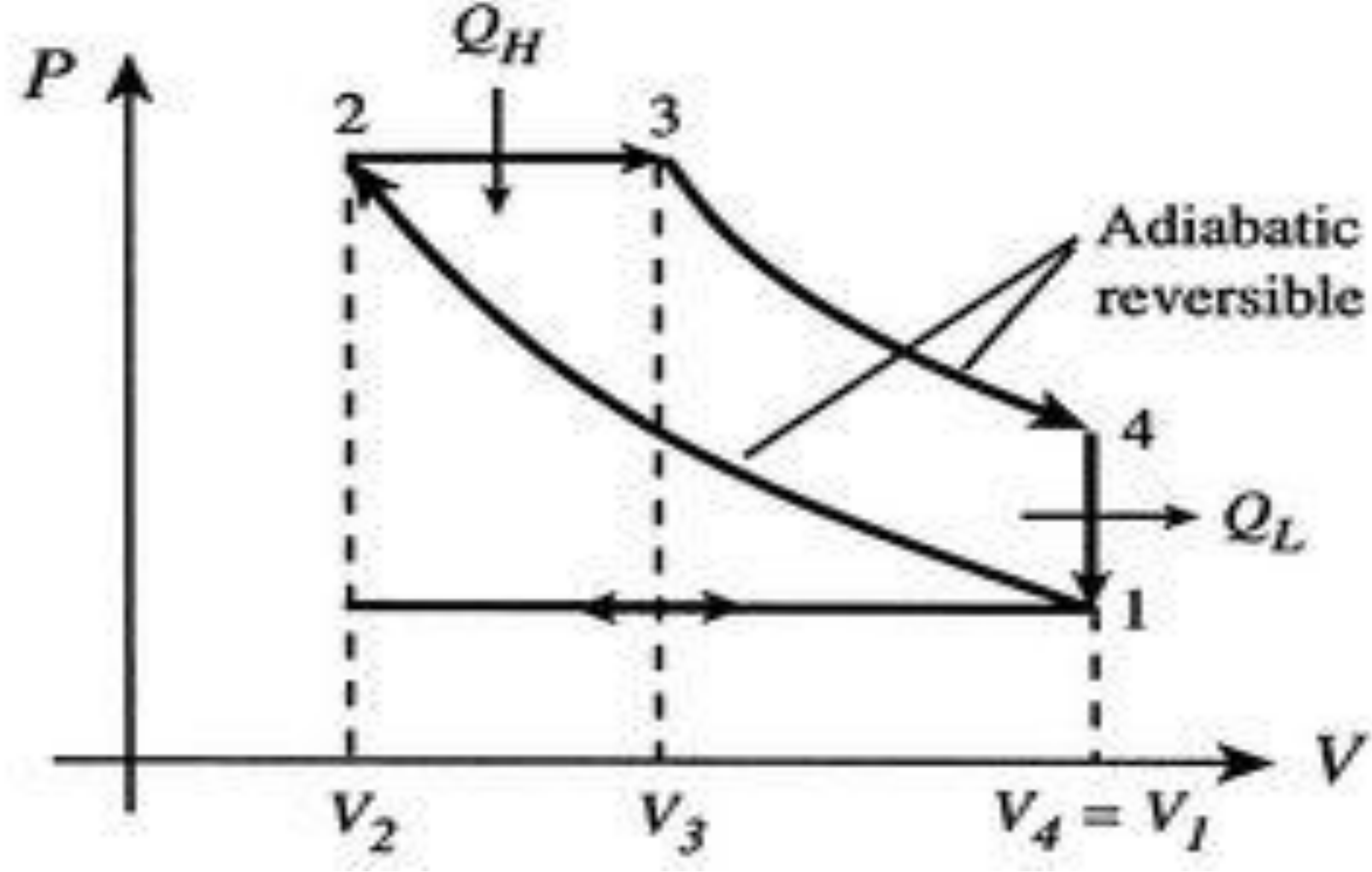


Figure8: Ideal diesel cycle P-V Diagram.

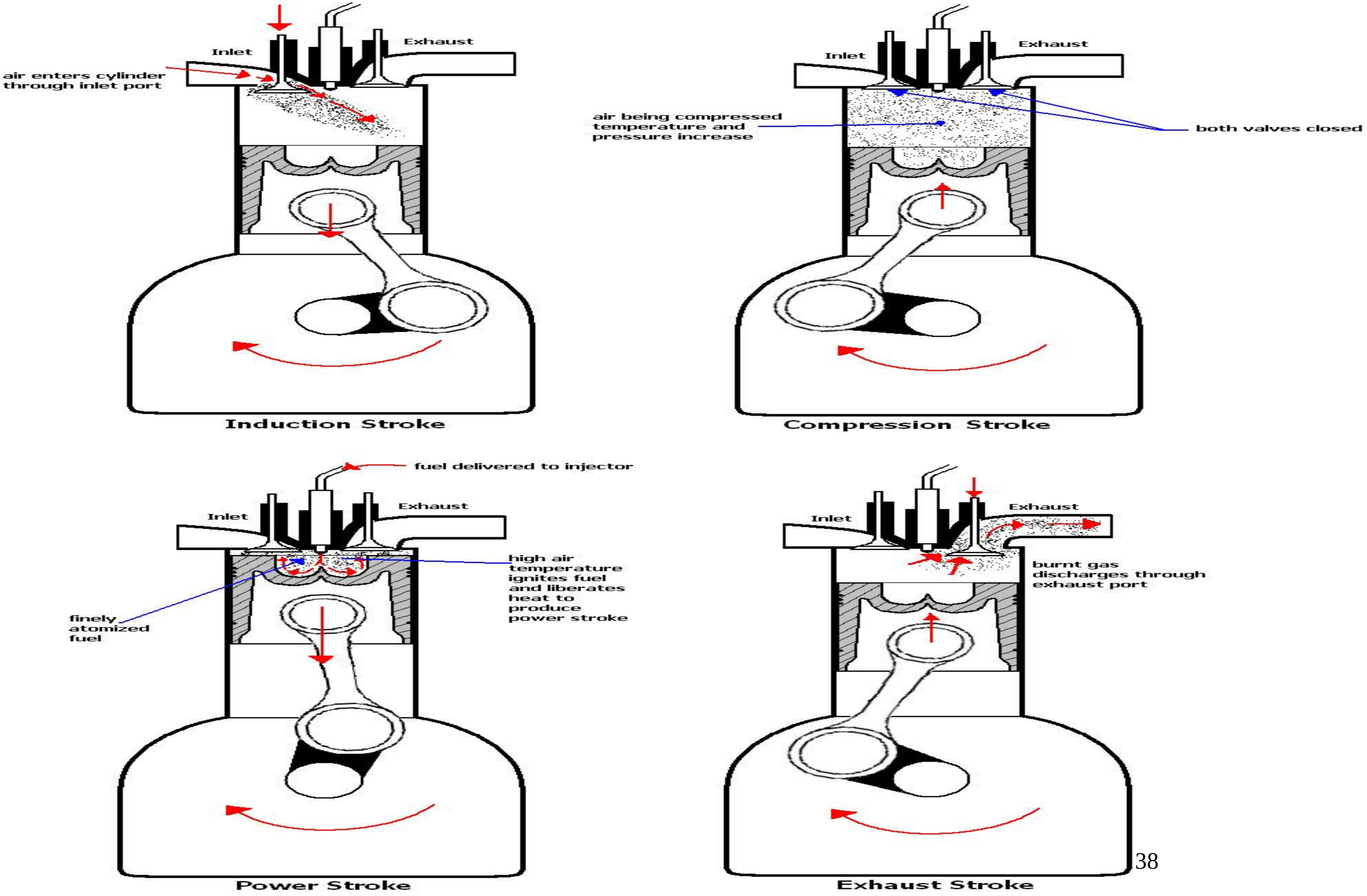


Figure9: Four strokes of ideal Diesel cycle.

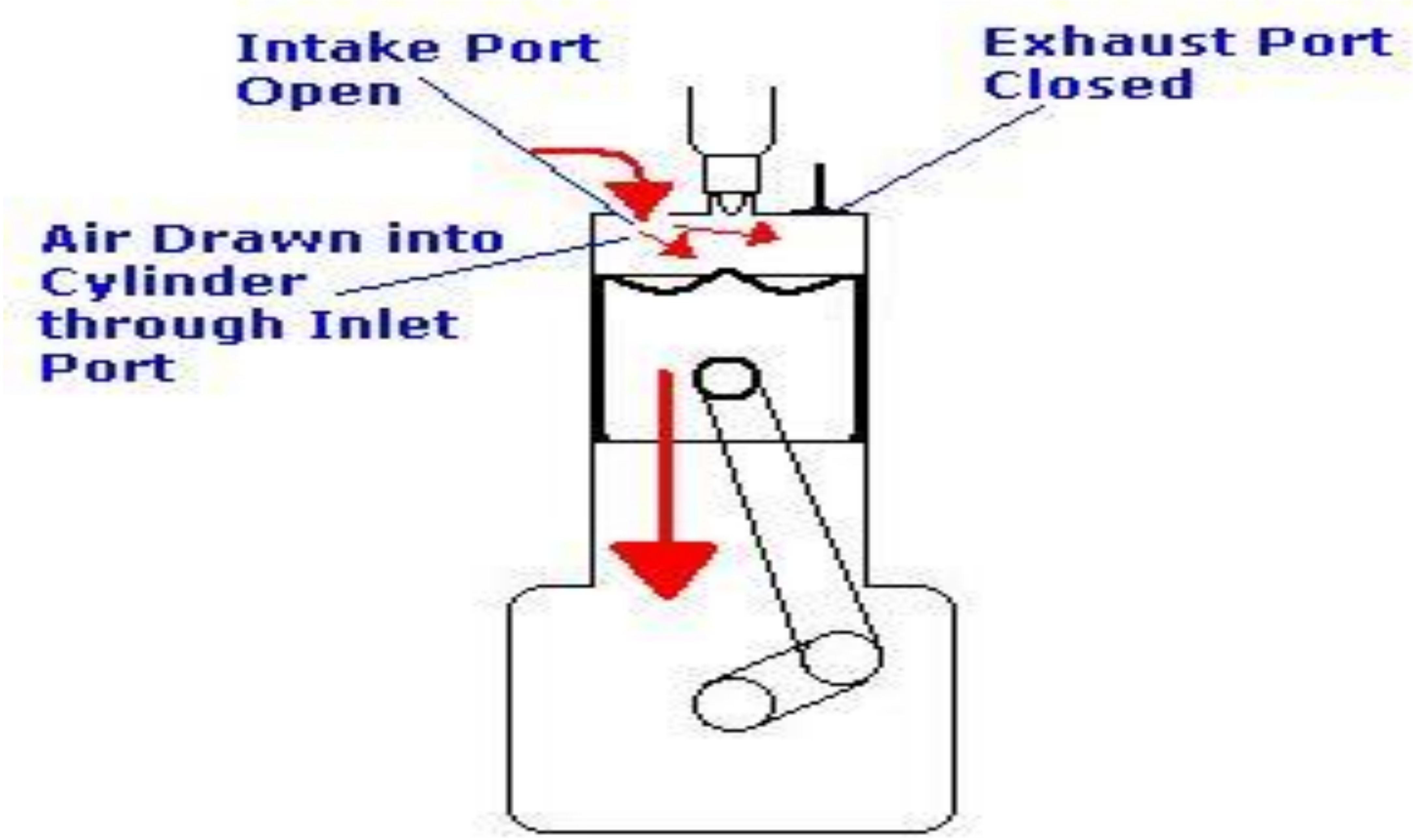


Figure10:Suction stroke

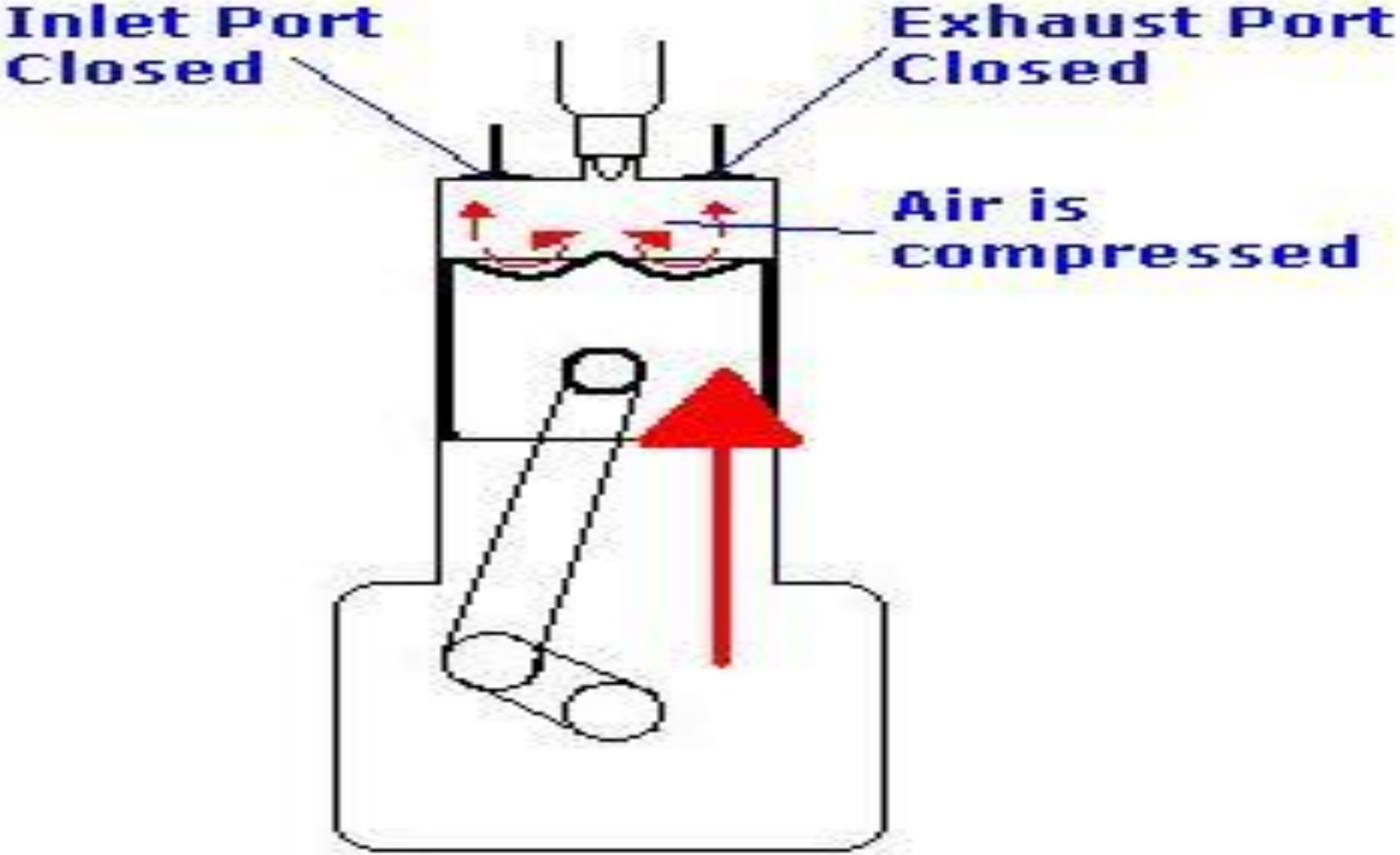


Figure11: Compression stroke

Four strokes of CI Engine Cycle :

- **Intake/Suction Stroke :** The same as the intake stroke in an SI engine with one major difference : no fuel is added to the incoming air, refer figure 10.
- **Compression Stroke :** The same as in an SI engine except that only air is compressed and compression is to higher pressures and temperature, refer figure11.
  - Late in the compression stroke fuel is injected directly into the combustion chamber, where it mixes with very hot air.
  - This causes the fuel to evaporate and self ignite, causing combustion to start.

» **Combustion** is fully developed by TDC and continues at about constant pressure until fuel injection is complete and the piston has started towards BDC, refer figure12.

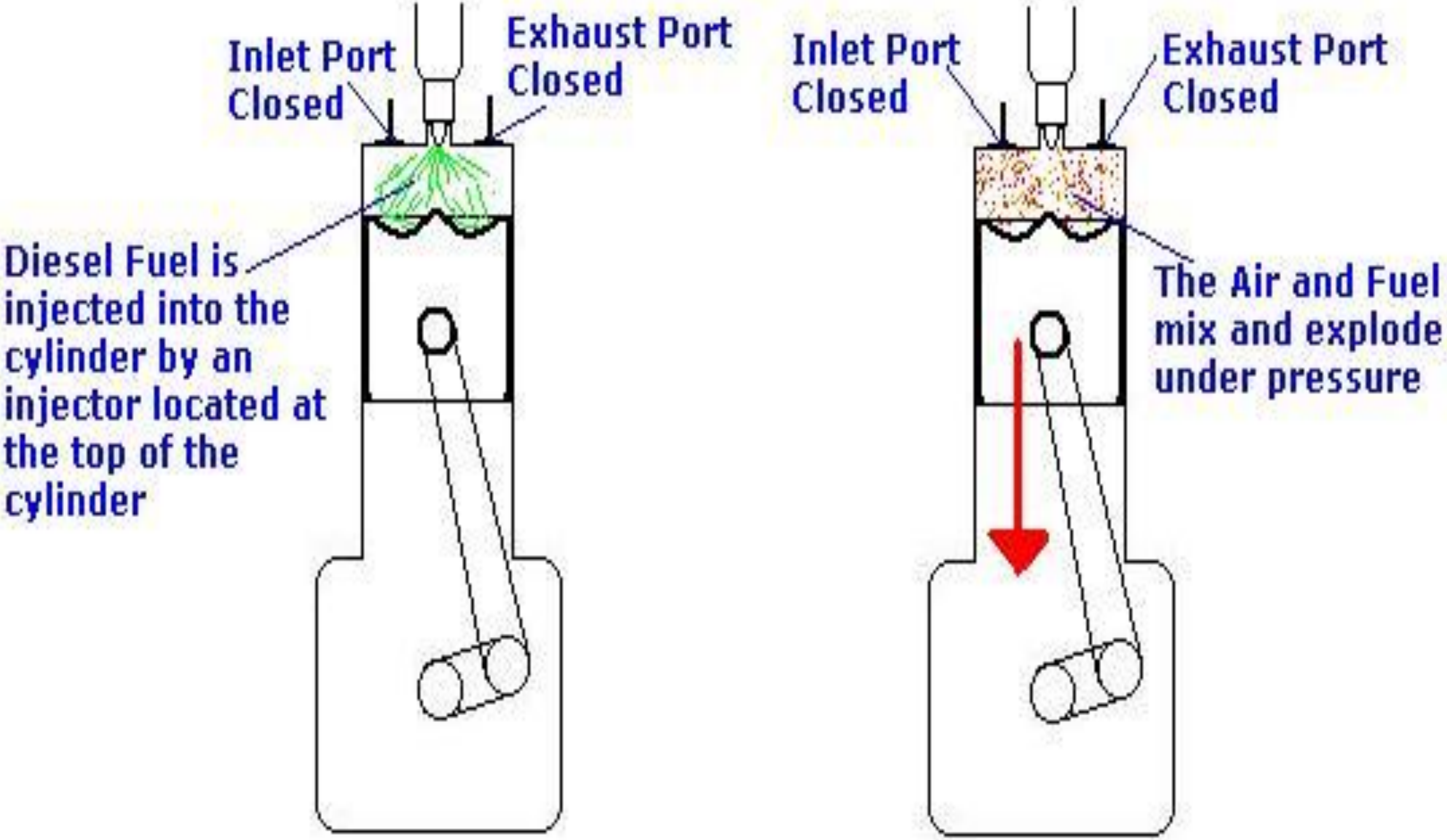


Figure12:Fuel injection and combustion followed by Expansion stroke .

