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New Scheme Based On AICTE Flexible Curricula

Mechanical Engineering, V-Semester

ME501- Internal Combustion Engines

Unit 1: Introduction of IC Engine:
Internal Combustion Engine: S.I. and C.I. engines of two and four stroke cycles, real cycle analysis of SI and CI engines, determination of engine dimensions, speed, fuel consumption, output, mean effective pressure, efficiency, factors effecting volumetric efficiency, heat balance, performance characteristics of SI and CI engines, cylinder arrangement, firing order, power balance for multi-cylinder engines .

Unit 2: Combustion in SI engines:
Flame development and propagation, Pressure-Crank Angle diagram, Stages of Combustion ignition lag, effect of air density, temperature, engine speed, turbulence and ignition timings, physical and chemical aspects, abnormal Combustion, effect of engine and fuel variables on abnormal combustion, pre-ignition, its causes and remedy, salient features of various type combustion chambers.

Unit 3: Combustion in CI Engines:
Various stages of combustion in CI Engines, delay period, diesel knock, knock inhibitors, salient features of various types of combustion chambers.Fuel injection in CI engine, Working Principle of fuel pump & fuel injectors, types of nozzles.
Fuel injection in SI engine (MPFI, TBI,CRDI), Theory of carburetion, Solex Carburetor, simple problems on carburetion. Fuel metering in CI engines

Unit 4: Fuel:
Classification of ICEngine fuels, Desirable characteristics of SI & CI engine fuels, Rating of SI & CI engine fuels, Alternative fuels for SI and CI engine (liquid, gaseous, hydrogen, LPG, CNG, Biogas etc.), Air requirement, Analysis of combustion products, HHV and LHV of fuels.

Unit 5: Supercharging & Turbo charging:
Methods of supercharging, & turbo charging Effects of super charging and turbo charging. Engine Modifications for supercharging, supercharging of two stroke engines. microprocessor controlled supercharging. Cooling & lubrication of SI & CI Engines.

References:

1. J.B. Heywood. Internal combustion Engines, Wiley
2. Ganeshan V; Internal Combustion engines; TMH
3. Mathur M L & Sharma RP; A. Course in IC engines; DhanpatRai
4. R Yadav, Internal Combustion Engines
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6. DomKundwar; Internal Combustion Engines;Dhanpat Rai Publications
7. Taylor GF; Internal Combustion Engines Theory & Practice; MIT Press
8. Richard Stone; Introduction to IC Engines; Society of Automotive Engr (Palgrave Mc Millan)

List of Experiments (please expand it);

1. Determination of Valve timing diagram
2. Load test on Petrol Engine
3. Heat Balance of SI engine
4. Heat Balance of CI Engine
5. Study of Battery Ignition system and Electronic Ignition System
6. Study of Diesel fuel pump
7. Study of Diesel fuel injectors
8. Study of Carburetors
9. Study of Fuel Injection system in SI Engine
10. Study of lubricating system in CI Engine

Unit-1 Internal Combustion Engines

At a design and development stage an engineer would design an engine with certain aims in his mind. The aims may include the variables like indicated power, brake power, brake specific fuel consumption, exhaust emissions, cooling of engine, maintenance free operation etc. The other task of the development engineer is to reduce the cost and improve power output and reliability of an engine. In trying to achieve these goals he has to try various design concepts. After the design the parts of the engine are manufactured for the dimensions and surface finish and may be with certain tolerances. In order verify the designed and developed engine one has to go for testing and performance evaluation of the engines.

Thus, in general, a development engineer will have to conduct a wide variety of engine tests starting from simple fuel and air-flow measurements to taking of complicated injector needle lift diagrams, swirl patterns and photographs of the burning process in the combustion chamber. The nature and the type of the tests to be conducted depend upon various factors, some of which are: the degree of development of the particular design, the accuracy required, the funds available, the nature of the manufacturing company, and its design strategy. In this chapter, only certain basic tests and measurements will be considered.

Objectives

After studying this unit, you should be able to

- Understand the performance parameters in evaluation of IC engine performance,
- calculate the speed of IC engine, fuel consumption, air consumption, etc.,
- evaluate the exhaust smoke and exhaust emission, and
- Differentiate between the performance of SI engine and CI engines.

Engine performance is an indication of the degree of success of the engine performs i ts assigned task, i.e. the conversion of the chemical energy contained in the fuel into the useful mechanical work. The performance of an engine is evaluated on the basis of the following:

(a) Specific Fuel Consumption.
(b) Brake Mean Effective Pressure.
(c) Specific Power Output.
(d) Specific Weight.
(e) Exhaust Smoke and Other Emissions.

The particular application of the engine decides the relative importance of these performance parameters.

For Example: For an aircraft engine specific weight is more important whereas for an industrial engine specific fuel consumption is more important.

For the evaluation of an engine performance few more parameters are chosen and the effect of various operating conditions, design concepts and modifications on these parameters is studied. The basic performance parameters are the following:

(a) Power and Mechanical Efficiency.
(b) Mean Effective Pressure and Torque.
(c) Specific Output.
(d) Volumetric Efficiency.
(e) Fuel-air Ratio.
(f) Specific Fuel Consumption.
(g) Thermal Efficiency and Heat Balance.
(h) Exhaust Smoke and Other Emissions.
(i) Specific Weight.

Power and Mechanical Efficiency

The main purpose of running an engine is to obtain mechanical power.

Power is defined as the rate of doing work and is equal to the product of force and linear velocity or the product of torque and angular velocity.

Thus, the measurement of power involves the measurement of force (or torque) as well as speed. The force or torque is measured with the help of a dynamometer and the speed by a tachometer.

The power developed by an engine and measured at the output shaft is called the brake power.

The total power developed by combustion of fuel in the combustion chamber is, however, more than the *bp* and is called indicated power (*ip*). Of the power developed by the engine, i.e. *ip*, some power is consumed in overcoming the friction between moving parts, some in the process of inducting the air and removing the products of combustion from the engine combustion chamber.

Indicated Power

It is the power developed in the cylinder and thus, forms the basis of evaluation of combustion efficiency or the heat release in the cylinder.

The difference between *ip* and *bp* is called friction power (*fp*).

Mean Effective Pressure

Mean effective pressure is defined as a hypothetical/average pressure which is assumed to be acting on the piston throughout the power stroke. If the mean effective pressure is based on *bp* it is called the brake mean effective pressure and if based on *ihp* it is called indicated mean effective pressure.

Specific Output

Specific output of an engine is defined as the brake power (output) per unit of piston displacement.

Volumetric Efficiency

Volumetric efficiency of an engine is an indication of the measure of the degree to which the engine fills its swept volume. It is defined as the ratio of the mass of air inducted into the engine cylinder during the suction stroke to the mass of the air corresponding to the swept volume of the engine at atmospheric pressure and temperature. Alternatively, it can be defined as the ratio of the actual volume inhaled during suction stroke measured at intake conditions to the swept volume of the piston.

Fuel-Air Ratio (*F*/*A*)

Fuel-air ratio (*F*/*A*) is the ratio of the mass of fuel to the mass of air in the fuel-air mixture. Air-fuel ratio (*A*/*F*) is reciprocal of fuel-air ratio. Fuel-air ratio of the mixture affects the combustion phenomenon in that it determines the flame propagation velocity, the heat release in the combustion chamber, the maximum temperature and the completeness of combustion.

Relative fuel-air ratio is defined as the ratio of the actual fuel-air ratio to that of the stoichiometric fuel-air ratio required to burn the fuel supplied. Stoichiometric fuel-air ratio is the ratio of fuel to air is one in which case fuel is completely burned due to minimum quantity of air supplied.

Brake Specific Fuel Consumption

Specific fuel consumption is defined as the amount of fuel consumed for each unit of brake power developed per hour. It is a clear indication of the efficiency with which the engine develops power from fuel.

Thermal Efficiency and Heat Balance

Thermal efficiency of an engine is defined as the ratio of the output to that of the chemical energy input in the form of fuel supply. It may be based on brake or indicated output. It is the true indication of the efficiency with which the chemical energy of fuel (input) is converted into mechanical work. Thermal efficiency also accounts for combustion efficiency, i.e., for the fact that whole of the chemical energy of the fuel is not converted into heat energy during combustion.