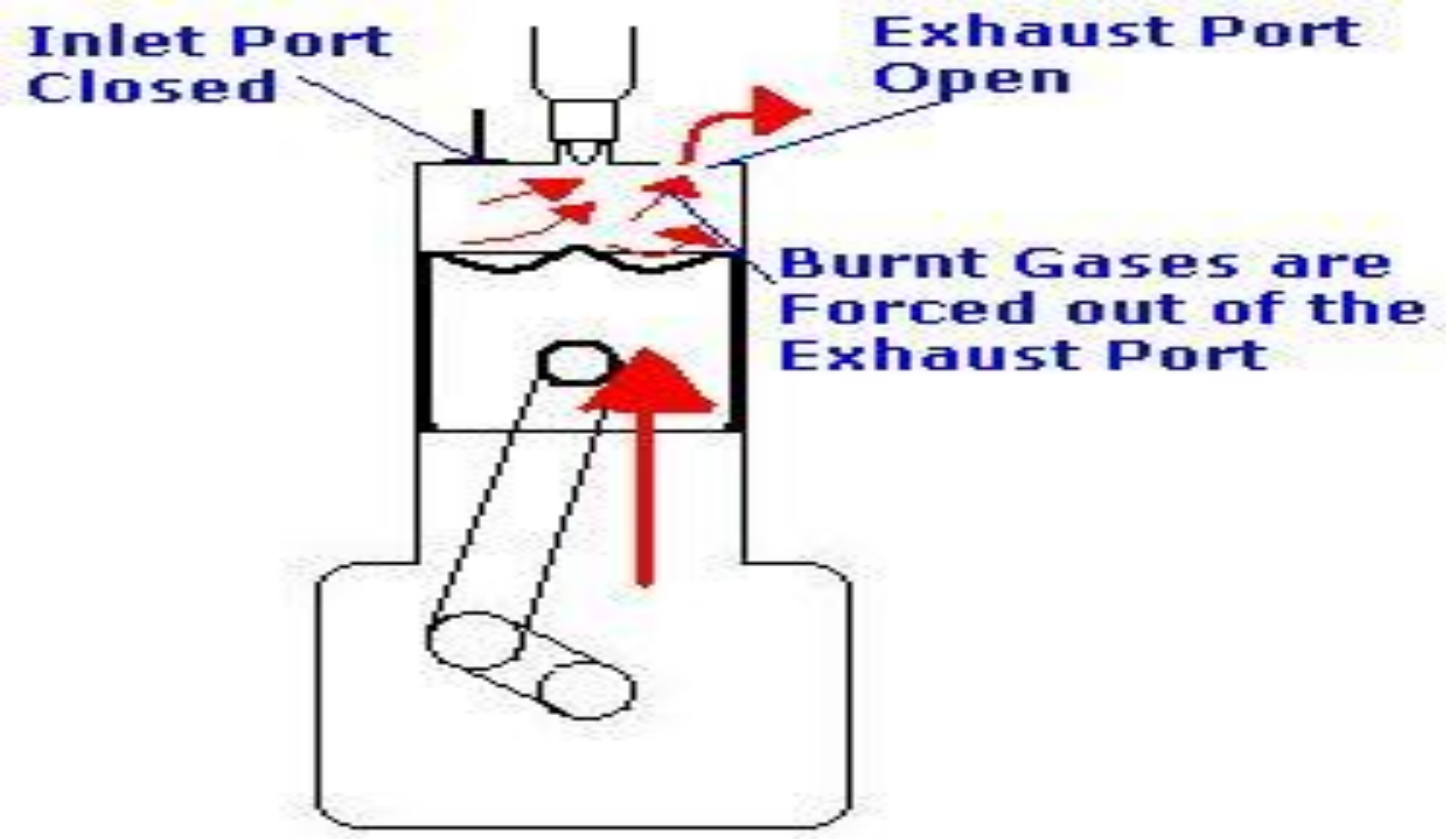


Figure13: Exhaust stroke followed by exhaust blowdown.

- **Expansion/Power stroke :** The power stroke continues as combustion ends and the piston travels towards BDC, refer figure 12.
  - **Exhaust blowdown** same as with an SI engine.
- **Exhaust stroke :** Same as with an SI engine, refer figure 13.

Concept explanation :

- Animation of internal combustion engine, for the specified 4-stroke engine should be able to show:
  - All four strokes
  - Combustion process
  - Pressure Volume (P-V)diagram.
- Based on the concept explanation on previous slides.

Problem statement:

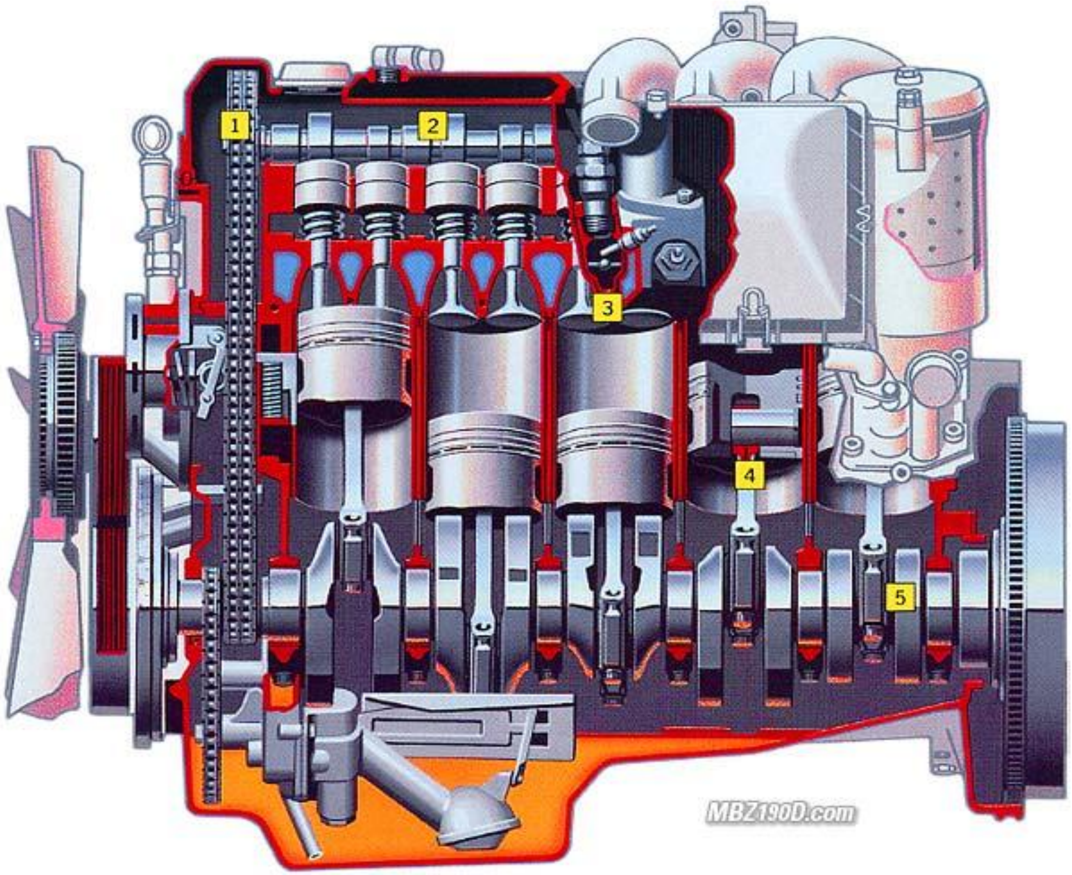
- Animation should show pressure variations during compression and expansion strokes of the engine.
- Graphical representation of pressure variation.
- It helps to know the pressure limits of the engine as well as compression ratio.
- Compression ratio defines the efficiency of the ideal engine cycle.

- With the **analogy** of human metabolism one can explain combustion of engine:
  - Human metabolism = Oxidization of food converts chemical energy into Mechanical energy.
    - Food = fuel
    - Oxygen=air
    - Optimum air fuel ratio leads to optimum engine performance = Balanced diet leads to healthy human life.
    - Cooling of engine via water, air or any coolant to maintain its temperature = Human body maintains its temperature by perspiration, sweating.

- User should be able to see the variation of pressure during expansion and compression processes of engine cycle :
  - Compression and Expansion are adiabatic processes defined by relation :
    - $P V^{\lambda} = \text{constant}$
    - The exponent λ for the compression and expansion processes is 1.4 for conventional fuels.
    - In other strokes, there is no pressure variations.

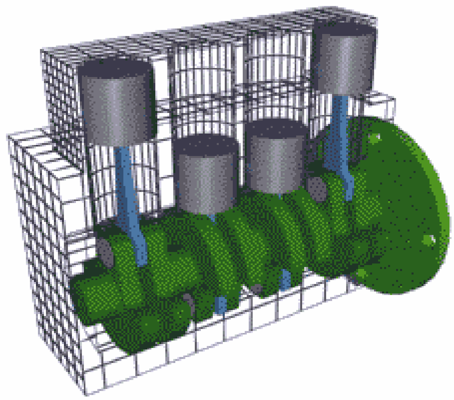
Internal combustion engine needs
fuel, ignition and compression
in order to run.

- Four-Stroke Gasoline Engine
- Two-Stroke Gasoline Engines
- Diesel Engine
- Rotary Engine
- Steam Engine

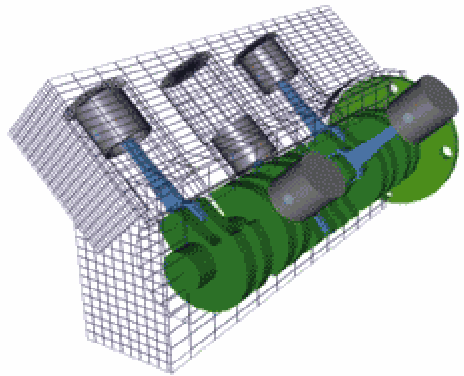


Configuration

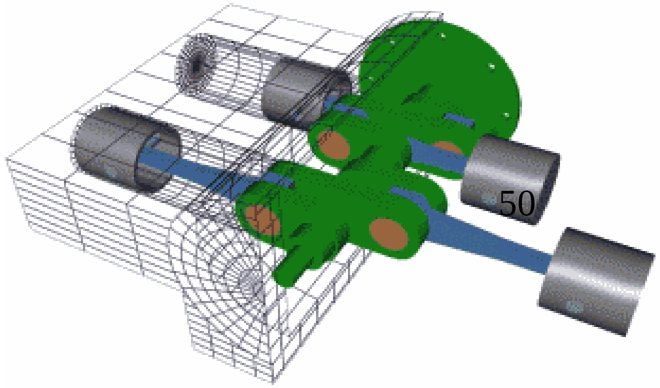
- <u>Inline Engines</u>: The cylinders are arranged in a line, in a single bank.



- <u>V Engines</u>: The cylinders are arranged in two banks, set at an angle to one another.

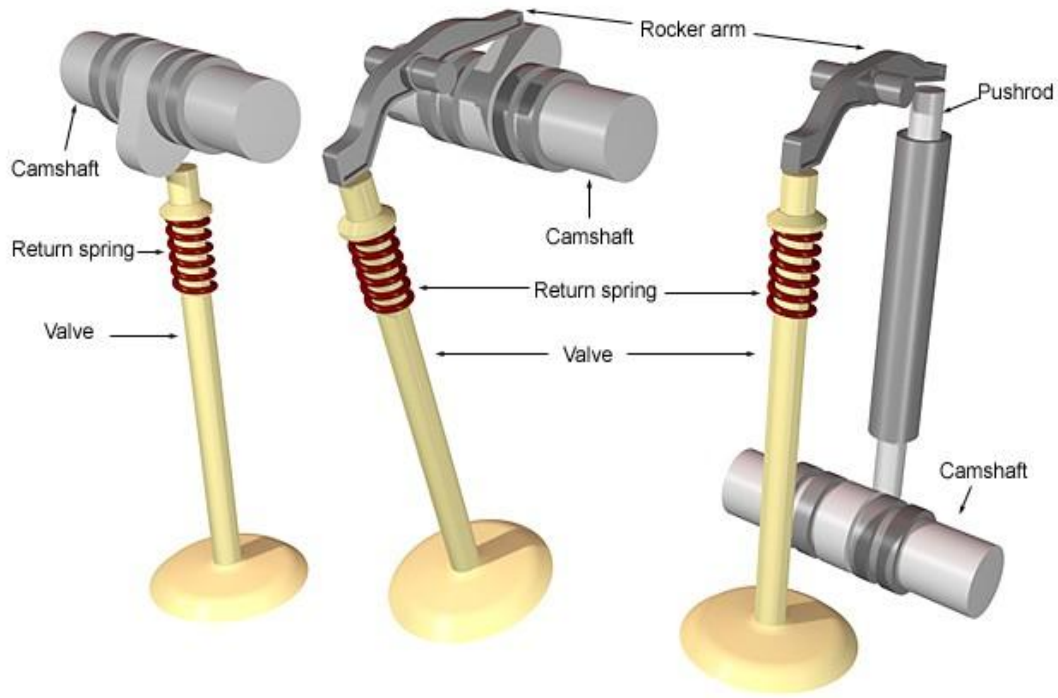


- <u>Flat Engines</u>: The cylinders are arranged in two banks on opposite sides of the engine



Parts

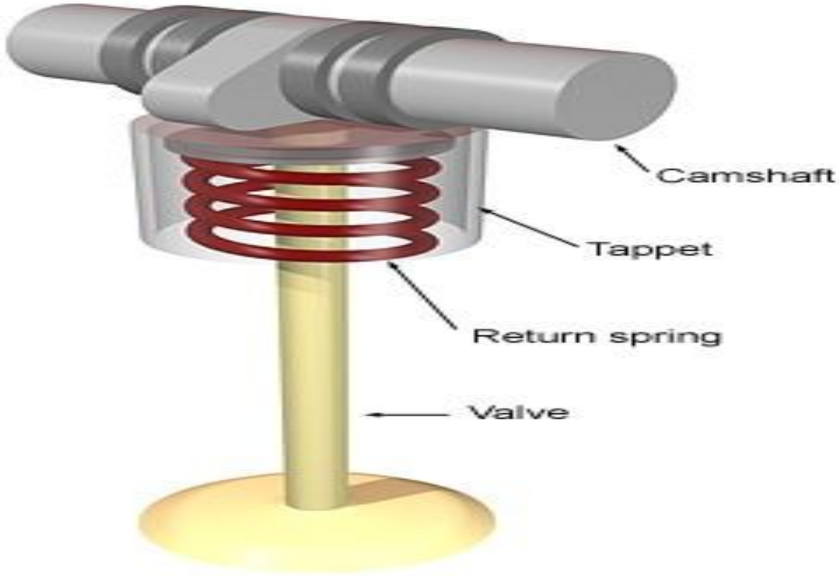
Valves: Minimum
Two Valves pre Cylinder



•Exhaust Valve lets the exhaust gases escape the combustion Chamber. (Diameter is smaller then Intake valve)

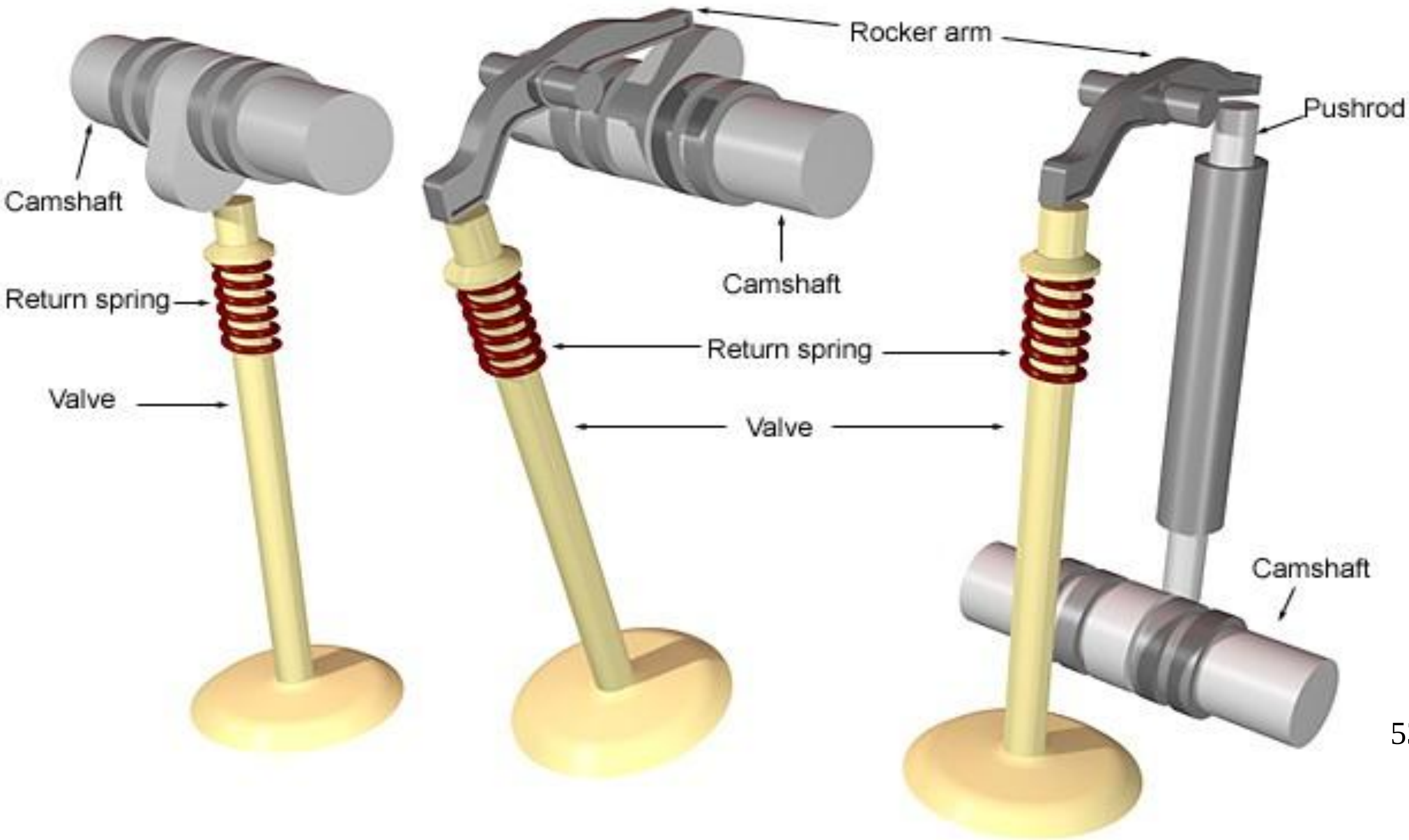
•Intake Valve lets the air or air fuel mixture to enter the combustion chamber. (Diameter is larger than the exhaust valve)

Valve Springs: Keeps the valves Closed.