The basic measurements to be undertaken to evaluate the performance of an engine on almost all tests are the following:

(a) Fuel consumption

(b) Air consumption

(c) Smoke density

(d) Brake horse-power

(e) Indicated horse power and friction horse power

(f) Heat going to cooling water

(g) Heat going to exhaust

(h) Exhaust gas analysis.

In addition to above a large number of other measurements may be necessary depending upon the aim of the test.

Firing Order

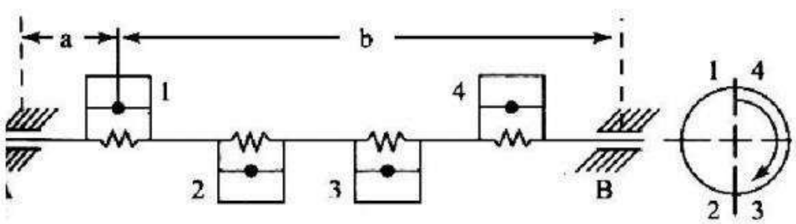
The firing order is the sequence of power delivery of each cylinder in a multi-cylinder reciprocating engine. This is achieved by sparking of the spark plugs in a gasoline engine in the correct order, or by the sequence of fuel injection in a Diesel engine. When designing an engine, choosing an appropriate firing order is critical to minimizing vibration, to improve engine balance and achieving smooth running, for long engine fatigue life and user comfort, and heavily influences crankshaft design.

Further, there are three factors which must be considered before deciding the optimum firing order of an engine. These are:

(i) Engine vibrations

(ii) Engine cooling and

(iii)Development of back pressure



Consider that the cylinder number 1 of the four-cylinder engine, shown in Fig., is fired first. A pressure p, generated in the cylinder number 1 will give rise to a force equal to {pA [b/(a + b)]} and {pA [a/(a + b)]} on the two bearings A and B respectively. The load on bearing A is much more than load on bearing B. If the next cylinder fired is cylinder number 2, this imbalance in load on the two bearings would furt her aggravate the problem of balancing of the crankshaft vibrations & would result in severe engine vibrations. If we fire cylinder number 3 after cylinder number 1, the load may be more or less evenly distributed.

Further, consider the effect of firing sequence on engine cooling. When the first cylinder is fired its temperature increases. If the next cylinder that fires is number 2, the portion of the engine between the cylinder number 1 and 2 gets overheated. If then the third cylinder is fired, overheating is shifted to the portion between the cylinders 2 and 4. Thus we see that the task of the cooling system becomes very difficult because it is then, required to cool more at one place than at other places and this imposes great strain on the cooling system. If the third cylinder is fired after the first the overheating problem can be controlled to a greater extent.

Next, consider the flow of exhaust gases in the exhaust pipe. After firing the first cylinder, exhaust gases flow out to the exhaust pipe. If the next cylinder fired is the cylinder number 2, we find that before the gases exhausted by the first cylinder go out of the exhaust pipe the gases exhausted from the second cylinder try to overtake them. This would require that the exhaust pipe be made bigger. Otherwise the back pressure in it would increase and the possibility of back flow would arise. If instead of firing cylinder number 2, cylinder number 3 is fired. Then by the time the gases exhausted by the cylinder 3 come into the exhaust pipe, the gases from cylinder 1 would have sufficient time to travel the distance between cylinder 1 and cylinder 3 and thus, the development of a high back pressure is avoided.

It should be noted that to some extent all the above three requirements are conflicting and therefore a trade-off is necessary.

Valve timing diagram

The valve timing diagram is defined as the graphical representations of the events of opening & closing of inlet & outlet valves during one complete engine cycle.

Its significance is to optimize valve timing events for a modern high speed internal combustion engine for the purpose of improving fuel economy during idle, high speed performance and allowing for a leaner fuel/air ratio during idle. The method is based on an analytical treatment of the instantaneous relationship between valve flow area and the changes in cylinder volume occurring because of piston motion.

Actual Opening and closing of Inlet Valve:

The inlet valve is made to open 10degree to 30degree before the piston reaches the Top Dead Center (TDC) during Suction Stroke and is allowed to close only after 30degree to 40degree after the piston reaches and leaves the BDC in the beginning of compression stroke.

Reason:

The reason for doing this is to facilitate silent operation of the engine under high speeds. The inlet valves are made to operate slowly to avoid noise and hence sufficient time should be provided for the air-fuel mix to get into the cylinder. Thus valves are made to open before the actual BDC. Since the inlet valve is a small opening sufficient mixture doesn't enter the cylinder in such short time, as the piston reaches BDC. Thus the inlet valve is kept open for some time period of time after BDC, to facilitate sufficient flow of charge into the cylinder.

Actual Opening and closing of Exhaust Valve:

The exhaust valve is made to open 30degree to 60degree before the TDC in the exhaust stroke and allowed to close only after 80 to 10 in0 the beginning of the suction stroke.

Reason:

The gases inside the cylinder posses a higher pressure even after the expansion stroke, this higher pressure enables it to move out of the cylinder through the exhaust valve reducing the work that needs to be done by the engine piston in pushing out these gases. Thus the exhaust valve is made to open before the piston reaches the BDC thus enabling the gases to escape outside on its own and the remaining gases are pushed out by the upward motion of the piston. When the piston reaches the TDC, if the exhaust valve is closed like in actual timing diagram, a certain amount of exhaust gases will get compressed and remain inside the Cylinder and will be carried to the next cycle also. To prevent this, the exhaust valves are allowed to close only a certain time after the piston reaches the TDC.

Heat balance sheet

A heat balance sheet is an account of heat supplied and heat utilized in various ways in the system. Necessary information concerning the performance of the engine is obtained from the heat balance sheet. The heat balance sheet is generally done on second basis or minute basis or hour basis.

The engine should be equipped with suitable loading arrangement to measure the brake power of the engine. Provisions are also made to measure the amount of air intake, amount of fuel consumed, temperature of cooling water at inlet and outlet of the engine amount of cooling water circulated and temperature of exhaust gases.

The heat supplied to the engine is only in the form of fuel – heat and is equal to.

$Qs = mf \times C.V$

Where,

mf = mass of fuel used in kg/min

C.V = Calorific value of fuel in KJ /kg

The various ways in which the heat is utilized are

1. Heat equivalent to break power of the engine.
2. Heat carried away by the cooling water
3. Heat carried away by the exhaust gases
4. Unaccounted heat losses.

Heat equivalent to B.P:

The brake power in KW is converted into KJ/min

$Q_{B.P} = B.P \times 60$ KJ/min

Heat carried away by the cooling water: (Qw)

Heat carried away by the exhaust gases: (Q_g)

Unaccounted heat losses:

$Qun = Qs - (Q.B.P + Qw + Qg)$ in KJ / min

Heat Balance Sheet

S No	Particulars	Credits	
		KJ/min	%
1	Qs		
2	QBP		
3	Q_w		
4	Qg		
5	Qun		
	Total		

Unit-2 Combustion in SI engines

Combustion may be defined as a relatively rapid chemical combination of hydrogen and carbon in fuel with oxygen in air resulting in liberation of energy in the form of heat.

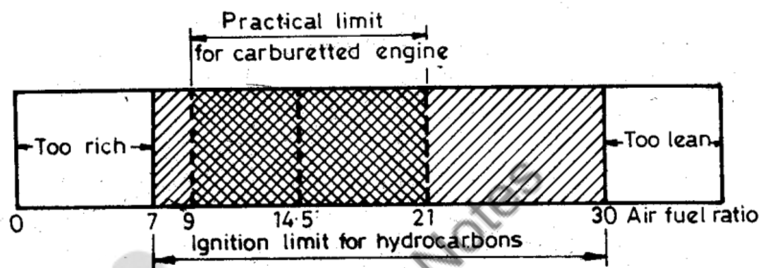
Following conditions are necessary for combustion to take place

1. The presence of combustible mixture
2. Some means to initiate mixture
3. Stabilization and propagation of flame in Combustion Chamber

In S I Engines, carburetor supplies a combustible mixture of petrol and air and spark plug initiates combustion

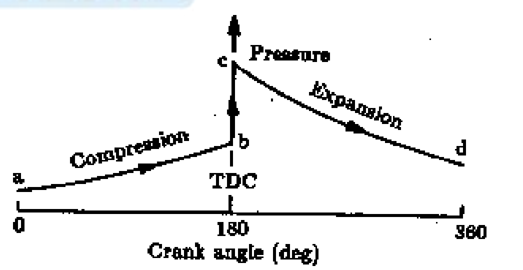
Ignition Limits

Ignition of charge is only possible within certain limits of fuel-air ratio. Ignition limits correspond approximately to those mixture ratios, at lean and rich ends of scale, where heat released by spark is no longer sufficient to initiate combustion in neighboring unburnt mixture. For hydrocarbons fuel the stoichiometric fuel air ratio is 1:15 and hence the fuel air ratio must be about 1:30 and 1:7



Theories of Combustion in Si Engine

Combustion in SI engine may be roughly divided into two general types: Normal and Abnormal (knock free or knocking). Theoretical diagram of pressure crank angle diagram is shown, a-b is compression process, b-c is combustion process and c-d is an expansion process. In an ideal cycle it can be seen from the diagram, the entire pressure rise during combustion takes place at constant volume i.e., at TDC. However, in actual cycle this does not happen.



Richard's Theory of Combustion

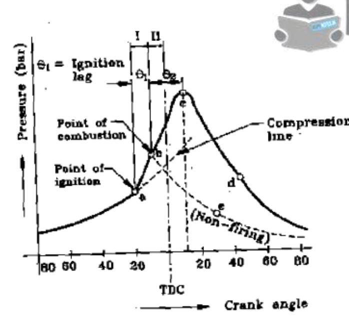
Sir Ricardo, known as father of engine research describes the combustion process can be imagined as if it is developing in two stages:

1. Growth and development of a self propagating nucleus flame. (Ignition lag)
2. Spread of flame through the combustion chamber

Three Stage of Combustion

According to Ricardo, There are three stages of combustion in SI Engine as shown

1. Ignition lag stage
2. Flame propagation stage
3. After burning stage



Ignition lag stage: There is a certain time interval between instant of spark and instant where there is a noticeable rise in pressure due to combustion. This time lag is called IGNITION LAG.

Ignition lag is the time interval in the process of chemical reaction during which molecules get heated up to self ignition temperature, get ignited and produce a self propagating nucleus of flame. The ignition lag is generally expressed in terms of crank angle. The period of ignition lag is shown by path ab. Ignition lag is very small and lies between 0.00015 to 0.0002 seconds. An ignition lag of 0.002 seconds corresponds to 35 deg crank rotation when the engine is running at 3000 RPM. Angle of advance increase with the speed this is a chemical process depending upon the nature of fuel, temperature and pressure, proportions of exhaust gas and rate of oxidation or burning.

Flame propagation stage:

Once the flame is formed at “b”, it should be self sustained and must be able to propagate through the mixture. This is possible when the rate of heat generation by burning is greater than heat lost by flame to surrounding. After the point “b”, the flame propagation is abnormally low at the beginning as heat lost is more than heat generated. Therefore pressure rise is also slow as mass of mixture burned is small. Therefore it is necessary to provide angle of advance 30 to 35 deg, if the peak pressure to be attained 5-10 deg after TDC. The time required for crank to rotate through an angle is known as combustion period during which propagation of flame takes place.

After burning:

Combustion will not stop at point “c” but continue after attaining peak pressure and this combustion is known as after burning. This generally happens when the rich mixture is supplied to engine.

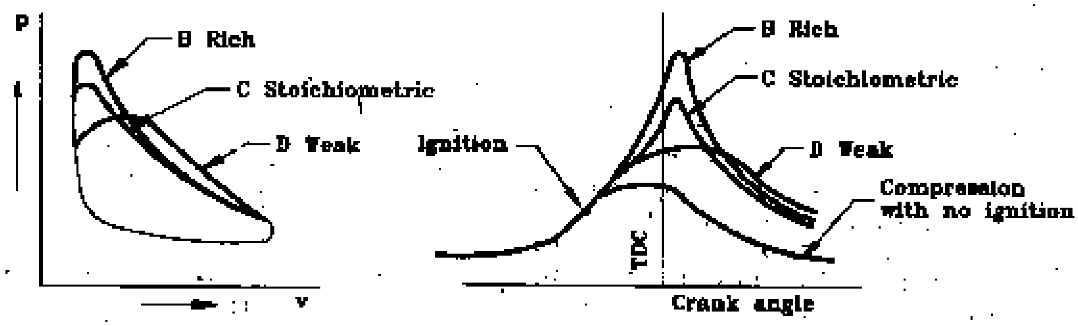
Factors Affecting the Flame Propagation

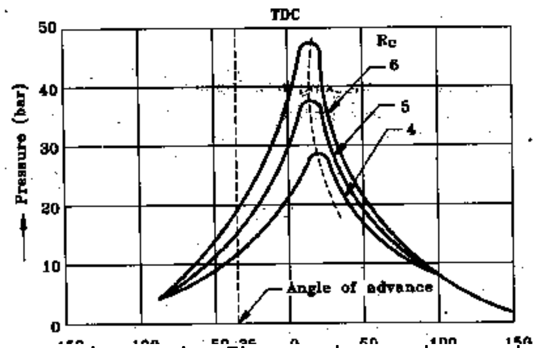
Rate of flame propagation affects the combustion process in SI engines. Higher combustion efficiency and fuel economy can be achieved by higher flame propagation velocities. Unfortunately flame velocities for most of fuel range between 10 to 30 m/second.

The factors which affect the flame propagations are

1. Air fuel ratio
2. Compression ratio
3. Load on engine
4. Turbulence and engine speed
5. Other factors

A: F ratio. The mixture strength influences the rate of combustion and amount of heat generated. The maximum flame speed for all hydrocarbon fuels occurs at nearly 10% rich mixture. Flame speed is reduced both for lean and as well as for very rich mixture. Lean mixture releases less heat resulting lower flame temperature and lower flame speed. Very rich mixture results incomplete combustion (C CO instead of C0 and also results in production of less heat and flame speed remains low. The effects of A: F ratio on p-v diagram and p-0 diagram are shown below:





Compression ratio: The higher compression ratio increases the pressure and temperature of the mixture and also decreases the concentration of residual gases. All these factors reduce the ignition lag and help to speed up the second phase of combustion.
The maximum pressure of the cycle as well as
Mean effective pressure of the cycle with increase in compression ratio. Figure above shows the effect of compression ratio on pressure (indirectly on the speed of combustion) with respect to crank angle for same A: F ratio and same angle of advance. Higher compression ratio increases the surface to volume ratio and thereby increases the part of the mixture which after-burns in the third phase.
Load on Engine. With increase in load, the cycle pressures increase and the flame speed also increases. In S.I. engine, the power developed by an engine is controlled by throttling. At lower load and higher throttle, the initial and final pressure of the mixture after compression decrease and mixture is also diluted by the more residual gases. This reduces the flame propagation and prolongs the ignition lag. This is the reason, the advance mechanism is also provided with change in load on the engine. This difficulty can be partly overcome by providing rich mixture at part loads but this definitely increases the chances of after- burning. The after burning is prolonged with richer mixture. In fact, poor combustion at part loads and necessity of providing richer mixture are the main disadvantages of S.I. engines which causes wastage of fuel and discharge of large amount of CO with exhaust gases.
Turbulence: Turbulence plays very important role in combustion of fuel as the flame speed is directly proportional to the turbulence of the mixture. This is because, the turbulence increases the mixing and heat transfer coefficient or heat transfer rate between the burned and unburned mixture. The turbulence of the mixture can be increased at the end of compression by suitable design of the combustion chamber (geometry of cylinder head and piston crown).
Insufficient turbulence provides low flame velocity and incomplete combustion and reduces the power output. But excessive turbulence is also not desirable as it increases the combustion rapidly and leads to detonation. Excessive turbulence causes to cool the flame generated and flame propagation is reduced.
Moderate turbulence is always desirable as it accelerates the chemical reaction, reduces ignition lag, increases flame propagation and even allows weak mixture to burn efficiently.

Engine Speed
The turbulence of the mixture increases with an increase in engine speed. For this reason the flame

speed almost increases linearly with engine speed. If the engine speed is doubled, flame to traverse the combustion chamber is halved. Double the original speed and half the original time give the same number of crank degrees for flame propagation. The crank angle required for the flame propagation, which is main phase of combustion will remain almost constant at all speeds. This is an important characteristic of all petrol engines.