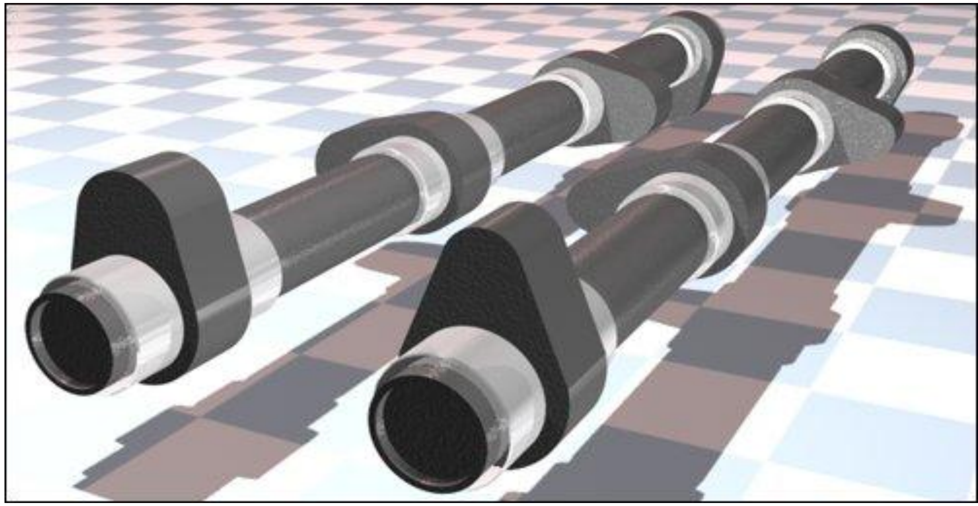


Valve Lifters: Rides the cam lobe and helps in opening the valves.

Different arrangement of valve and camshaft.



<u>Cam Shaft</u>: The shaft that has intake and Exhaust cams for operating the valves.



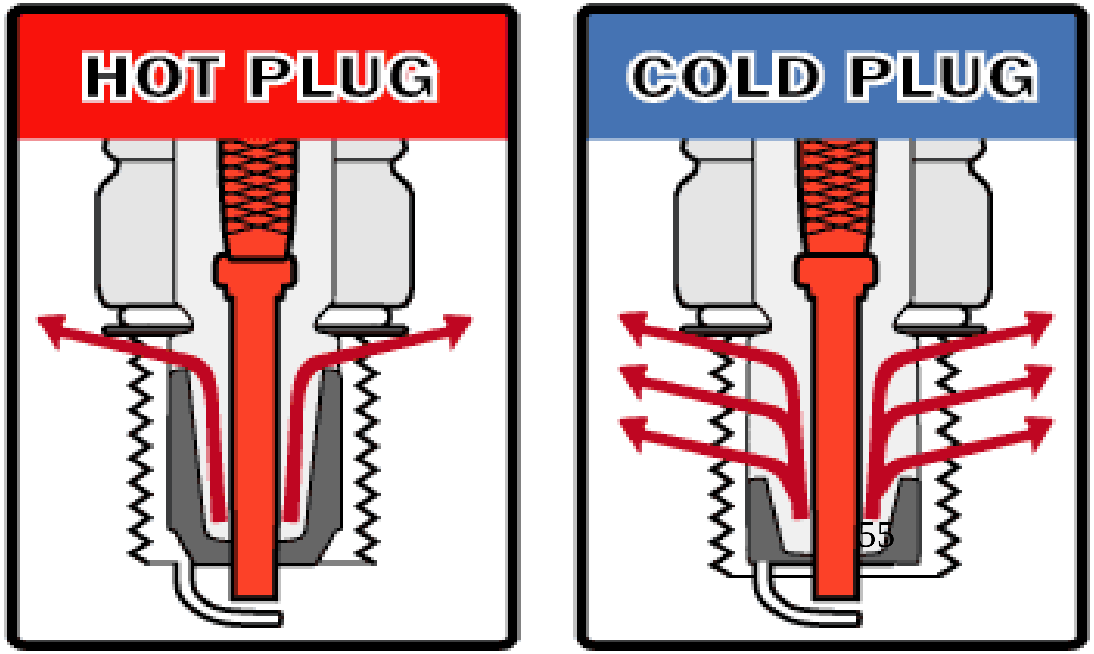
<u>Cam Lobe</u>: Changes rotary motion into reciprocating motion.

Camshaft location is one way to classify engines.
Overhead cam, SOHC, DOHC

Spark Plug

It provides the means of ignition when the gasoline engine’s piston is at the end of compression stroke, close to Top Dead Center(TDC)

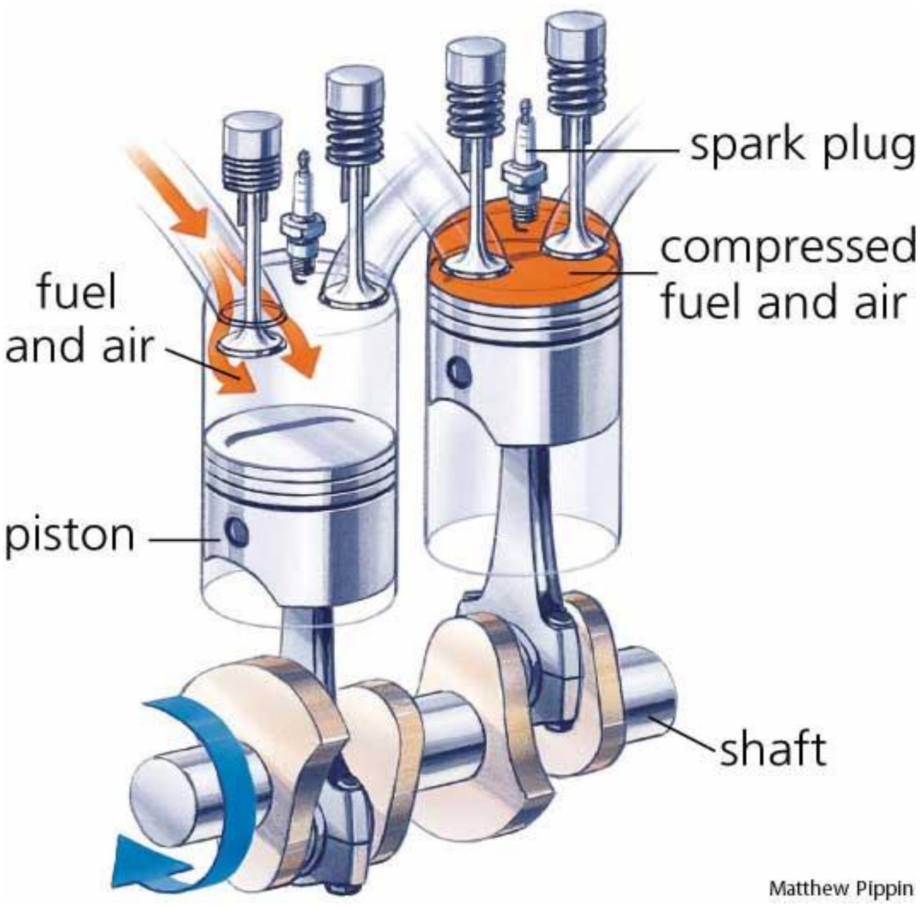
The difference between a "hot" and a "cold" spark plug is that the ceramic tip is longer on the hotter plug.



Piston

A movable part fitted into a cylinder, which can receive and transmit power.

Through connecting rod, forces the crank shaft to rotate.



Cylinder head

Part that covers and encloses the Cylinder. It contains cooling fins or water jackets and the valves. Some engines contains the cam shaft in the cylinder head.

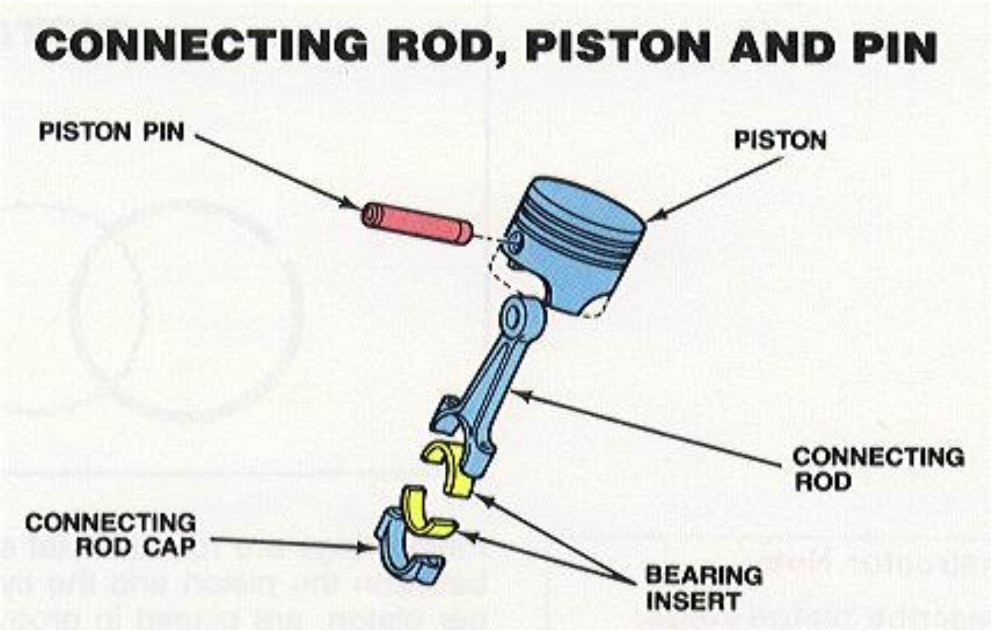
Engine Block

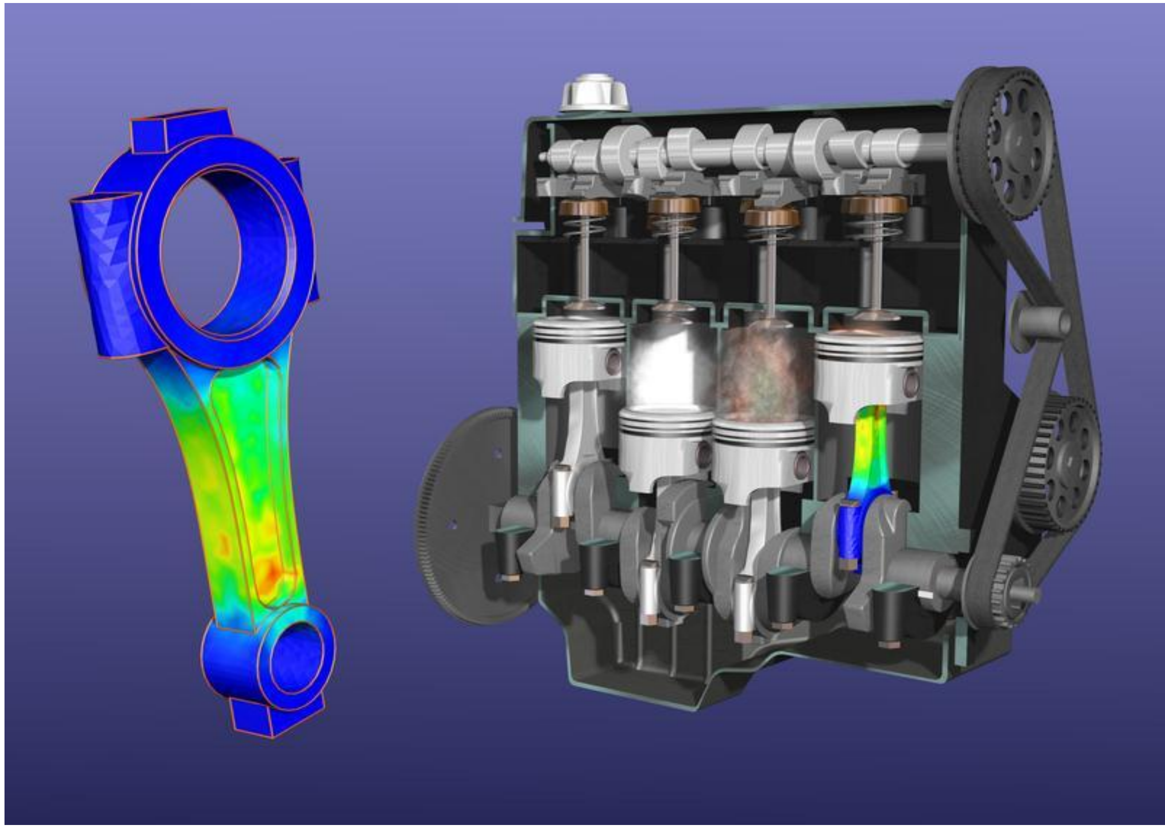
Foundation of the engine and contains pistons, crank shaft, cylinders, timing sprockets and sometimes the cam shaft. Also called short block.

Engine without cylinder heads, exhaust manifold, or intake manifold attached to it is called **bare** block.

Connecting (conn.) Rod

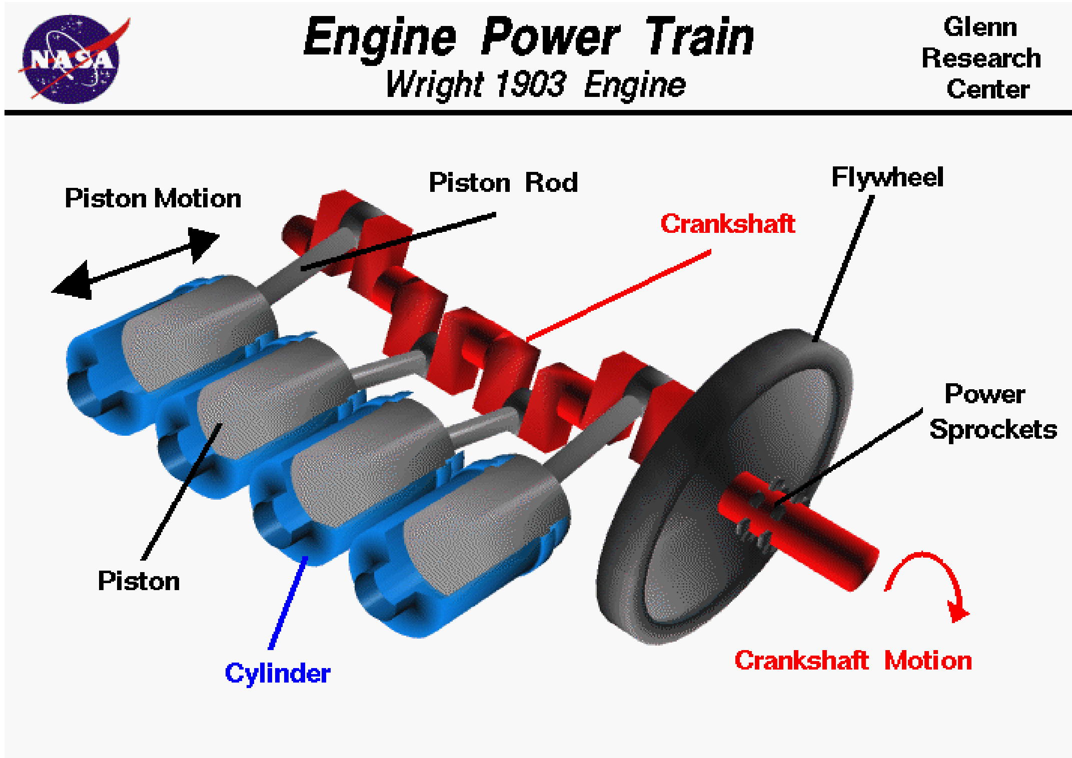
Attaches piston (wrist-pin) to the crank shaft (conn. rod caps).





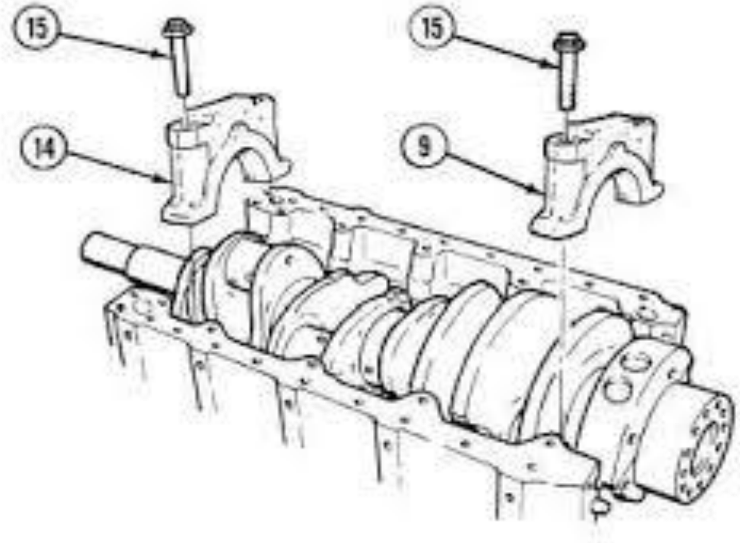
Crank Shaft

Converts up and down motion into circular motion.
Transmits the power to transmission.