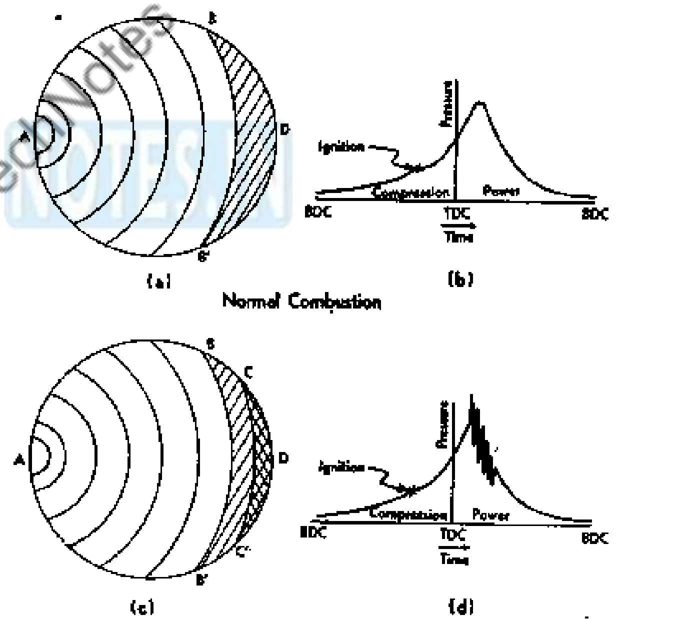
Engine Size

Engines of similar design generally run at the same piston speed. This is achieved by using small engines having larger RPM and larger engines having smaller RPM. Due to same piston speed, the inlet velocity, degree of turbulence and flame speed are nearly same in similar engines regardless of the size. However, in small engines the flame travel is small and in large engines large. Therefore, if the engine size is doubled the time required for propagation of flame through combustion space is also doubled. But with lower RPM of large engines the time for flame propagation in terms of crank would be nearly same as in small engines. In other words, the number of crank degrees required for flame travel will be about the same irrespective of engine size provided the engines are similar.

Other Factors Among the other factors, the factors which increase the flame speed are supercharging of the engine, spark timing and residual gases left in the engine at the end of exhaust stroke. The air humidity also affects the flame velocity but its exact effect is not known. Anyhow, its effect is not large compared with A: F ratio and turbulence.

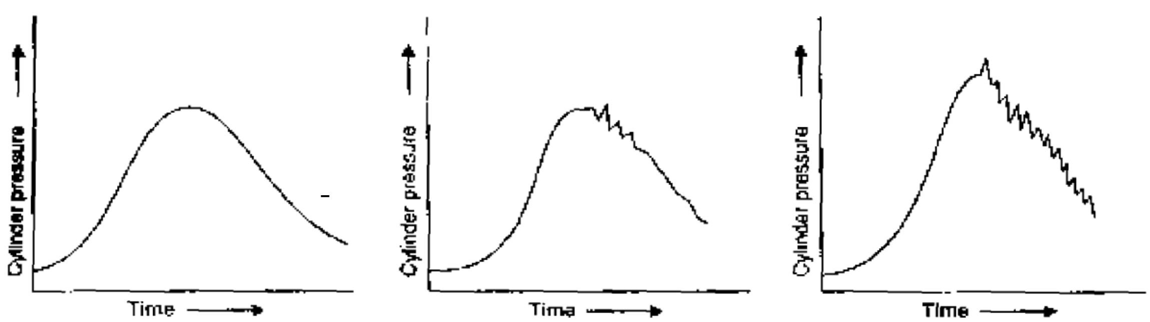
Phenomenon of Knocking In Si Engine

Knocking is due to auto ignition of end portion of unburned charge in combustion chamber. As the normal flame proceeds across the chamber, pressure and temperature of unburned charge increase due to compression by burned portion of charge. This unburned compressed charge may auto ignite under certain temperature condition and release the energy at a very rapid rate compared to normal combustion



Combustion With Detonation

process in cylinder. This rapid release of energy during auto ignition causes a high pressure differential in combustion chamber and a high pressure wave is released from auto ignition region. The motion of high pressure compression waves inside the cylinder causes vibration of engine parts and pinging noise



(i) Normal combustion with no knock (ii) Combustion with slight knock (iii) Combustion with heavy knock and it is known as knocking or detonation. This pressure frequency or vibration frequency in SI engine can be up to 5000 Cycles per second.

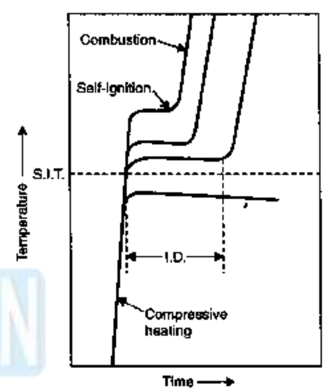
Denotation is undesirable as it affects the engine performance and life, as it abruptly increases sudden large amount of heat energy. It also put a limit on compression ratio at which engine can be operated which directly affects the engine efficiency and output.

AUTO IGINITION

A mixture of fuel and air can react spontaneously and produce heat by chemical reaction in the absence of flame to initiate the combustion or self-ignition. This type of self-ignition in the absence of flame is known as Auto-Ignition. The temperature at which the self-ignition takes place is known as self-igniting temperature. The pressure and temperature abruptly increase due to auto-ignition because of sudden release of chemical energy.

This auto-ignition leads to abnormal combustion known as detonation which is undesirable because its bad effect on the engine performance and life as it abruptly increases sudden large amount of heat energy. In addition to this knocking puts a limit on the compression ratio at which an engine can be operated which directly affects the engine efficiency and output.

Auto-ignition of the mixture does not occur instantaneously as soon as its temperature rises above the self-ignition temperature. Auto-ignition occurs only when the mixture stays at a temperature equal to or higher than the self-ignition temperature for a “finite time”. This time is known as delay period or reaction time for auto-ignition. This delay time as a function of compression ratio is shown in adjacent figure.



S.I.T. → Self-ignition temperature
I.D. → Ignition delay

As the compression ratio increases, the delay period decreases and this is because of increase in initial (before combustion) pressure and temperature of the charge. The self-ignition temperature is a characteristic of fuel air mixture and it varies from fuel to fuel and mixture strength to mixture - strength of the same fuel.

PRE -IGINITION

Pre-ignition is the ignition of the homogeneous mixture of charge as it comes in contact with hot surfaces, in the absence of spark.

Auto ignition may overheat the spark plug and exhaust valve and it remains so hot that its temperature is sufficient to ignite the charge in next cycle during the compression stroke before spark occurs and this causes the pre-ignition of the charge.

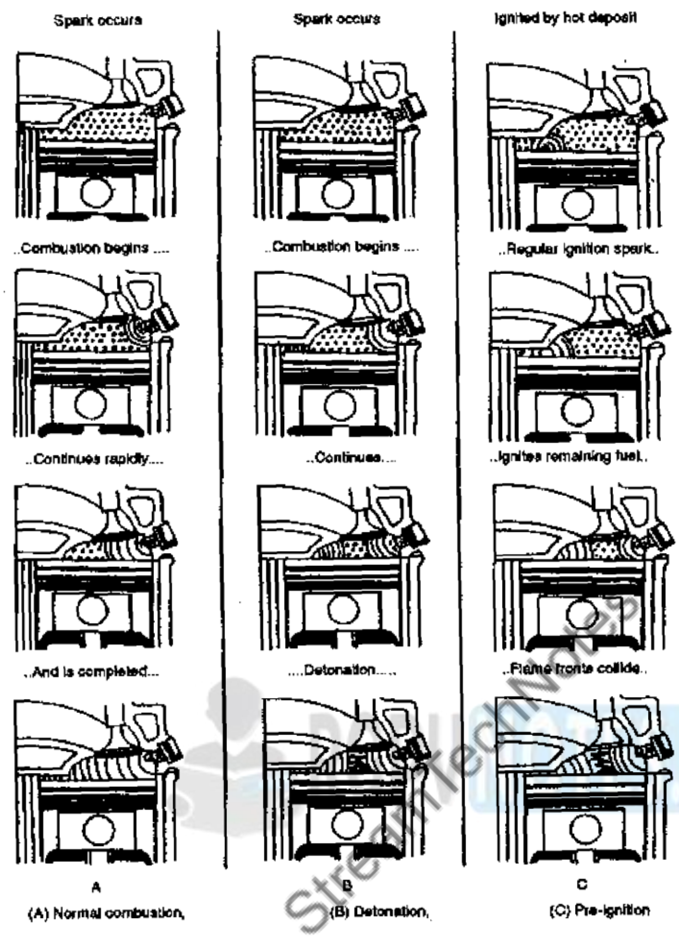
Pre-ignition is initiated by some overheated projecting part such as the sparking plug electrodes; exhaust valve head, metal corners in the combustion chamber, carbon deposits or protruding cylinder head gasket rim etc.

Pre-ignition is also caused by persistent detonating pressure shockwaves scoring away the stagnant gases which normally protect the combustion chamber walls. The resulting increased heat flow through the walls raises the surface temperature of any protruding poorly cooled part of the chamber, and this therefore provides a focal point for pre- ignition.

Effects of Pre-ignition

- It increase the tendency of denotation in the engine
- It increases heat transfer to cylinder walls because high temperature gas remains in contact with for a longer time

- Pre-ignition in a single cylinder will reduce the speed and power output
- Pre-ignition may cause seizer in the multi-cylinder engines, only if only cylinders have pre-ignition



DIFFERENCE BETWEEN NORMAL/ABNORMAL COMBUSTION AND PRE- INGINITON

EFFECT OF DETONATION

The harmful effects of detonation are as follows:

1. Noise and Roughness. Knocking produces a loud pulsating noise and pressure waves. These waves which vibrates back and forth across the cylinder. The presence of vibratory motion causes crankshaft vibrations and the engine runsrough.

2. Mechanical Damage.

(a) High pressure waves generated during knocking can increase rate of wear of parts of combustion chamber. Sever erosion of piston crown (in a manner similar to that of marine propeller blades by Cavitation), cylinder head and pitting of inlet and outlet valves may result in complete wreckage of the engine.

(b) Detonation is very dangerous in engines having high noise level. In small engines the knocking noise is easily detected and the corrective measures can be taken but in aero-engines it is difficult to detect knocking noise and hence corrective measures cannot be taken. Hence severe detonation may persist for a long time which may ultimately result in complete wreckage of the piston.

3. Carbon deposits. Detonation results in increased carbon deposits.

4. Increase in heat transfer. Knocking is accompanied by an increase in the rate of heat transfer to the combustion chamber walls.

The increase in heat transfer is due to two reasons.

- The minor reason is that the maximum temperature in a detonating engine is about 150°C higher than in a non-detonating engine, due to rapid completion of combustion
- The major reason for increased heat transfer is the scouring away of protective layer of inactive stagnant gas on the cylinder walls due to pressure waves. The inactive layer of gas normally reduces the heat transfer by protecting the combustion and piston crown from direct contact with flame.

5. Decrease in power output and efficiency. Due to increase in the rate of heat transfer the power output as well as efficiency of a detonating engine decreases.

6 Pre-ignition: The increase in the rate of heat transfer to the walls has yet another effect. It may cause local overheating, especially of the sparking plug, which may reach a temperature high enough to ignite the charge before the passage of spark, thus causing pre-ignition. An engine detonating for a long period would most probably lead to pre-ignition and this is the real danger of detonation.

EFFECT OF ENGINE OPERATING VARIABLES ON THE ENGINE KNOCKING DETONATION

The various engine variables affecting knocking can be classified as:

- Temperature factors
- Density factors
- Time factors
- Composition factors

(A) TEMPERATURE FACTORS

Increasing the temperature of the unburned mixture increase the possibility of knock in the SI engine we shall now discuss the effect of following engine parameters on the temperature of the unburned mixture:

RAISING THE COMPRESSION RATIO increasing the compression ratio increases both the temperature and pressure (density of the unburned mixture). Increase in temperature reduces the delay period of the end gas which in turn increases the tendency to knock.

SUPERCHARGING It also increases both temperature and density, which increase the knocking tendency of engine

COOLANT TEMPERATURE Delay period decreases with increase of coolant temperature, decreased delay period increase the tendency to knock.
TEMPERATURE OF THE CYLINDER AND COMBUSTION CHAMBER WALLS: The temperature of the end gas depends on the design of combustion chamber. Sparking plug and exhaust valve are two hottest parts in the combustion chamber and uneven temperature leads to pre-ignition and hence the knocking.

(B) DENSITY FACTORS

Increasing the density of unburnt mixture will increase the possibility of knock in the engine. The engine parameters which affect the density are as follows:

- Increased compression ratio increase the density
- Increasing the load opens the throttle valve more and thus the density
- Supercharging increase the density of the mixture
- Increasing the inlet pressure increases the overall pressure during the cycle. The high pressure end gas decreases the delay period which increase the tendency of knocking.

Advanced spark timing: quantity of fuel burnt per cycle before and after TDC position depends on spark timing. The temperature of charge increases by increasing the spark advance and it increases with rate of burning and does not allow sufficient time to the end mixture to dissipate the heat and increase the knocking tendency.

(C) TIME FACTORS

Increasing the time of exposure of the unburned mixture to auto-ignition conditions increase the possibility of knock in SI engines
Flame travel distance: If the distance of flame travel is more, then possibility of knocking is also more. This problem can be solved by combustion chamber design, spark plug location and engine size. Compact combustion chamber will have better anti-knock characteristics, since the flame travel and combustion time will be shorter. Further, if the combustion chamber is highly turbulent, the combustion rate is high and consequently combustion time is further reduced; this further reduces the tendency to knock.
Location of sparkplug: A spark plug which is centrally located in the combustion chamber has minimum tendency to knock as the flame travel is minimum. The flame travel can be reduced by using two or more spark plugs.
Location of exhaust valve: The exhaust valve should be located close to the spark plug so that it is not in the end gas region; otherwise there will be a tendency to knock.
Engine size: Large engines have a greater knocking tendency because flame requires a longer time to travel across the combustion chamber. In SI engine therefore, generally limited to 100mm
Turbulence of mixture decreasing the turbulence of the mixture decreases the flame speed and hence increases the tendency to knock. Turbulence depends on the design of combustion chamber and one engine speed.

(D) COMPOSITION

The properties of fuel and A/F ratio are primary means to control knock:

(a) Molecular Structure. The knocking tendency is markedly affected by the type of the fuel used. Petroleum fuels usually consist of many hydro-carbons of different molecular structure. The structure of the fuel molecule has enormous effect on knocking tendency. Increasing the carbon-chain increases the knocking tendency and centralizing the carbon atoms decreases the knocking tendency. Unsaturated hydrocarbons have less knocking tendency than saturated hydro-carbons.

Paraffins

Increasing the length of carbon chain increases the knocking tendency. Centralizing the carbon atoms decreases the knocking tendency. Adding methyl group (CH to the side of the carbon chain in the centre position decreases the knocking tendency.

Olefins

Introduction of one double bond has little effect on anti-knock quality but two or three double bond results less knocking tendency except C and C

Napthenes and Aromatics

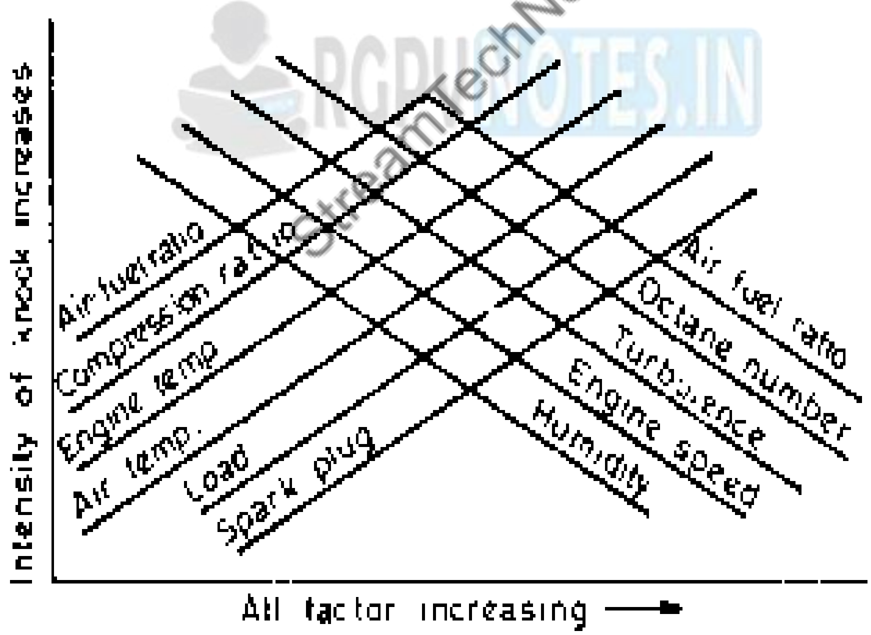
Napthenes have greater knocking tendency than corresponding aromatics. With increasing double-bonds, the knocking tendency is reduced. Lengthening the side chains increases the knocking tendency whereas branching of the side chain decreases the knocking tendency.