DAMPNER PULLEY
Controls Vibration

Crank Shaft main bearings

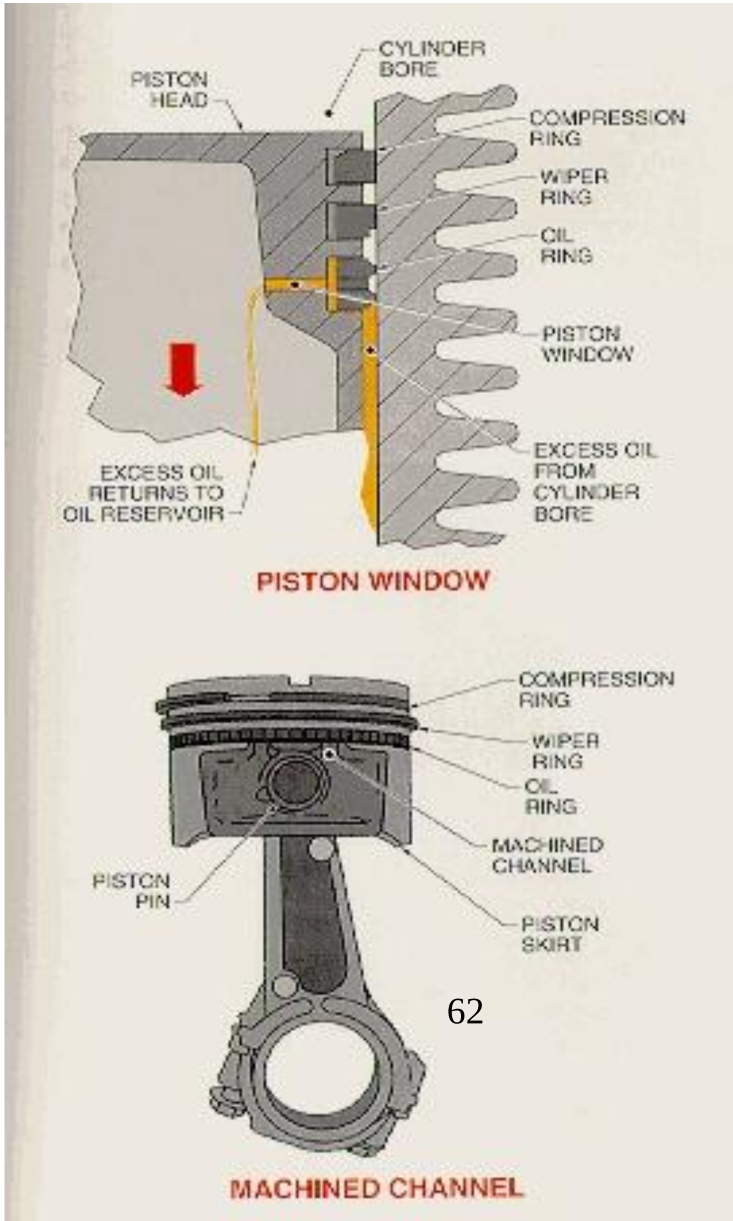


Main bearings are fitted between crank shaft and the main journals.

Piston Rings

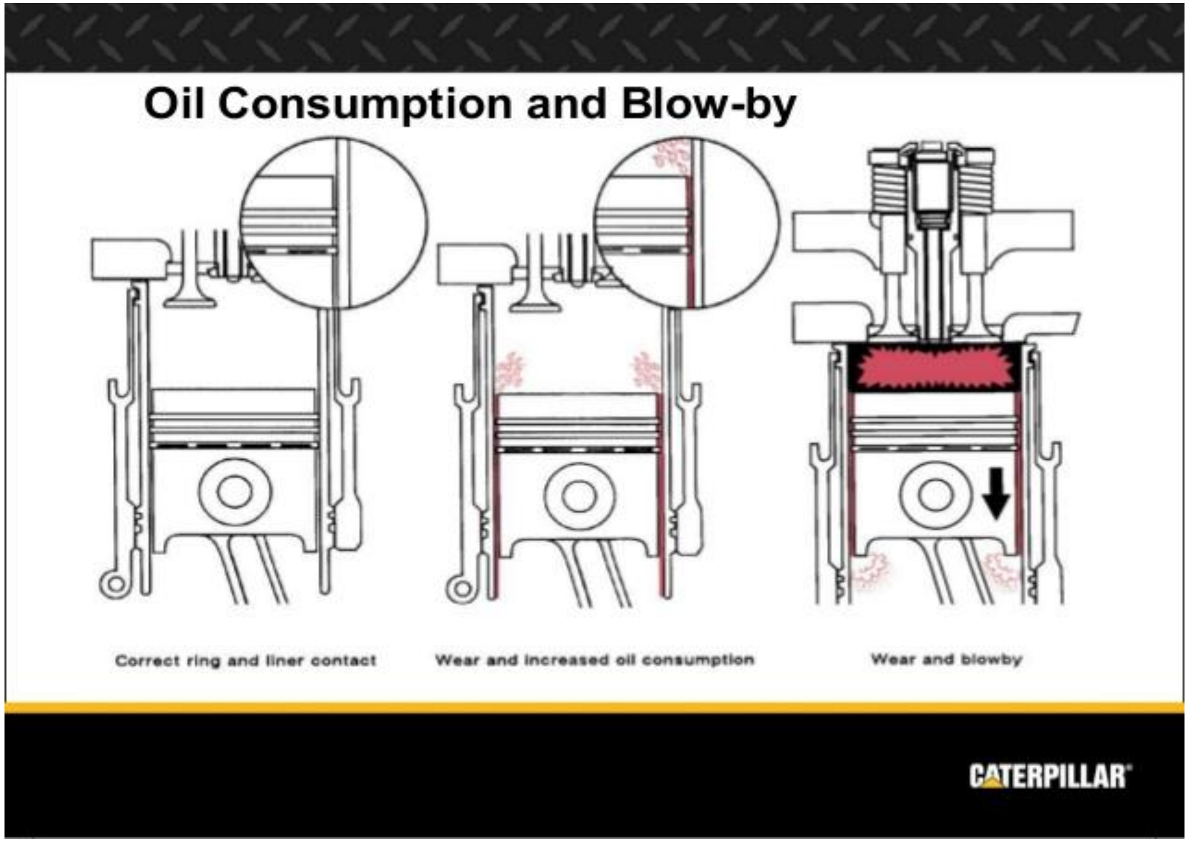
Four stroke: Three rings
Top two are compression rings (sealing the compression pressure in the cylinder) and the third is an oil ring (scrapes excessive oil from the cylinder walls)

Two Stroke: Two Rings
Both the rings are Compression rings.



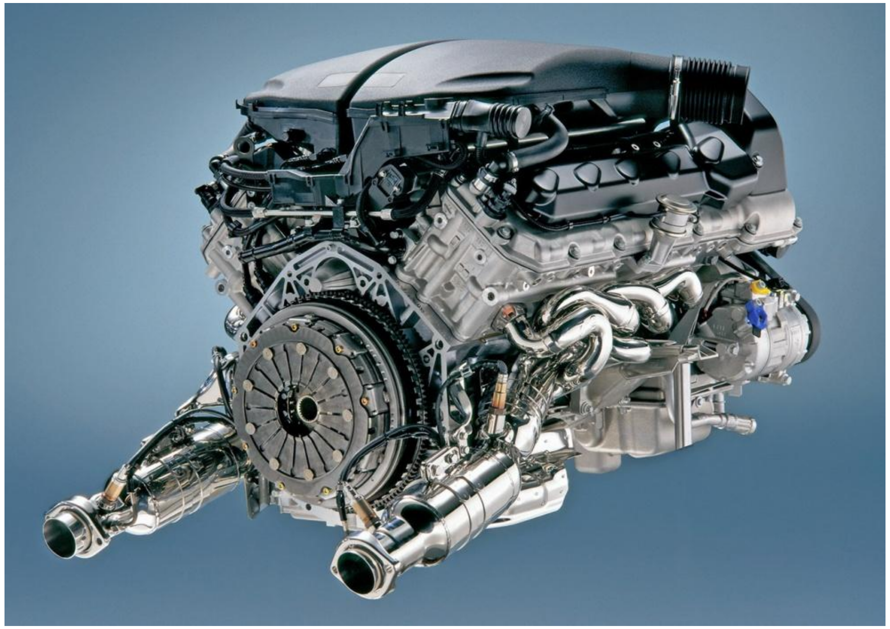
Blow-by from Piston Rings

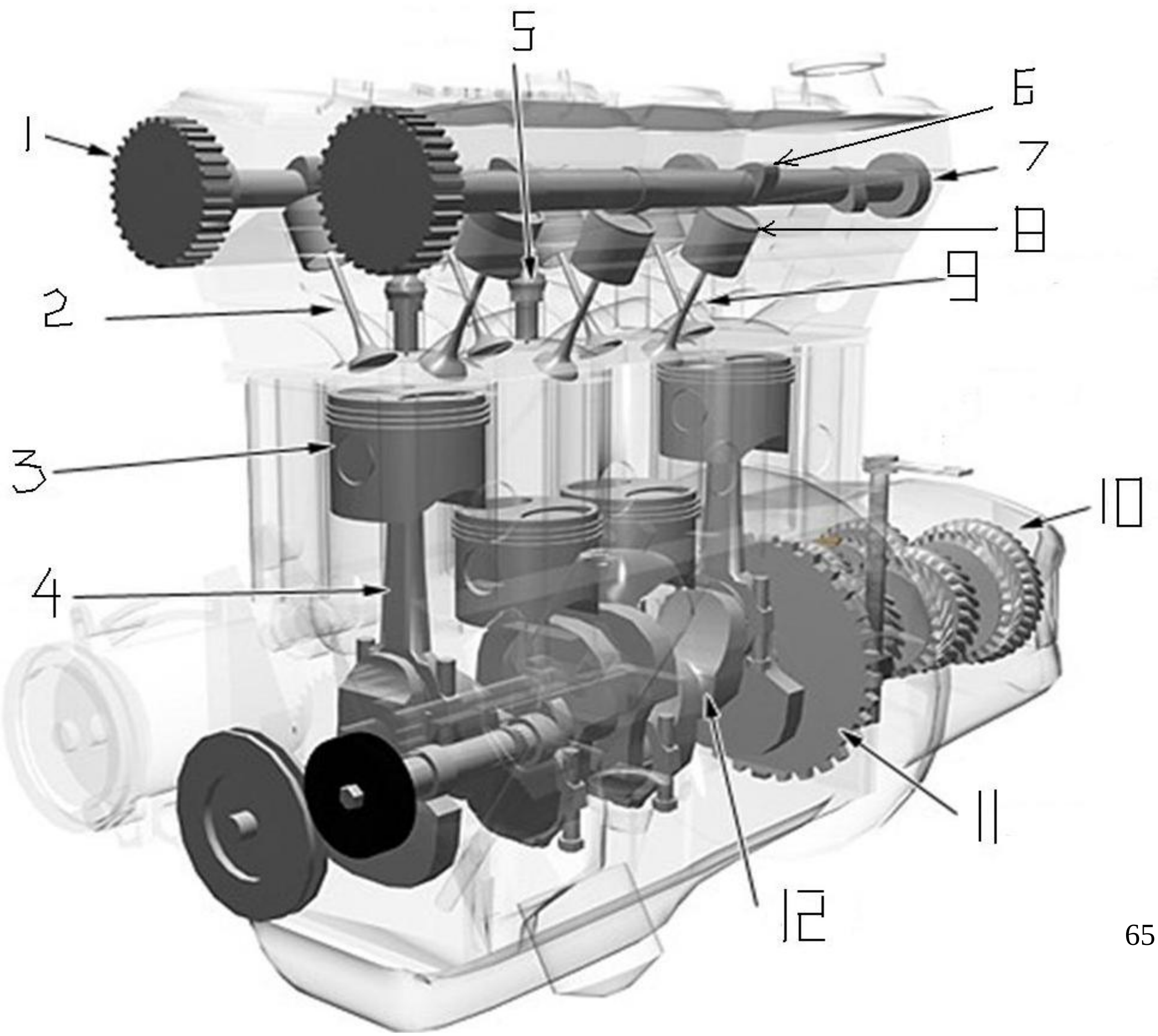
Engine blow-by will cause oil burning in the combustion chamber, producing blue(grey) smoke.



Flywheel

1. Attached to the crankshaft
2. Reduces vibration
3. Cools the engine (air cooled)
4. Used during initial start-up
5. Transfers power from engine to Drive train
6. Helps glide through strokes

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UNIT II
Combustion in SI and CI Engines

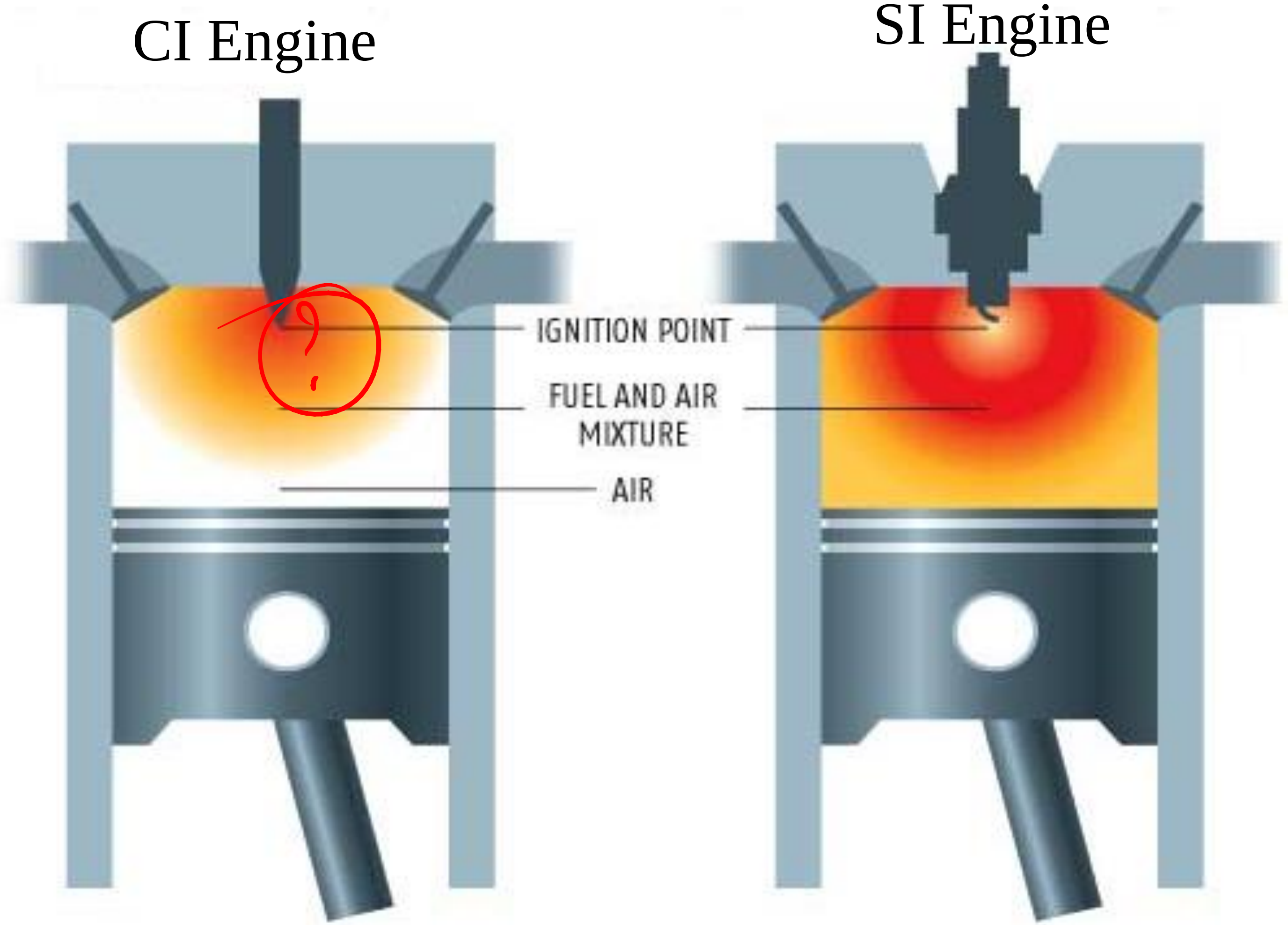
Pre-processing of fuel & Air Vs Combustion Mechanism

- Pre mixing of fuel and air
- Partial Pre mixing of fuel and air
- No Pre mixing of fuel and air

Care for Occurrence of Combustion

Occurrence of combustion in SI Engine : A Child Care Event.

Occurrence of combustion in CI Engine: A Teen Care Event.