(b) Fuel-air ratio. The most important effect of fuel-aft ratio is on the reaction time or ignition delay.

(c) When the mixture is nearly 10% richer than stoichiometric (fuel-air ratio = 0.08) ignition lag of the end gas is minimum and the velocity of flame propagation is maximum. By making the mixture leaner or richer (than F/A 0.08) the tendency to knock is decreased. A too rich mixture is especially effective in decreasing or eliminating the knock due to longer delay and lower temperature of compression.

(d) Humidity of air. Increasing atmospheric humidity decreases the tendency to knock by decreasing the reaction time of the fuel

The trends of the most of the above factors on knocking tendency of the engine are given below:



Effect of engine variables on Knocking in SI engine

1. Compression ratio: The pressure and temperature at the end of compression increases with increase in compression ratio. This in turn increase the maximum pressure during the combustion and creates a tendency toknock
2. Supercharging: increase the temperature and density of mixture and thus the tendency to knock is increased.
3. Turbulence : decreasing the turbulence of mixture decreases the flame speed and hence increase the tendency to knock
4. Octane rating of fuel: higher the octane number, less the tendency to knock. Paraffins have maximum tendency to knock and aromatic series have minimum tendency to knock. (also see Influence of chemical structure on knocking)

Factors that limits the compression ratio in petrol engine

In petrol engine we use the mixture of air and petrol and thermal efficiency of petrol engine increase with increase in compression ratio. But the value of compression ratio is limited by phenomenon of knocking. The pressure and temperature at the end of compression increases with increase in compression ratio this in turn increase the maximum pressure during the combustion and creates a tendency to knock. Thus, higher compression ratio, higher is the tendency to knock; therefore the value of compression ratio in petrol engine is limited to 6 to 10.

Compression ratio can be marginally improved by using fuel with Tetra-ethyl lead. TEL delays the auto ignition and allows it to occur at higher temperature and thus reduces knocking. The use of TEL is now in disfavor because of atmospheric pollution (lead is toxic and has serious environmental and health hazards).

KNOCK RATING OF SI ENGINE FUELS (OCTANE NUMBER)

The tendency to detonate depends on composition of fuel. Fuel differs widely in their ability to resist knock. The property of fuel which describes how fuel will or will nor self ignite is called the OCTANE NUMBER. It is defined as the percentage of Iso-octane by volume in a mixture of Iso-octane and n-heptanes which exactly matches the knocking tendency of a given fuel, in a standard fuel under given standard operating conditions. The rating of a particular SI fuel is done by comparing its antiknock performance with that of standard reference fuel which is usually combination of Iso-octane and n- heptanes. Iso-octane (C_8H_{18}) which has a very high resistance to knock and therefore it is arbitrarily assigned a rating of 100 octane number N-heptanes (C_7H_{16}) which is very prone to knock and therefore given a zero value.

For example: Octane number 80 means that the fuel has same knocking tendency as mixture of 80% iso-octane and 20% n-heptane (by volume basis).

A fuel having an octane number of 110 means fuel has the same tendency to resist as a mixture of 10 cc of Tetra ethyl lead (TEL) in one U.S gallon of Iso-octane.

HIGHEST USEFUL COMPRESSION RATIO (HUCR)

The thermal efficiency of IC engine increase with increase in Compression Ratio The maximum compression ratio of any SI engine is limited by its tendency to knock. HUCR is the highest compression ratio employed at which a fuel can be used in a specified engine under specified set of operating conditions, at which detonation first becomes audible with both ignition and mixture strength adjusted to give highest efficiency.

HUCR of different fuel

Iso-octane	10.96
n-heptane	3.75
Toulene	15

Cyclo hexane	8.20

Anti Knock Agents

The knock resistance tendency of a fuel can be increased by adding anti-knock agents. The anti knock agents are substances which decreases the rate of preflame reaction by delaying the auto ignition of the end mixture in engine until flame generated by spark plug.

Increased or higher inlet pressure is used to take advantage of an increase in octane number. The use of leaded gasoline However is not perfect solution to problem. It leads to emission of lead into atmosphere which is known to be very hazardous.

The following table shows some anti knock agents and effectiveness.

Compound	Chemical Symbol	Weight for given effect (gm)	Relative weight
Tetraethyl lead	$Pb(C_2H_5)_4$	0.029	1
Aniline	$C_6H_5NH_2$	1	34
Ethyl Iodide	C_2H_5I	1.55	53
Ethyl alcohol	C_2H_5OH	4.75	161
Xylene	$[C_6H_4CH_3]_2$	8.00	271
Toluene	$C_6H_5CH_3$	8.8	298
Benzene	C_6H_6	9.8	332

The following table gives the relative effectiveness of anti knocks

Compound	Relative effectiveness
Tetra ethyl lead (TEL)	100
Methyl cyclo pentadienyl	65
Manganese tricarbonyl Ironcarbonyl	43
Copper methyl arnino methyle necetate	40
Nickel carbonyl	30
Tri ethyl bismuth	20
Tetra ethyl tin	3
N-Methyl aniline-Ethyl iodide	11

Unit-3 Combustion in CI engines

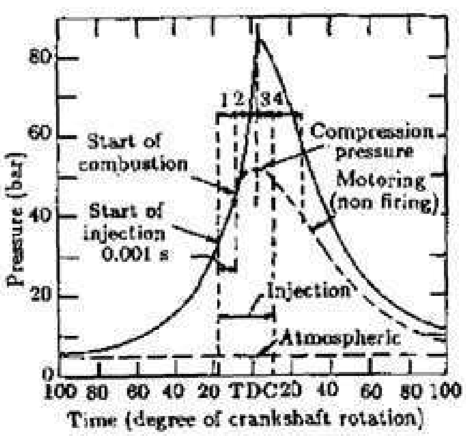
In SI engine, uniform A: F mixture is supplied, but in CI engine A: F mixture is not homogeneous and fuel remains in liquid particles, therefore quantity of air supplied is 50% to 70% more than stoichiometric mixture.

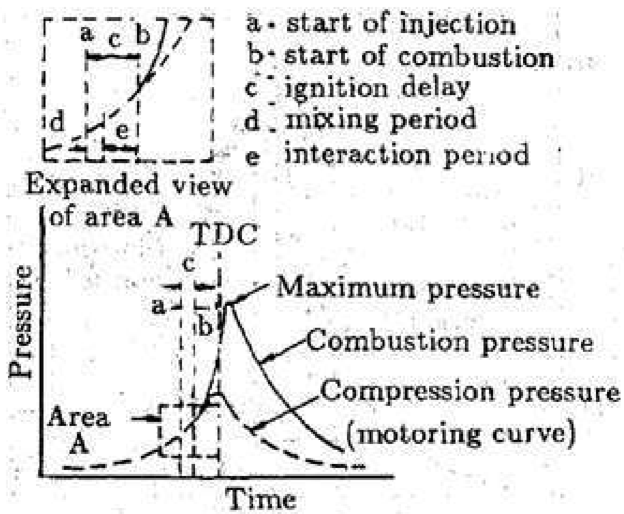
The combustion in SI engine starts at one point and generated flame at the point of ignition propagates through the mixture for burning of the mixture, where as in CI engine, the combustion takes place at number of points simultaneously and number of flames generated are also many. To burn the liquid fuel is more difficult as it is to be evaporated; it is to be elevated to ignition temperature and then burn.

Stages of Combustion In CI Engine

The combustion in CI engine is considered to be taking place in four phases:

- Ignition Delay period /Pre-flame combustion
- Uncontrolled combustion
- Uncontrolled combustion
- After burning





1 Ignition Delay period /Pre-flame combustion

The fuel does not ignite immediately upon injection into the combustion chamber. There is a definite period of inactivity between the time of injection and the actual burning this period is known as the ignition delay period.

In Figure the delay period is shown on pressure crank angle (or time) diagram between points a and b. Point "a" represents the time of injection and point "b" represents the time of combustion. The ignition delay period can be divided into two parts, the physical delay and the chemical delay.

The delay period in the CI engine exerts a very great influence on both engine design and performance. It is of extreme importance because of its effect on both the combustion rate and knocking and also its influence on engine starting ability and the presence of smoke in the exhaust.

2 Period of Rapid Combustion

The period of rapid combustion also called the uncontrolled combustion, is that phase in which the pressure rise is rapid. During the delay period, a considerable amount of fuel is accumulated in combustion chamber, these accumulated fuel droplets burns very rapidly causing a steep rise in pressure. The period of rapid combustion is counted from end of delay period or the beginning of the combustion to the point of maximum pressure on the indicator diagram. The rate of heat-release is maximum during this period. This is also known as uncontrolled combustion phase, because it is

difficult to control the amount of burning / injection during the process of burning.
It may be noted that the pressure reached during the period of rapid combustion will depend on the duration of the delay period (the longer the delay the more rapid and higher is the pressure rise since more fuel would have been present in the cylinder before the rate of burning comes under control).

3 Period of Controlled Combustion

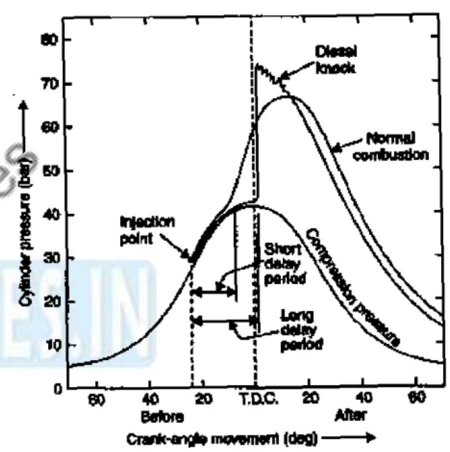
The rapid combustion period is followed by the third stage, the controlled combustion. The temperature and pressure in the second stage are so high that fuel droplets injected burn almost as they enter and find the necessary oxygen and any further pressure rise can be controlled by injection rate. The period of controlled combustion is assumed to end at maximum cycle temperature.

4 Period of After-Burning

Combustion does not stop with the completion of the injection process. The unburnt and partially burnt fuel particles left in the combustion chamber start burning as soon as they come into contact with the oxygen. This process continues for a certain duration called the after-burning period. This burning may continue in expansion stroke up to 70 to 80% of crank travel from TDC.

Ignition Delay or Ignition Lag

The delay period is the time between the start of injection and start of combustion. The delay period extends for about 13 deg movement of crank. This delay time decreases with increase in speed. If there is no delay, the fuel would burn at injector and there would be oxygen deficiency around the injector, which results in incomplete combustion. If the delay period is too long, amount of fuel availability for simultaneous explosion, is too great, which results in rapid pressure rise. The delay period should be as short as possible since long delay period gives more rapid rise in pressure and thus causes knocking.



Component of Ignition Delay or Ignition Lag

Ignition delay can be divided into two parts:

<u>Physical Delay:</u> The physical delay is the time between the beginning of injection and the attainment of chemical reaction conditions. During this period, the fuel is atomized, vaporized, mixed with air and raised to its self-ignition temperature. This physical delay depends on the type of fuel, i.e., for light fuel the physical delay is small while for heavy viscous fuels the physical delay is high. The physical delay is greatly reduced by using high injection pressures and high turbulence to facilitate breakup of the jet and improving evaporation.

<u>Chemical Delay:</u> During the chemical delay reactions start slowly and then accelerate until inflammation or ignition takes place. Generally, the chemical delay is larger than the physical delay. However, it depends on the temperature of the surroundings and at high temperatures, the chemical reactions are faster and the physical delay

Combustion phenomenon in CI engine V/s combustion in SI engine.

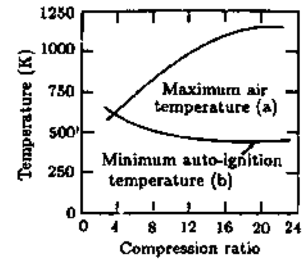
SL N	COMUSTION IN SI ENGINE	COMBUSTION IN CI ENGINE
1	Homogeneous mixture of petrol vapor and air is compressed (CR 6:1 to 11:1) at the end of compression stroke and is ignited at one place by spark plug.	Air alone is compressed through large Compression ratio (12:1 to 22:1) and fuel is injected at high pressure of 110 to 200 bar using fuel injector pump.
2	Single definite flame front progresses through air fuel mixture and entire mixture will be in combustible range	Fuel is not injected at once, but spread over a period of time. Initial droplets meet air whose temperature is above self ignition temperature and ignite
3	For effective combustion, turbulence is required. Turbulence which is required in SI engine implies disordered air motion with no general direction of flow to break up the surface of flame front and to distribute the shreds of flame thought-out in externally prepared homogeneous combustible mixture.	For effective combustion, swirl is required. Swirl which is required in CI engine implies an orderly movement of whole body of air with a particular direction of flow, to bring a continuous supply of fresh air to each burning droplets and sweep away the products of combustion which otherwise
4	In SI Engine ignition occurs at one point with a slow rise in pressure	In the CI engine, the ignition occurs at many points simultaneously with consequent rapid rise in pressure. There is no definite flame front.
5	In SI engine physical delay is almost zero and chemical delay controls combustion	In CI engine physical delay contr
6	In SI engine , A/F ratio remains close to stoichiometric value from no load to full load	In CI engine, irrespective of load, at any speed, an approximately constant supply of air enters the cylinder. With change in load, quantity of fuel is changed to vary A/F ratio. The overall
5	Delay period must be as long as possible. High octane fuel (low cetane) is required.	Delay period must be as short as possible. High cetane (low octane)

Effect of Various Factors On Delay Period In CI Engine

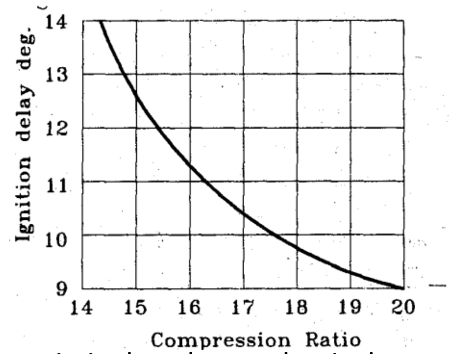
Many design and operating factors affect the delay period. The important ones are:

- compression ratio
- engine speed
- output
- injection timing
- quality of the fuel
- intake temperature
- intake pressure

1. <u>Compression Ratio.</u> The increase in the compression temperature of the air with increase in compression ratio evaluated at the end of the compression stroke is shown in Fig. It is also seen from the same figure that the minimum auto ignition temperature of a fuel decreases due to increased density of the compressed air. This results in a closer contact between the molecules of fuel and oxygen reducing the time of reaction. The increase in the compression temperature as well as the decrease in the minimum auto ignition temperature decrease the delay period. The maximum peak pressure during the combustion process is only marginally affected by the compression ratio (because delay period is shorter with higher compression Ratio and hence the pressure rise is lower).



Effect of Compression Ratio on Maximum Air Temperature and Minimum Autoignition Temperature

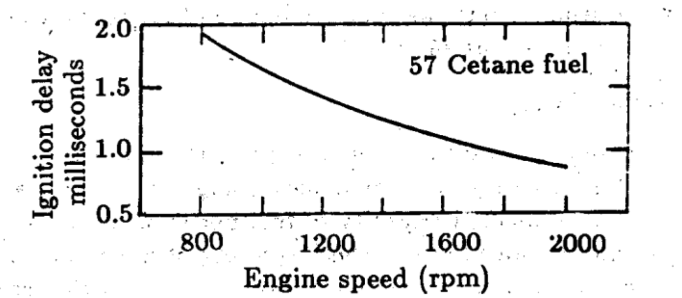


Then why we do not use very high compression ratio in CI?

One of the practical disadvantages of using a very high compression ratio is that the mechanical efficiency tends to decrease due to increase in weight of the reciprocating parts. Therefore, engine designers always try to use a lower compression ratio which helps in easy cold starting and light load running at high speeds.