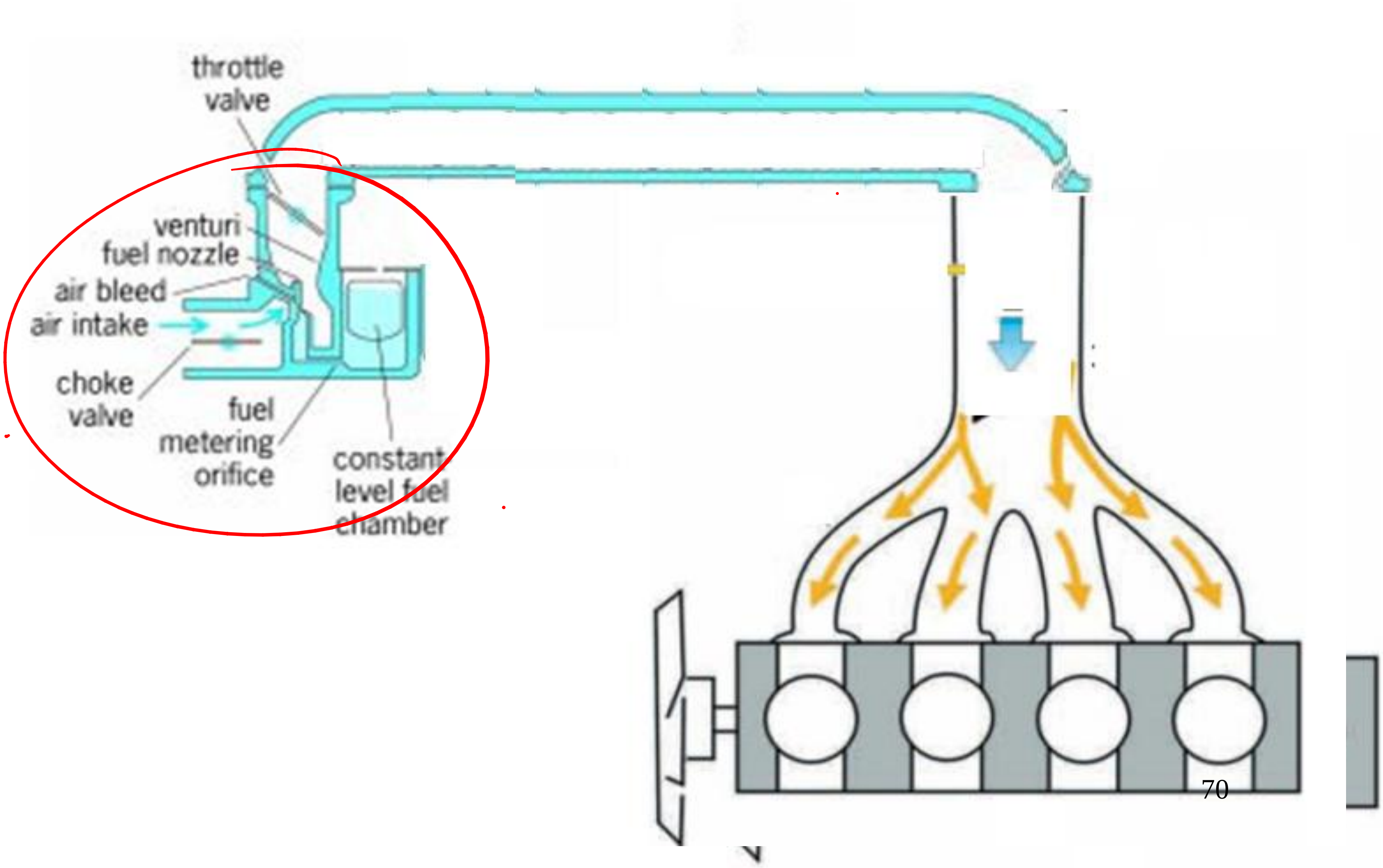


Type of Fuel Vs Traditional Combustion Strategy

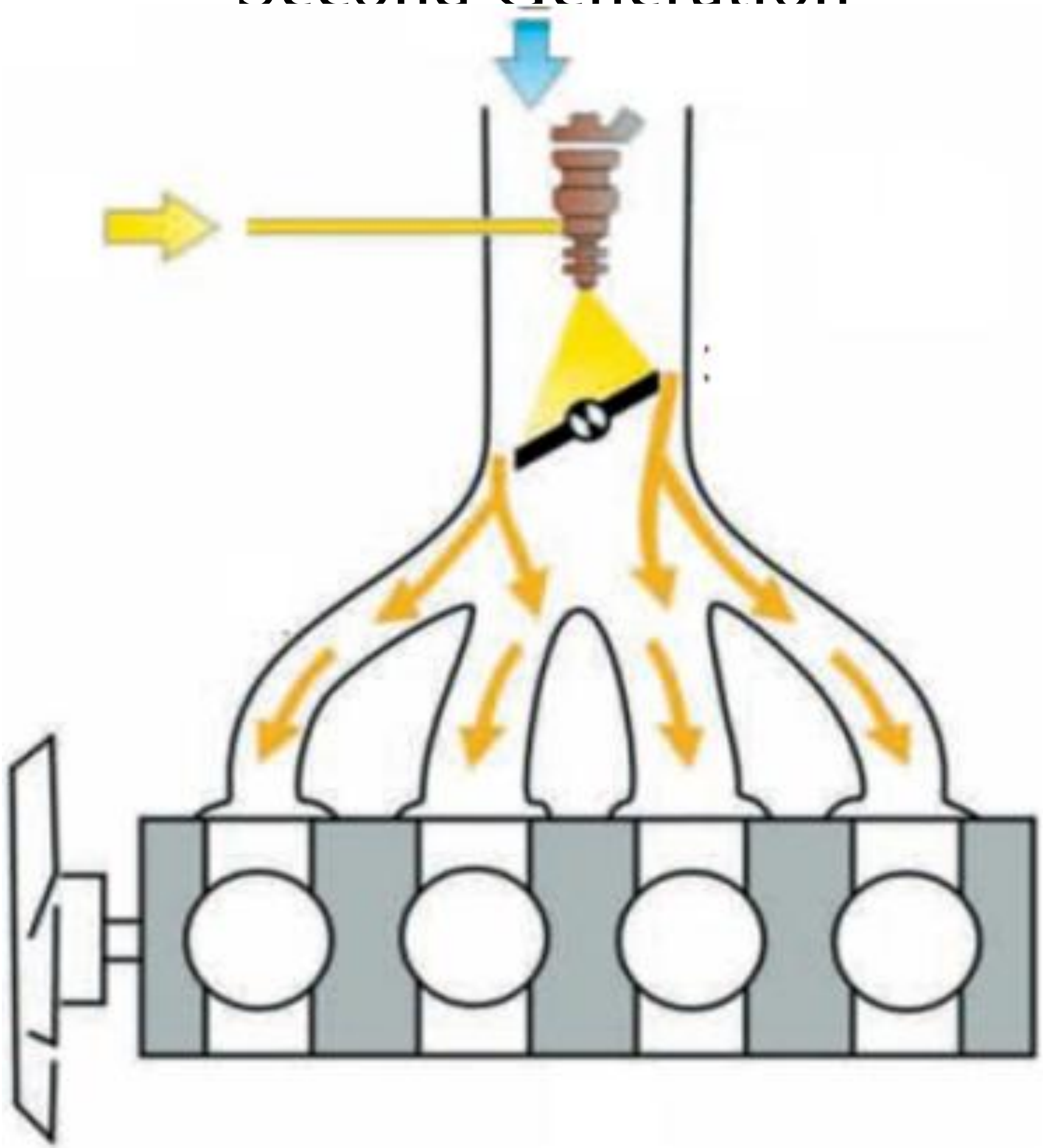
Highly volatile with High self Ignition Temperature: Spark Ignition. Ignition after thorough mixing of air and fuel.

Less Volatile with low self Ignition Temperature: Compression Ignition , Almost simultaneous mixing & Ignition.

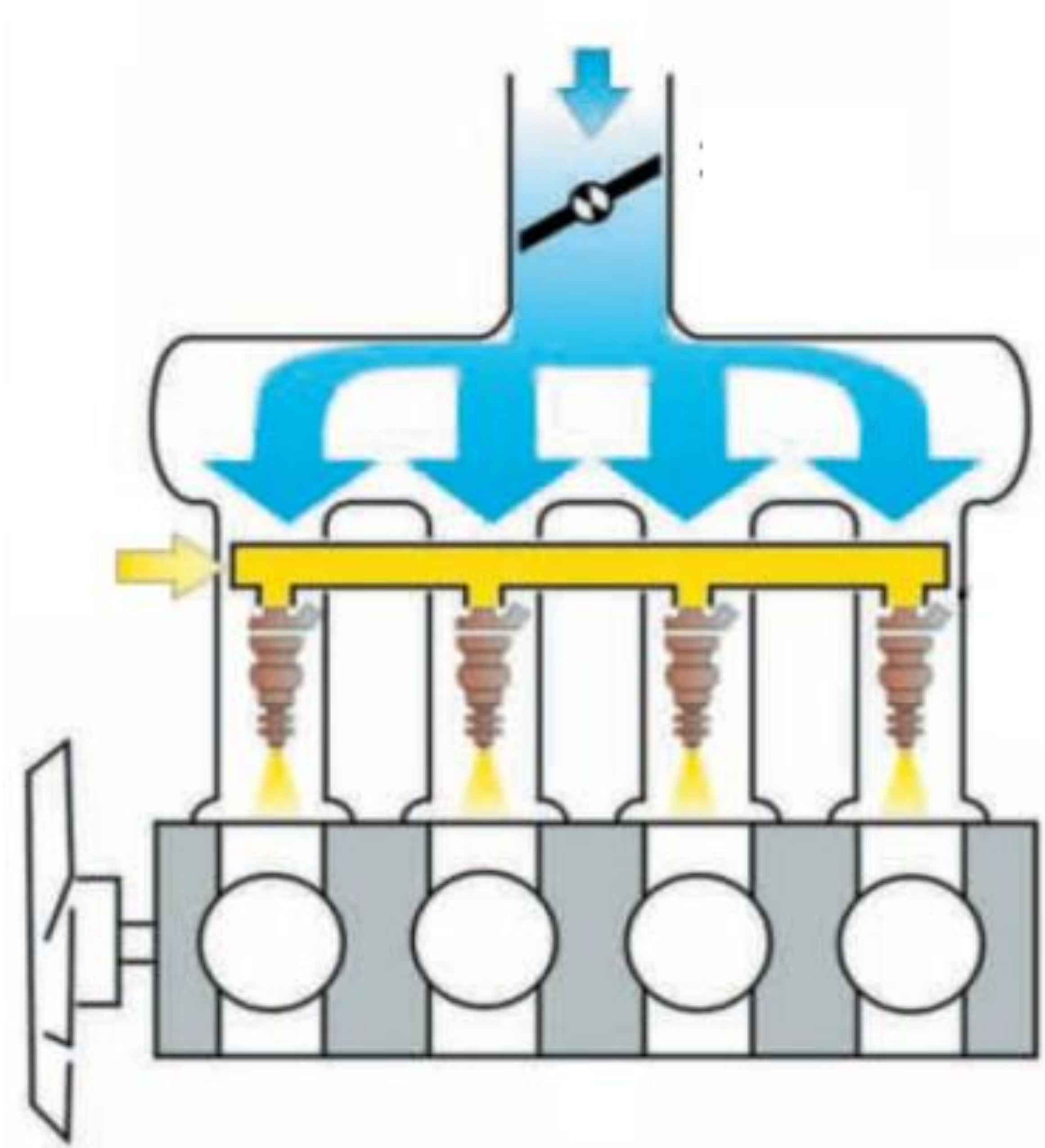
Evolution of Fuel Inductions Systems : SI Engines – First Generation



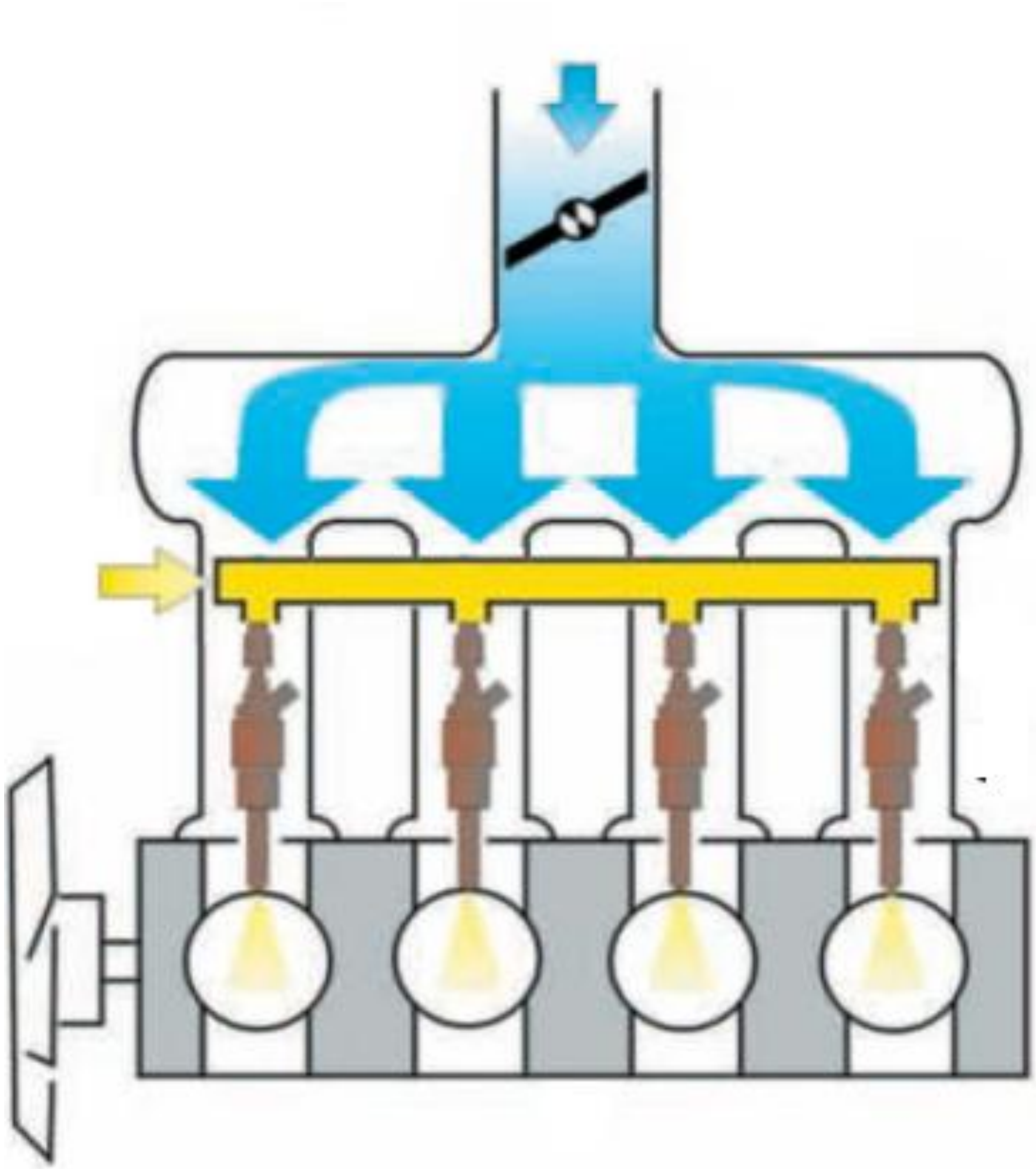
Evolution of Fuel Inductions Systems : SI Engines – Second Generation



Evolution of Fuel Inductions Systems : Third Generation



Evolution of Fuel Inductions Systems : Next Generation



Carbureted S.I. Engines

There are some very obscure auto makers, primarily in Africa and Russia, who still build cars with carburetors.

These cars are typically designs that have been purchased from their original manufacturers and remade for a new market.

To keep expenses down, these auto makers avoid computer controls and use mechanical components such as a carburetor on their cars to make them more easily repairable.

Many motorcycles, are one of the last holdouts of the factory production carburetors today.

Capacity check

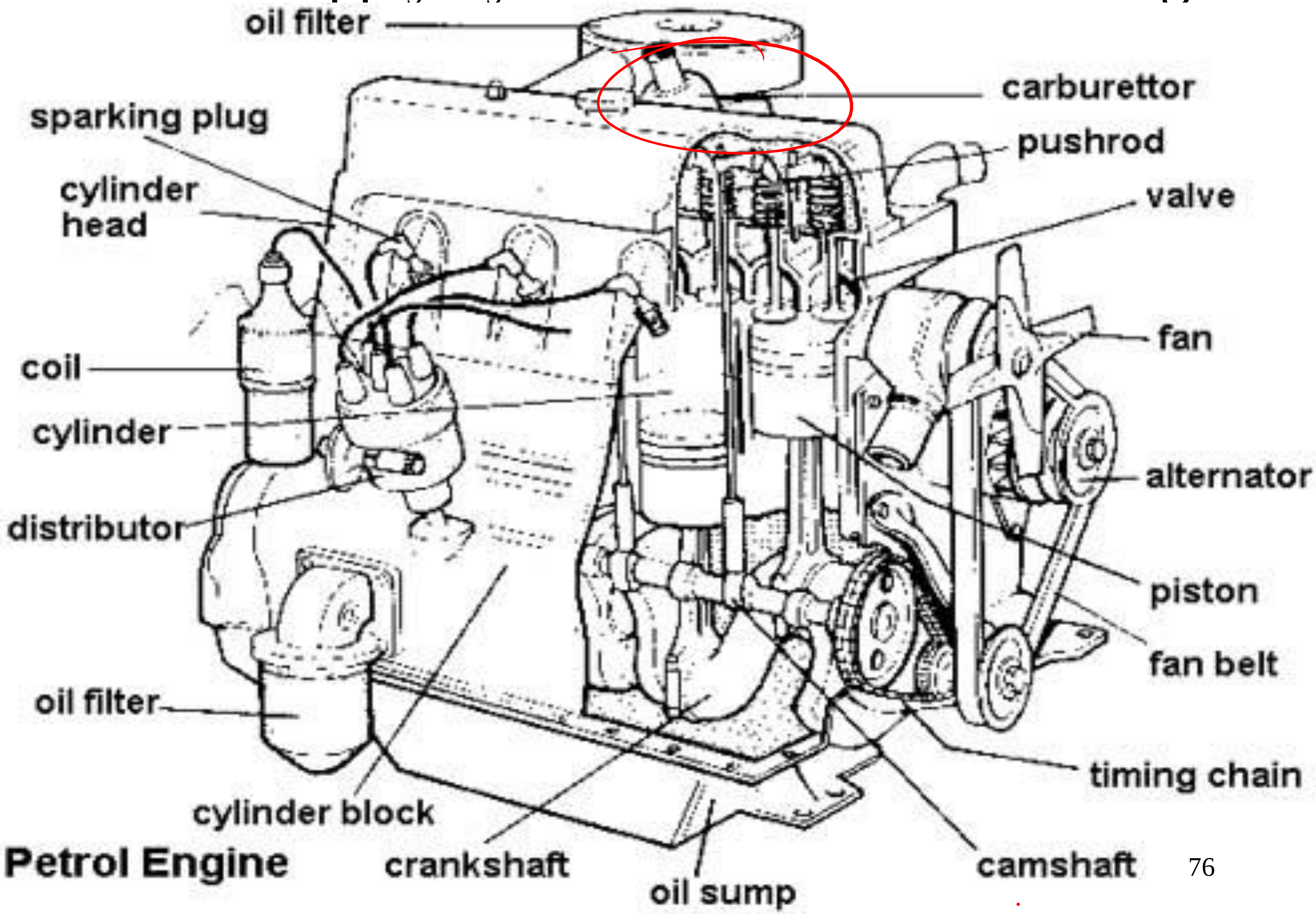
Vehicles going the eco-way

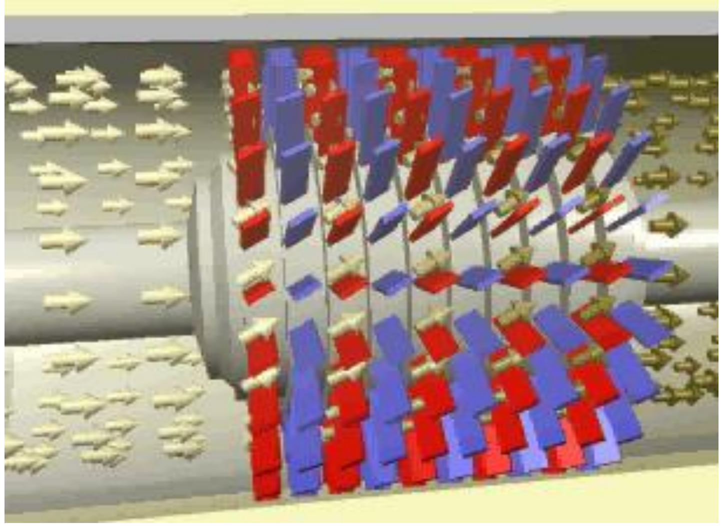
Vehicle	Category	Engine CC	Vehicle technology	Fuel injection possibility
Moped	Moped	60-70		
	Scooterette	60-75	Mostly two-stroke	Very low
	Step-through	74-75		
Scooter	Scooter	100-150	Two and four-stroke	Low
Motorcycle	Entry level	97-99		
	Executive level	97-125	Mostly four-stroke	Very high in higher engine segments
	Premium level	109-179		
	Super premium	174-223		

CC = Cubic capacity.

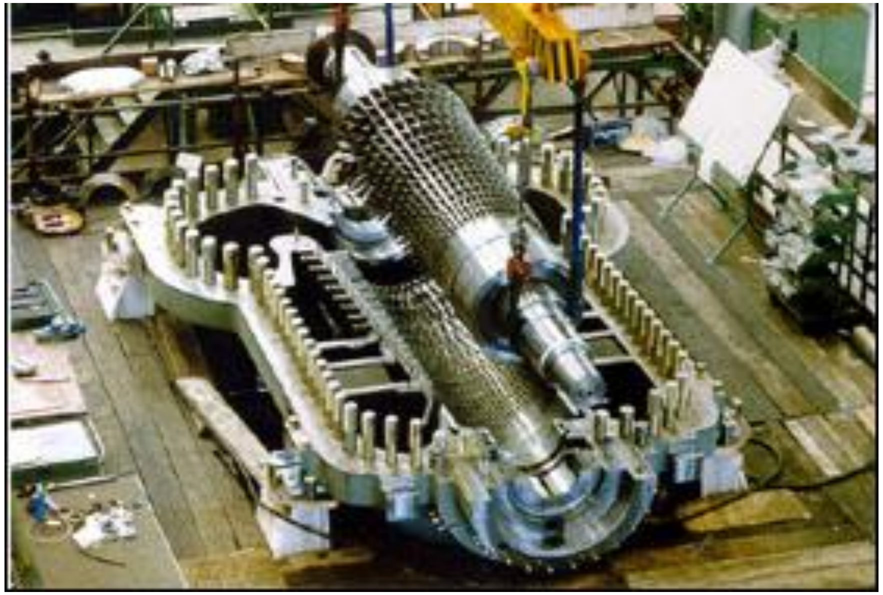
Source: compiled from N V Iyer 2006

Air-Fuel Supply Systems : Carbureted S.I. Engines





UNIT III
Compressors



Goals

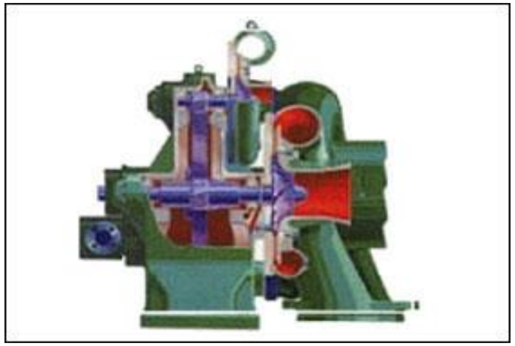
- Describe the two basic types of compressors and their typical applications
- Describe how the design equations for compressors are derived from the MEB and the total energy balance (TEB) (understand the assumptions)

Types of Compressors

Gasses can be compressed in the following ways:

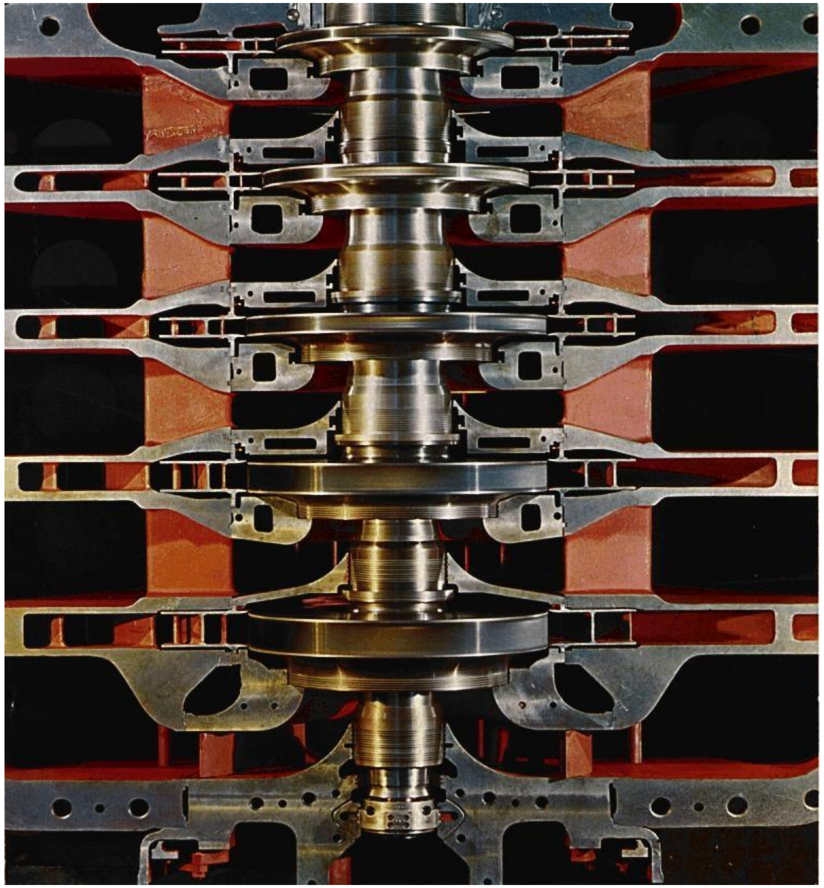
- Reciprocating piston compressors
  - Low flow rates
  - High compression ratios
- Rotating centrifugal compressors
  - High flow rates
  - Low compression ratios
  - Several centrifugal stages may be used to obtain higher compression ratios

Types of Compressors



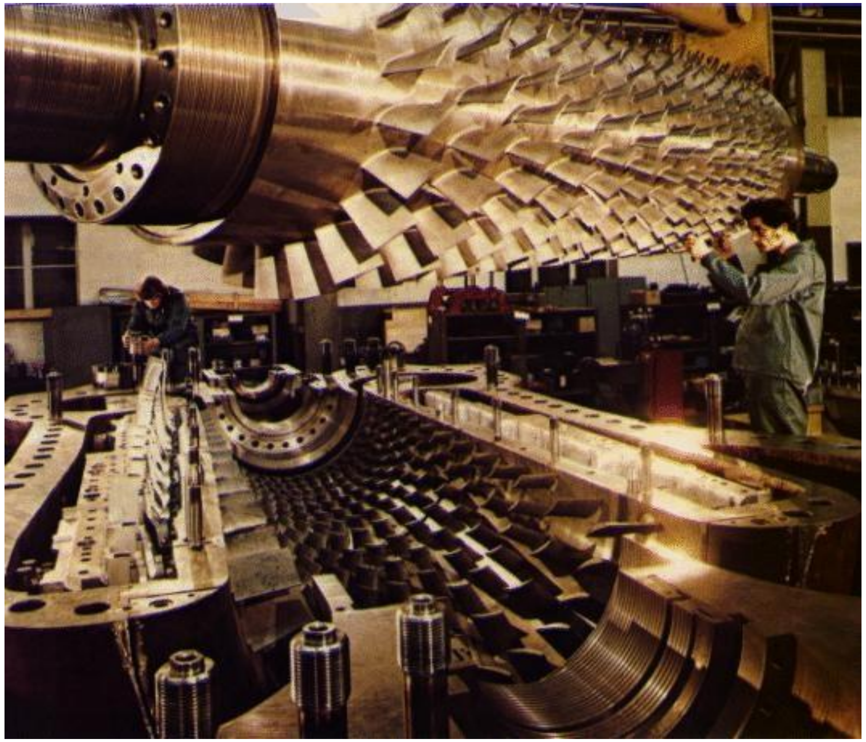
Centrifugal Compressors

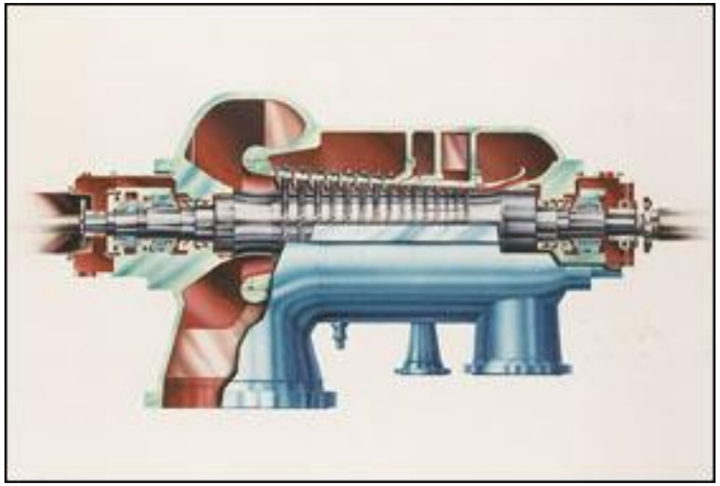
Types of Compressors



Radial Flow Compressors (multi-stage)

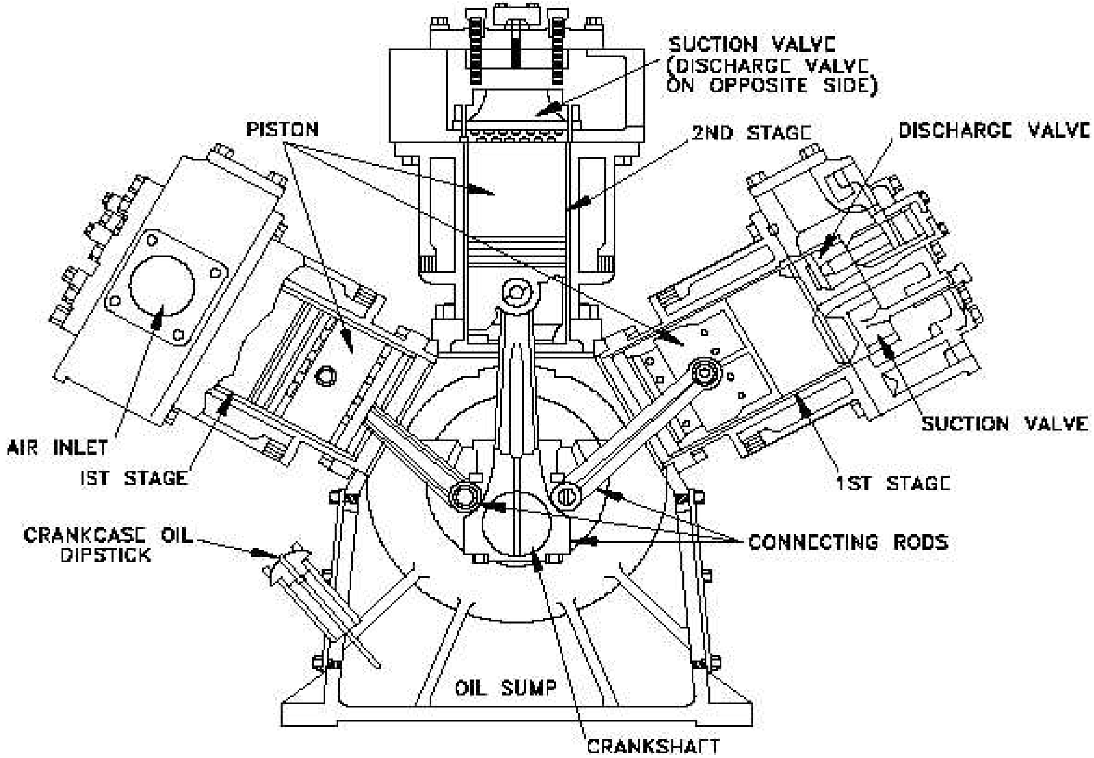
Types of Compressors





Axial Compressor

Types of Compressors



Reciprocating Compressor

Typical Texas Compressor Installation

UNIT IV

Rotary Compressors and Axial Compressors

Compressor Design Equations

Mechanical Energy Balance

$$\hat{W} = \Delta\left(\frac{\alpha u^2}{2} + gZ\right) + \int_{p_1}^{p_2}\left(\frac{dp}{\rho}\right) + h_f$$

What is the unexpected assumption?

Viscous dissipation is negligible!

h_f will be accounted for via the efficiency of the compressor

Mechanical Energy Balance

$$\hat{W} = \int_{p_1}^{p_2} \left(\frac{dp}{\rho} \right)$$

$\hat{W}$ is the work done on the fluid by the compressor

ρ must remain inside integral since ρ changes with p.

Total Energy Balance

$$\Delta\left(\frac{\alpha u^2}{2} + gZ + H\right) = \frac{Q}{\dot{m}} + \hat{W}_c$$

adiabatic compression

$$\hat{W}_c = \Delta H = C_p\left(T_2 - T_1\right)$$

Note that $\hat{W}_c$ in TEB includes efficiency while $\hat{W}$ in MEB does not include efficiency

Isentropic Work of Compression

As a first approximation, a compressor without any internal cooling can be assumed to be adiabatic. If the process is also assumed to be reversible, it will be isentropic.

$$p/\rho^{\gamma} = p_1/\rho_1^{\gamma} = const. \qquad \frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}$$

Solve for ρ, substitute into MEB, and integrate

Isentropic Work of Compression

Upon Integration

$$\hat{W}_{\Delta S=0} = \frac{p_1 \gamma}{\rho_1 (\gamma - 1)} \left[\left(\frac{p_2}{p_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right]$$

This is the isentropic (adiabatic) work of compression.

The quantity p_2/p_1 is the compression ratio.

Compressor Work

Compression is not reversible, however. Deviations from ideal behavior must be accounted for by introducing an isentropic compressor efficiency such that the true work of compression is given by.

$$\hat{W}_c = \frac{\hat{W}_{\Delta S=0}}{\eta_{ad}}$$

How can η_{ad} be found?

$$\hat{W}_c = C_p\left(T_2 - T_1\right)$$

Isothermal Compression

If sufficient cooling is provided to make the compression process isothermal, the work of compression is simply:

$$\hat{W}_{\Delta T=0} = \frac{RT_1}{M} \ln \frac{p_2}{p_1}$$

For a given compression ratio and suction condition, the work requirement in isothermal compression is less than that for adiabatic compression. This is one reason that cooling is useful in compressors.

Polytropic Compression

In actuality the $\Delta S = 0$ path assumed in writing the expression $p/\rho^{\gamma} = $ const. is not the true thermodynamic path followed by gases in most large compressors and the compression is neither adiabatic not isothermal. A polytropic path is a better representation for which:

$$p/\rho^{n} = p_1/\rho_1^{n} = const.$$

Here n depends on the nature of the gas and details of the compression process.

Polytropic Compression

$$\hat{W}_p = \frac{p_1 n}{\rho_1 (n-1)} \left[\left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} - 1 \right]$$

where $\hat{W}_p$ is the work for polytropic compression

Again the actual work of compression is larger than the calculated work and:

$$\hat{W}_c = \frac{\hat{W}_p}{\eta_p}$$

Polytropic Compression

The polytropic efficiency η_p is often the efficiency quoted by manufacturers. From this efficiency useful relations can be stated to convert from polytropic to adiabatic results:

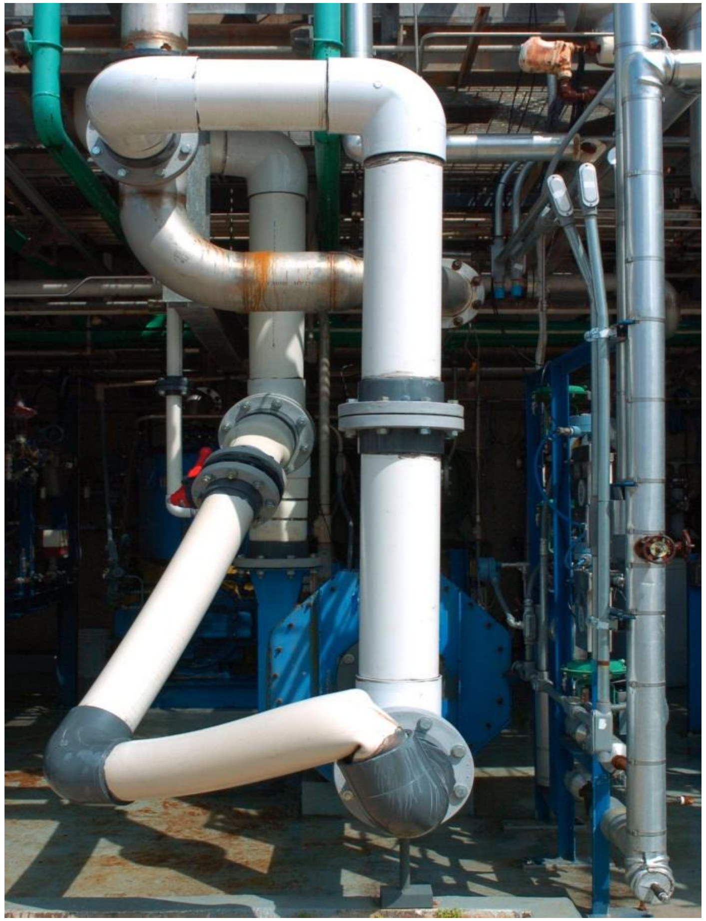
To get n the polytropic exponent:

$$n = \frac{\eta_p \gamma}{1 + \eta_p \gamma - \gamma} \quad \text{or} \quad \frac{n}{n-1} = \frac{\gamma}{\gamma - 1}\eta_p$$

To get relationships between T or ρ and compression ratio simply replace γ with n.

$$e.g. \quad \frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}$$

A “REAL” Impact of Efficiency



Multistage Compression

Consider a two stage compression process p1→p2→p3 with perfect intercooling (temperature reduced to T_1 after each compression)

$$\hat{W}_{\Delta S=0} = \frac{\gamma R T_1}{\gamma - 1}\left[\left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] + \frac{\gamma R T_1}{\gamma - 1}\left[\left(\frac{p_3}{p_2}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]$$

Now find p_2 which will minimize work, differentiate wrt p_2

$$p_2^{opt} = \sqrt{p_1 p_3}$$

Multistage Compression

$$\frac{p_2}{p_1} = \frac{p_3}{p_2} = \left(\frac{p_3}{p_1}\right)^{1/2}$$

So the compression ratio that minimizes total work is such that each stage has an identical ratio.

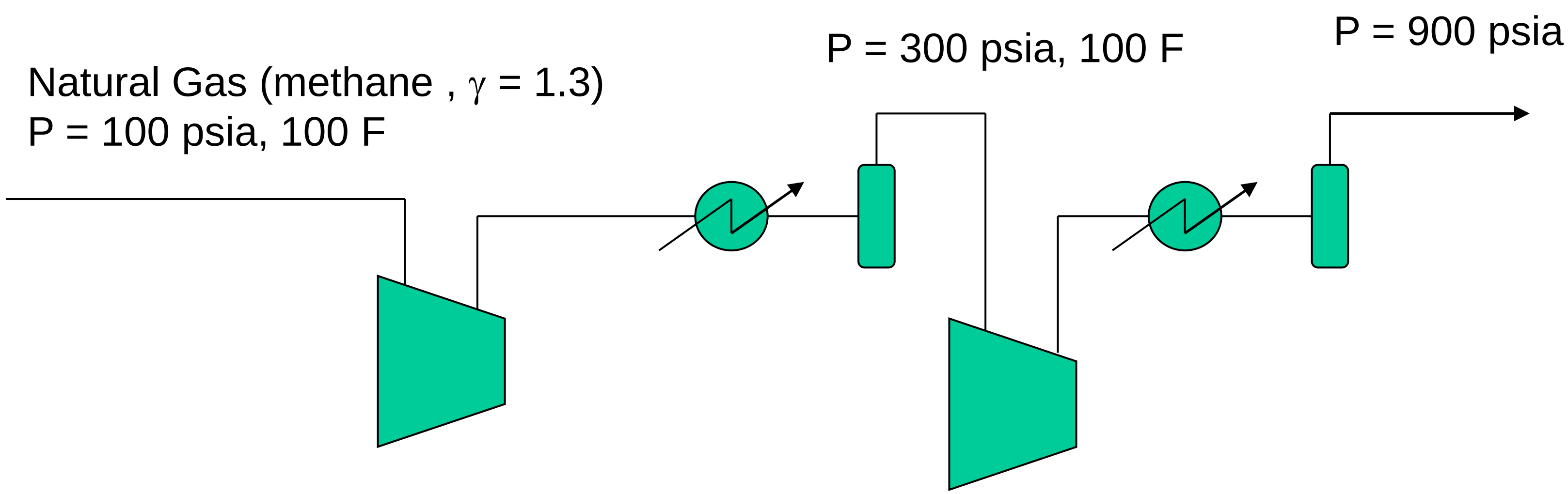
This can be generalized for n stages as:

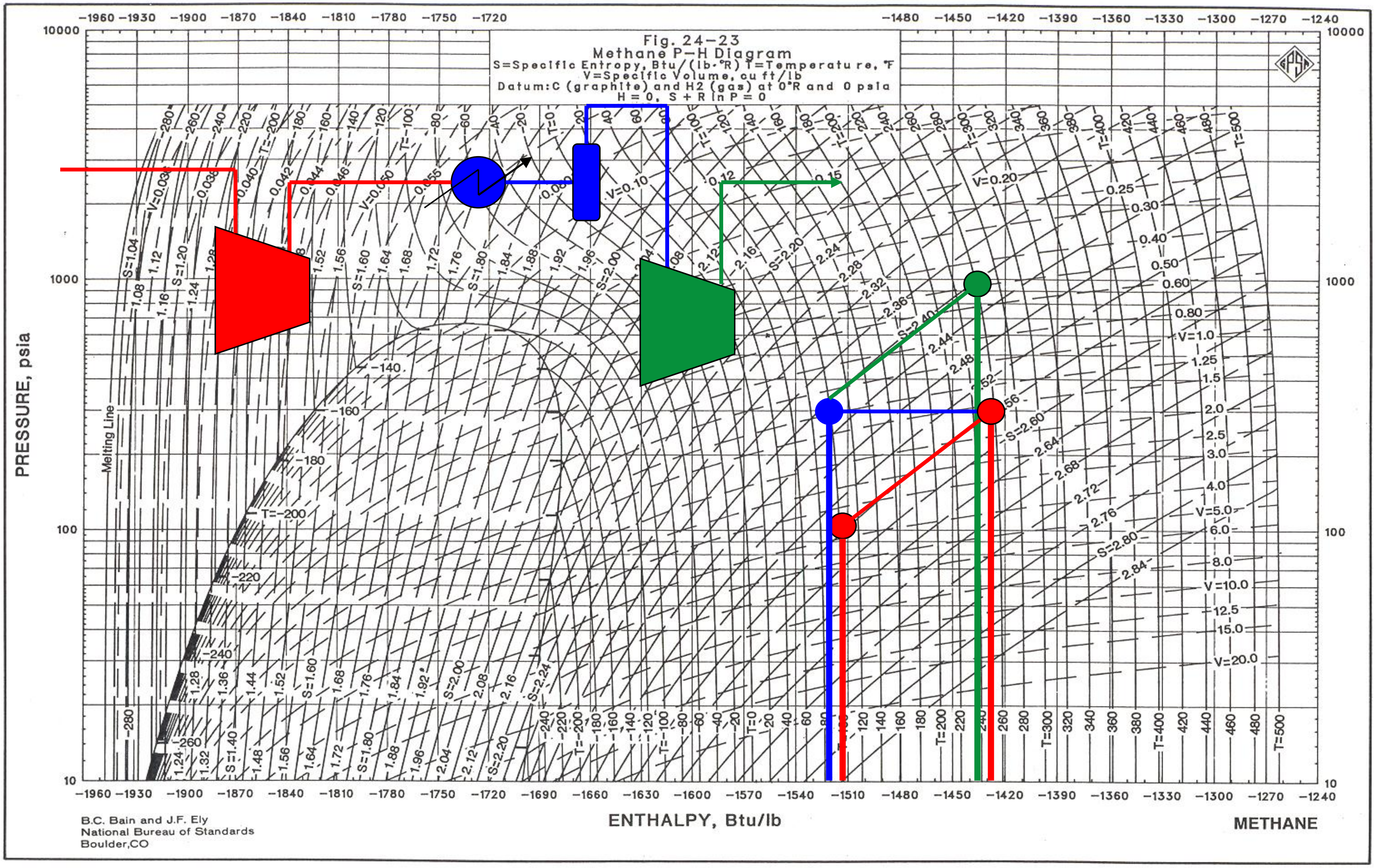
$$\frac{p_2}{p_1} = \frac{p_3}{p_2} = \Lambda = \left(\frac{p_{n+1}}{p_1}\right)^{1/n}$$

When T is not cooled to T_1: $T_i\left(\frac{p_{i+1}}{p_i}\right)^{\frac{\gamma-1}{\gamma}} = const.$ $\quad T_i \uparrow \quad \frac{p_{i+1}}{p_i} \downarrow$

Multistage Compression

Equation and P-H Chart Method Example





Isentropic Compression

UNIT V
Refrigeration

Basics

Refrigeration is the removal of heat from a material or space, so that it's temperature is lower than that of it's surroundings.

When refrigerant absorbs the unwanted heat, this raises the refrigerant's temperature ("Saturation Temperature") so that it changes from a liquid to a gas — it evaporates. The system then uses condensation to release the heat and change the refrigerant back into a liquid. This is called "Latent Heat".

This cycle is based on the physical principle, that a liquid extracts heat from the surrounding area as it expands (boils) into a gas.

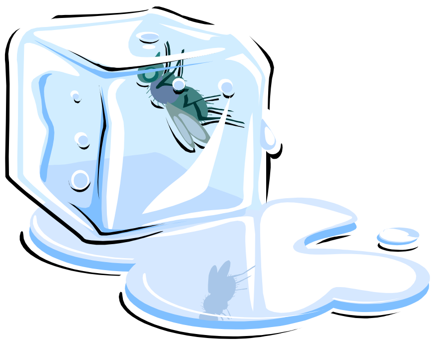
To accomplish this, the refrigerant is pumped through a closed looped pipe system.

The closed looped pipe system stops the refrigerant from becoming contaminated and controls its stream. The refrigerant will be both a vapor and a liquid in the loop.

“Saturation Temperature” – can be defined as the temperature of a liquid, vapor, or a solid, where if any heat is added or removed, a change of state takes place.

A change of state transfers a large amount of energy. At saturation temperature, materials are sensitive to additions or removal of heat. Water is an example of how saturation property of a material, can transfer a large amount of heat. Refrigerants use the same principles as ice. For any given pressure, refrigerants have a saturation temperature. If the pressure is low, the saturation temperature is low. If pressure is high, saturation temperature is high.

"Latent Heat"- The heat required to change a liquid to a gas (or the heat that must be removed from a gas to condense it to a liquid), without any change in temperature.



Heat is a form of energy that is transferred from one object to another object.

Heat Is a form of energy transferred by a difference in temperature.

Heat transfer can occur, when there is a temperature difference between two or more objects. Heat will only flow from a warm object to a colder object.

The heat transfer is greatest, when there is a large temperature difference between two objects.

The Refrigeration Cycle

There are four main components in a refrigeration system:

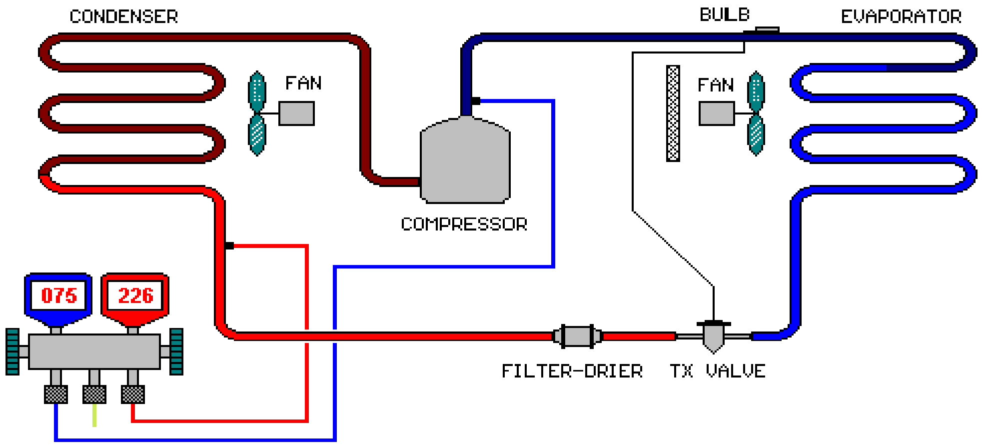
The Compressor

The Condensing Coil

The Metering Device

The Evaporator

Two different pressures exist in the refrigeration cycle. The evaporator or low pressure, in the "low side" and the condenser, or high pressure, in the "high side". These pressure areas are divided by the other two components. On one end, is the metering device which controls the refrigerant flow, and on the other end, is the compressor.



The Compressor

The compressor is the heart of the system. The compressor does just what it's name is. It compresses the low pressure refrigerant vapor from the evaporator and compresses it into a high pressure vapor.

The inlet to the compressor is called the "Suction Line". It brings the low pressure vapor into the compressor.

After the compressor compresses the refrigerant into a high pressure Vapor, it removes it to the outlet called the "Discharge Line".

The Condenser

The "Discharge Line" leaves the compressor and runs to the inlet of the condenser.

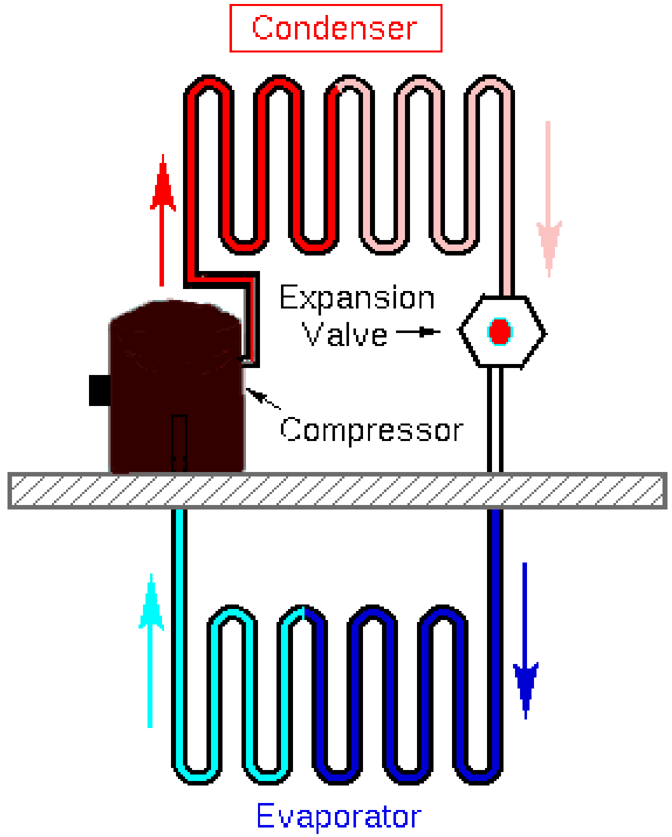
Because the refrigerant was compressed, it is a hot high pressure vapor (as pressure goes up – temperature goes up).

The hot vapor enters the condenser and starts to flow through the tubes.

Cool air is blown across the out side of the finned tubes of the condenser (usually by a fan or water with a pump).

Since the air is cooler than the refrigerant, heat jumps from the tubing to the cooler air (energy goes from hot to cold – "latent heat").

As the heat is removed from the refrigerant, it reaches it's "saturated temperature" and starts to "flash" (change states), into a high pressure liquid.



Metering Devices

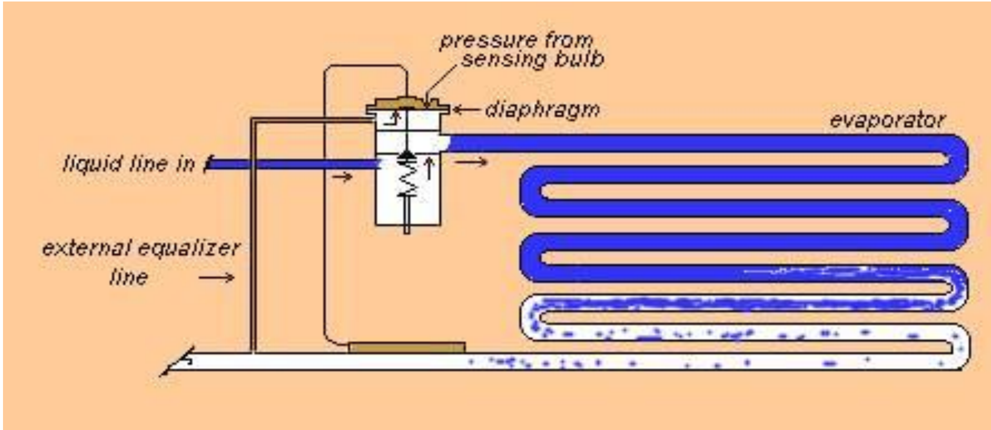
Metering devices regulate how much liquid refrigerant enters the evaporator .

Common used metering devices are, small thin copper tubes referred to as "cap tubes", thermally controller diaphragm valves called "TXV's" (thermal expansion valves) and single opening "orifices".

The metering device tries to maintain a preset temperature difference or "super heat", between the inlet and outlet openings of the evaporator.

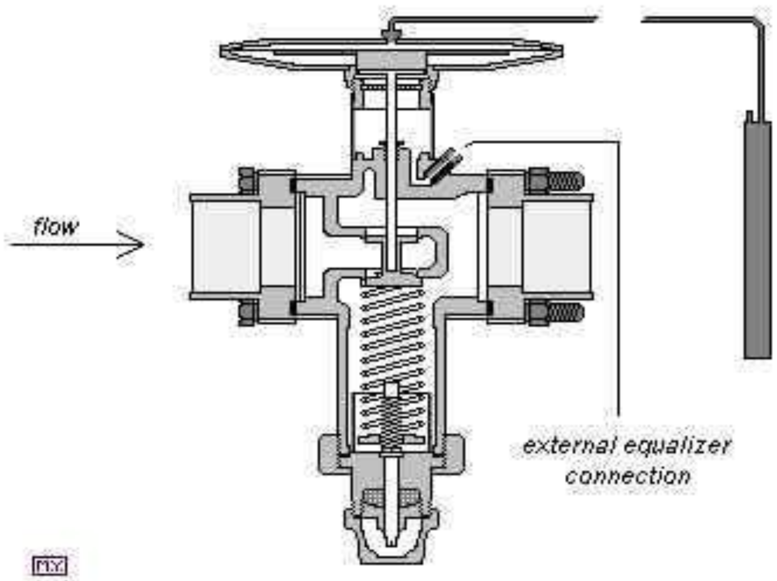
As the metering devices regulates the amount of refrigerant going into the evaporator, the device lets small amounts of refrigerant out into the line and looses the high pressure it has behind it.

Now we have a low pressure, cooler liquid refrigerant entering the evaporative coil (pressure went down – so temperature goes down).



Thermal expansion Valves

A very common type of metering device is called a TX Valve (*Thermostatic Expansion Valve*). This valve has the capability of controlling the refrigerant flow. If the load on the evaporator changes, the valve can respond to the change and increase or decrease the flow accordingly.



The TXV has a sensing bulb attached to the outlet of the evaporator. This bulb senses the suction line temperature and sends a signal to the TXV allowing it to adjust the flow rate. This is important because, if not all, the refrigerant in the evaporator changes state into a gas, there could be liquid refrigerant content returning to the compressor. This can be fatal to the compressor. Liquid can not be compressed and when a compressor tries to compress a liquid, mechanical failing can happen. The compressor can suffer mechanical damage in the valves and bearings. This is called" liquid slugging".

The Evaporator

The evaporator is where the heat is removed from your house , business or refrigeration box.

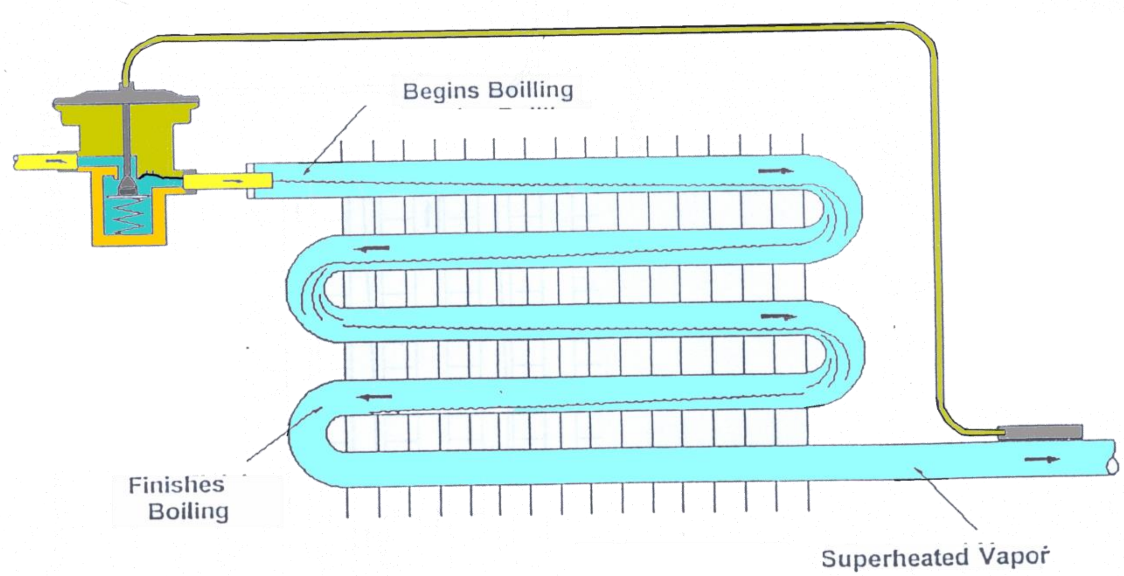
Low pressure liquid leaves the metering device and enters the evaporator.

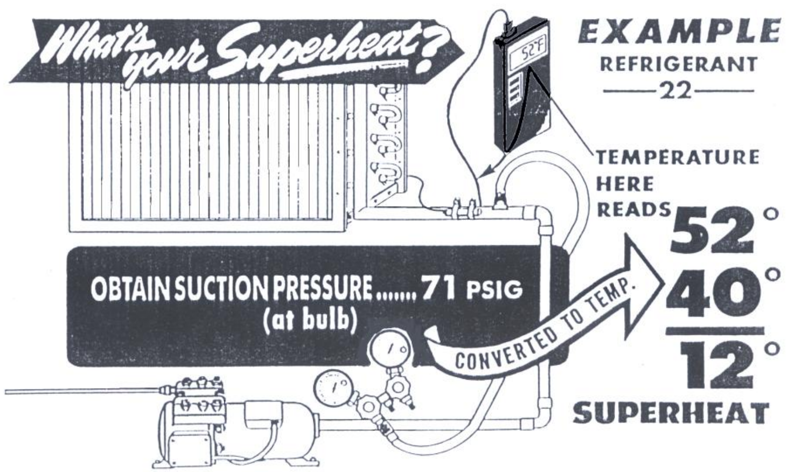
Usually, a fan will move warm air from the conditioned space across the evaporator finned coils.

The cooler refrigerant in the evaporator tubes, absorb the warm room air. The change of temperature causes the refrigerant to "flash" or "boil", and changes from a low pressure liquid to a low pressure cold vapor.

The low pressure vapor is pulled into the compressor and the cycle starts over.

The amount of heat added to the liquid to make it saturated and change states is called "Super Heat".





Basic Refrigeration Cycle

Starting at the compressor;

Low pressure vapor refrigerant is compressed and discharged out of the compressor.

The refrigerant at this point is a high temperature, high pressure, “superheated” vapor.

The high pressure refrigerant flows to the condenser by way of the "Discharge Line".

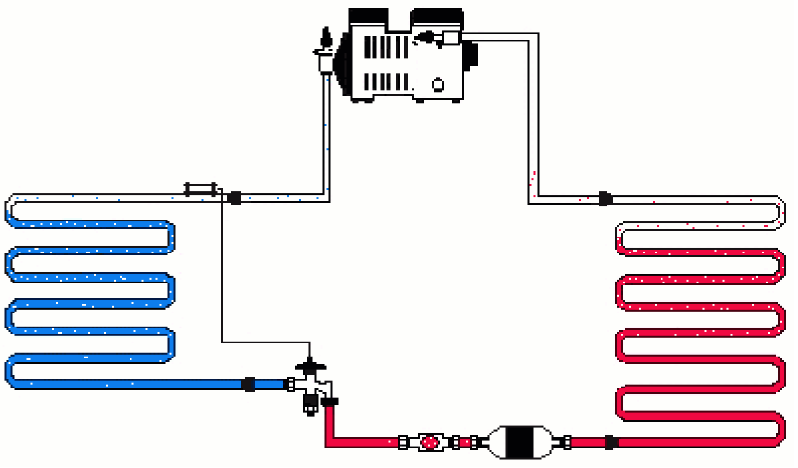
The condenser changes the high pressure refrigerant from a high temperature vapor to a low temperature, high pressure liquid and leaves through the "Liquid Line".

The high pressure refrigerant then flows through a filter dryer to the Thermal Expansion valve or TXV.

The TXV meters the correct amount of liquid refrigerant into the evaporator.

As the TXV meters the refrigerant, the high pressure liquid changes to a low pressure, low temperature, saturated liquid/vapor.

This saturated liquid/vapor enters the evaporator and is changed to a low pressure, dry vapor.



Sub-Cooling & Super-Heat

Measure Sub-cooling:

Get the refrigerant saturation pressure-temperature. Take a pressure reading of the liquid line leaving the condenser. Refrigerant saturation temperature is the pressure-temperature, when the refrigerant is turning from a high-pressure vapor into a high-pressure liquid (giving up heat). At saturation pressure-temperature, both liquid and vapor are at the same temperature.

(1) Convert pressure to temperature with a P/T chart.

(2) Take a temperature reading at the leaving liquid line of the condenser.

Compare both, the saturated temperature and leaving liquid line temperature. Subtracting one from the other, the difference is the amount the refrigerant has cooled past saturated temperature.

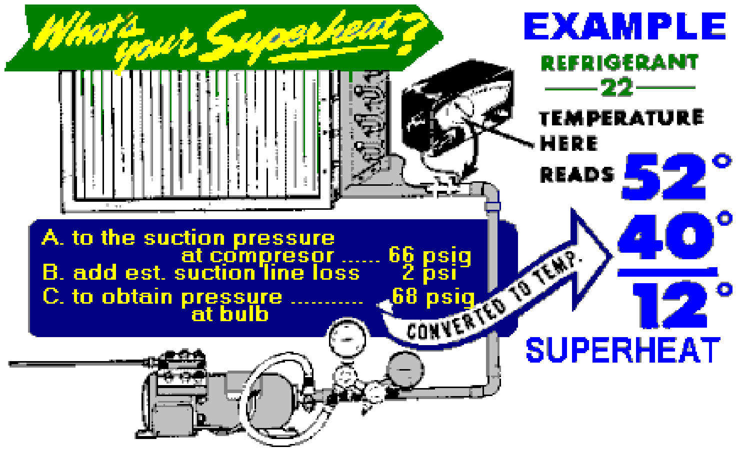
Measure Evaporator Superheat:

Get a pressure reading of the suction line leaving the evaporator to get refrigerant saturation pressure-temperature. Refrigerant saturation temperature is the pressure-temperature, when the refrigerant is turning from a low-pressure liquid to a low-pressure vapor (absorbing heat). At saturation pressure-temperature, both liquid and vapor are at the same temperature.

Convert pressure to temperature with a P/T chart. If reading is obtained at the compressor, not at the evaporator line leaving, you may have to add a few pounds of pressure due to pressure drop in the suction line.

Take a temperature reading at the leaving suction line of the evaporator.

Compare both, the saturated temperature and the leaving suction line temperature. Subtracting one from the other, the difference is the amount the refrigerant gas has heated past saturated temperature.



Terms And Information

BTU's - An air conditioner's capacity is measured in "British Thermal Units", or BTUs. A BTU is the amount of heat required to raise, by one degree, the temperature of a pound of water. So if you buy an air conditioner rated at 10,000 BTUs, it has the ability to cool 10,000 pounds -- about 1,200 gallons -- of water, one degree in an hour. Refrigeration is normally measured in "Tons". 12,000 BTU's equal 1 ton.

Latent Heat - Latent Heat is the heat given up or absorbed by a substance as it changes state. It is called latent because it is not associated with a change in temperature. Each substance has a characteristic latent heat of fusion, latent heat of vaporization, latent heat of condensation and latent heat of sublimation.

Superheated Vapor - Refrigerant vapor is heated above its saturation temperature. If a refrigerant is superheated, there is no liquid present. Superheat is an indication of how full the evaporator is of liquid refrigerant. High superheat means the evaporator is empty. Low superheat means the evaporator is full.

Saturation Temperature - Also referred to as the boiling point or the condensing temperature. This is the temperature at which a refrigerant will change state from a liquid to a vapor or vice versa.

Sensible Heat - Heat, that when added or removed, causes a change in temperature but not in state.

Sub-Cooling - Sub-cooling is a temperature below saturated pressure-temperature. Sub-cooling is a measurement of how much liquid is in the condenser. In air conditioning, it is important to measure sub-cooling because the longer the liquid stays in the condenser, the greater the sensible (visible) heat loss. Low sub-cooling means that a condenser is empty. High sub-cooling means that a condenser is full. Over filling a system, increases pressure due to the liquid filling of a condenser that shows up as high sub-cooling. To move the refrigerant from condenser to the liquid line, it must be pushed down the liquid line to a metering device. If a pressure drop occurs in the liquid line and the refrigerant has no sub-cooling, the refrigerant will start to re-vaporize (change state from a liquid to a vapor) before reaching the metering devise.

What is a Refrigerant

Refrigerants are used as working substances in a Refrigeration systems.

Fluids suitable for refrigeration purposes can be classified into primary and secondary refrigerants.

Primary refrigerants are those fluids, which are used directly as working fluids, for example in vapour compression and vapour absorption refrigeration systems.

These fluids provide refrigeration by undergoing a phase change process in the evaporator.

Secondary refrigerants are those liquids, which are used for transporting thermal energy from one location to other. Secondary refrigerants are also known under the name brines or antifreezes

What is ChloroFloroCarcons

Today’s refrigerants are predominantly from a group of compounds called halocarbons (halogenated hydrocarbons) or specifically fluorocarbons.

Chlorofluorocarbons were first developed by General Motor’s researchers in the 1920’s and commercialized by Dupont as “Freons”.

Halocarbon Refrigerants

Halocarbon Refrigerant are all synthetically produced and were developed as the Freon family of refrigerants.

Examples :CFC's : R11, R12, R113, R114, R115

Importance of Refrigerant

The thermodynamic efficiency of a refrigeration system depends mainly on its operating temperatures.

However, important practical issues such as the system design, size, initial and operating costs, safety, reliability, and serviceability etc. depend very much on the type of refrigerant selected for a given application.

Due to several environmental issues such as ozone layer depletion and global warming and their relation to the various refrigerants used, the selection of suitable refrigerant has become one of the most important issues in recent times.

Refrigerant selection criteria

Selection of refrigerant for a particular application is based on the following requirements:

i. Thermodynamic and thermo-physical properties

ii. Environmental and safety properties

Iii. Economics

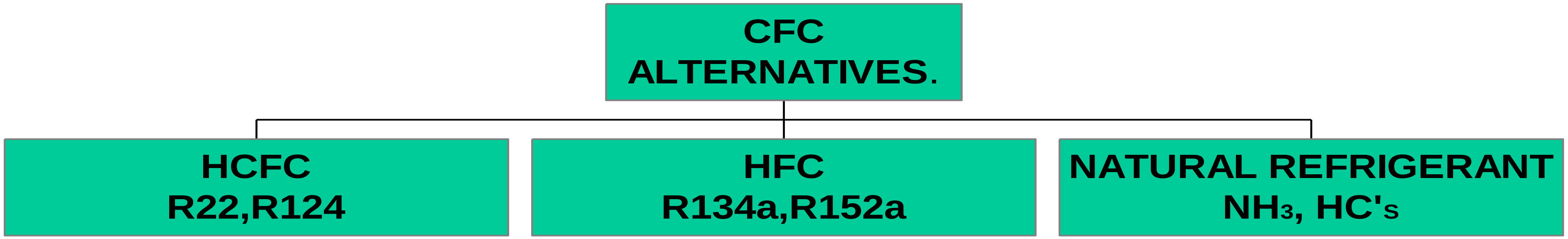
Environmental Effects of Refrigerants

Global warming :

Refrigerants directly contributing to global warming when released to the atmosphere

Indirect contribution based on the energy consumption of among others the compressors (CO_2 produced by power stations)

ECO-FRIENDLY REFRIGERANTS



Halocarbon Refrigerants

Halocarbon Refrigerant are all synthetically produced and were developed as the Freon family of refrigerants.

Examples :

CFC’s : R11, R12, R113, R114, R115

HCFC’s : R22, R123

HFC’s : R134a, R404a, R407C, R410a

HFCs

Remain a popular choice
especially for R22 phase out
Good efforts at improving leakage performance
e.g. Real Zero project
Interest in R407A to replace R404A
50% reduction in GWP

Inorganic Refrigerants

Carbon Dioxide

Water

Ammonia

Air

Sulphur dioxide

HCFC

Transitional compounds with low ODP

Partially halogenated compounds of hydrocarbon

Remaining hydrogen atom allows Hydrolysis and can be absorbed.

R22, R123

HCFC

Production frozen at 1996 level

35% cut by 2005,65% by 2010

90% by 2015,100 % by 2030

10 year grace period for developing countries.

R22

ODP-0.05, GWP-1700

R22 has 40% more refrigerating capacity

Higher pressure and discharge temp and not suitable for low temp application

Extensively used in commercial air conditioning and frozen food storage and display cases

HFC

Zero ODP as no chlorine atom contains only Hydrogen and Flurodine

Very small GWP values

No phase out date in Montreal Protocol

R134a and R152 a – Very popular refrigerants

HFC refrigerants are costly refrigerants

R134a

ODP-0, GWP-1300

Used as a substitute for R12 and to a limited range for R22

Good performance in medium and high temp application

Toxicity is very low

Not miscible with mineral oil

Hydrocarbon

Very promising non-halogenated organic compounds

With no ODP and very small GWP values

Their efficiency is slightly better than other leading alternative refrigerants

They are fully compatible with lubricating oils conventionally used with CFC12.

Hydrocarbon Refrigerants

Extraordinary reliability- The most convincing argument is the reliability of the hydrocarbon system because of fewer compressor failures.

But most of the hydrocarbons are highly flammable and require additional safety precaution during its use as refrigerants.

Virtually no refrigerant losses

Hydrocarbons have been used since the beginning of the century and now being considered as long term solutions to environmental problems,

Hydrocarbons

Dominant in domestic market like household refrigerators and freezers

Growing use in very small commercial systems like car air-conditioning system

Examples: R170, Ethane, C_2H_6

R290 , Propane C_3H_3

R600, Butane, C_4H_{10}

R600a, Isobutane, C_4H_{10}

Blends of the above Gases

R 600a

- ODP-0,GWP-3
- Higher boiling point hence lower evaporator pressure
- Discharge temp is lowest
- Very good compatibility with mineral oil

Flammability

Approximate auto ignition temperatures

R22	630 ºC
R12	750 ºC
R134a	740 ºC
R290	465 ºC
R600a	470 ºC

Carbon Dioxide

Zero ODP & GWP

Non Flammable, Non toxic

Inexpensive and widely available

Its high operating pressure provides potential for system size and weight reducingpotential.

<u>Drawbacks:</u>

Operating pressure (high side) : 80 bars

Low efficiency

Ammonia –A Natural Refrigerant

Ammonia is produced in a natural way by human beings and animals; 17 grams/day for humans.

Natural production	3000 million tons/year
Production in factories	120 million tons/year
Used in refrigeration	6 million tons/year

Ammonia as Refrigerant

ODP = 0

GWP = 0

Excellent thermodynamic characteristics: small molecular mass, large latent heat, large vapour density and excellent heat transfer characteristics

High critical temperature (132C) : highly efficient cycles at high condensing temperatures

Its smell causes leaks to be detected and fixed before reaching dangerous concentration

Relatively Low price

Some Drawbacks of Ammonia as Refrigerant

Toxic

Flammable (16 – 28% concentration)

Not compatible with copper

Temperature on discharge side of compressor is higher compared to other refrigerants

Water

Zero ODP & GWP

Water as refrigerant is used in absorption system.New developing technology has created space for it for use in compression cycles also.

But higher than normal working pressure in the system can be a factor in restricted use of water as refrigerant

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