Engine Speed:

The delay period could be given either in terms of absolute time (in milliseconds) or in terms of crank angle degrees



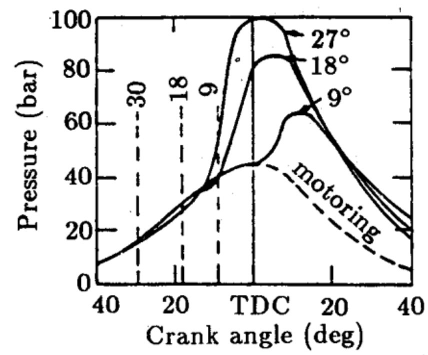
With increase in engine speed, the loss of heat during compression decreases, resulting in the rise of both the temperature and pressure of the compressed air thus reducing the delay period in milliseconds. However, in degrees of crank travel the delay period increases as the engine operates at a higher rpm. The fuel pump is geared to the engine, and hence the amount of fuel injected during the delay period depends on crank degrees and not on absolute time. Hence, at high speeds, there will be more fuel present in the cylinder to take part in the second stage of uncontrolled combustion resulting in high rate of pressure rise.

<u>**Outputs**</u>

With an increase in engine output the air-fuel ratio decreases, operating temperatures increase and hence delay period decreases. The rate of pressure rise is unaffected but the peak pressure reached may be high.

Injection timing:

The effect of injection advance on the pressure variation is shown in Fig. for three injection advance timings of 90°, 18°, and 27° before TDC. The injected quantity of fuel per cycle is constant. As the pressure and temperature at the beginning of injection are lower for higher ignition advance, the delay period increases with increase in injection advance. The optimum angle of injection advance depends on many factors but generally it is about 20°bTDC.



Effect of Injection Timing on Indicator Diagram

Quality of Fuel used:

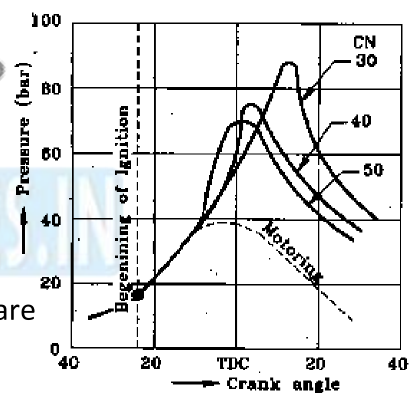
The physical and chemical properties of fuel play very important role in delay period. The most important property of fuel which is responsible for chemical delay is its self- ignition temperature. Lower the self-ignition temperature, lower the delayperiod.

The cetane number (CN) of the fuel is another important parameter which is responsible for the delay period. A fuel of higher cetane number

Gives lower delay period and provides smoother engine operation.

The effect of cetane number on the indicator diagram when injection timing is same is shown in adjacent figure.

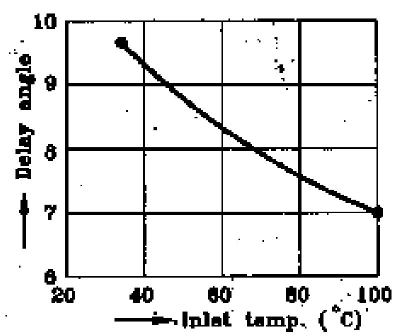
The delay period for a fuel having CN = 50 is lowest and pressure rise is also smooth and maximum pressure rise is least as most of the fuel burns during controlled combustion.



The other properties of fuel which affects the physical delay period are Volatility, latent heat, viscosity and surface tension the viscosity and Surface tension are responsible for the better atomization whereas Latent heat and viscosity are responsible for the rapid evaporation of fuel.

Intake Temperature

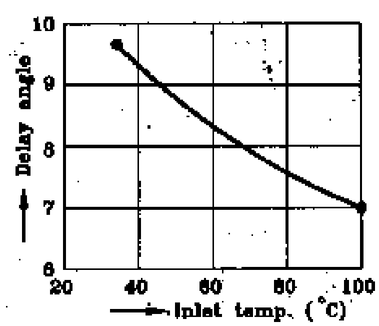
The delay period is reduced either with increased temperature. However, preheating of charge for this purpose is not desirable because it reduces the density of charge and volumetric efficiency and power output.



(a)

Intake pressure

Increase in intake pressure or supercharging reduces the auto ignition temperature and hence reduces the delay period. The peak pressure will be higher since the compression pressure will increase with intake pressure.



(a)

The following table gives the summary of the factors which influence the delay period in CI engine.

EFFECT OF VARIABLE ON DELAY PERIOD – SUMMARY

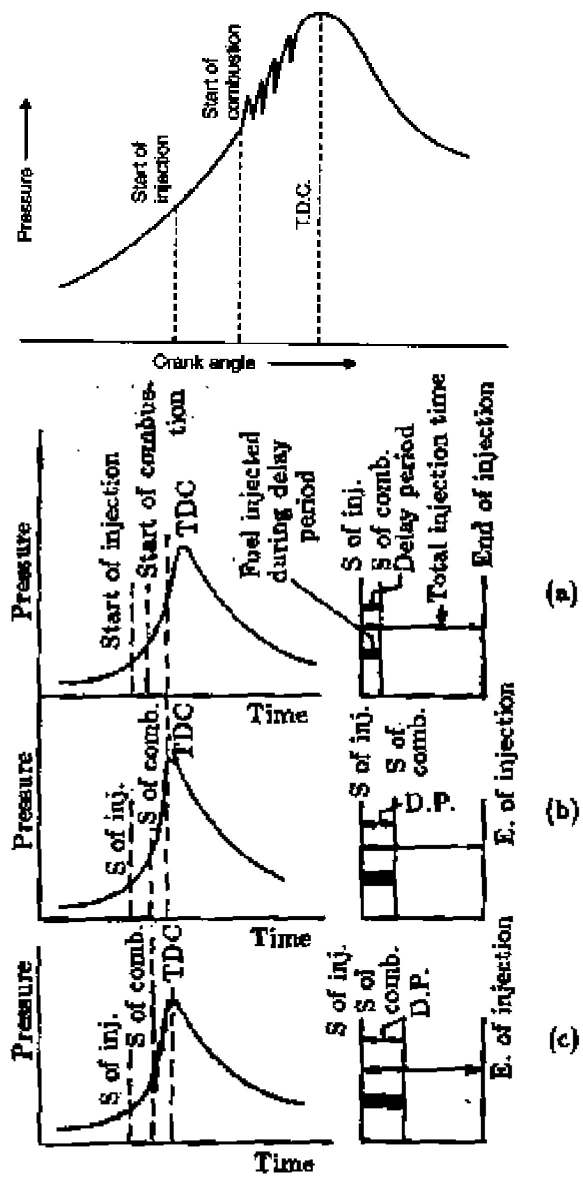
SL No	Increase in variables	Effect on Delay period	Reason
1	Cetane Number of fuel	Reduce	Reduces the self ignition temperature
2	Injection pressure	Reduce	Reduces the physical delay due to greater surface to volume
3	Injection timing advance	Increase	Reduces the pressure and temperature when the injection begins
4	Compression ratio	Reduce	Increases air temperature and pressure and reduces auto ignition temperature
5	Intake temperature	Reduce	Increase air temperature
6	Jacket water temperature	Reduce	Increase wall and hence air temperature
7	Fuel temperature	Reduce	Increases chemical reaction due
8	Intake pressure	Reduce	Increases the density and also reduces the auto ignition temperature
9	Speed	Increase in terms of crank angle but reduces in terms of milliseconds.	Reduce loss of heat
10	Load (Fuel/air ratio)	Decrease	Increase the operating
11	Engine size	Increase in terms of crank angle but little effect in terms of	Larger engines operate at normally slow speeds.
12	Type of combustion chamber	Lower for engines with pre-combustion	Due to compactness of the chamber.

PHENOMENON OF DIESEL KNOCK

Knocking is violet gas vibration and audible sound produced by extreme pressure differentials leading to the very rapid rise during the early part of uncontrolled second phase of combustion.

In C.I. engines the injection process takes place over a definite interval of time. Consequently, as the first f e w Droplets injected a r e p a s s i n g through The ignitionlagperiod; additional droplets are being injected into the chamber. If the ignition delay is longer, the actual burning of the first few droplets is delayed and a greater quantity of fuel droplets gets accumulated in the chamber. When the actual burning commences, the additional fuel can cause too rapid a rate of pressure rise, as shown on pressure crank angle diagram above, resulting in Jamming of forces against the piston (as if struck bya hammer) and rough engine operation. If the ignition delay is quite long, so much fuel can accumulate that the rate of pressure rise is almost instantaneous. Such, a situation produces extreme Pressure differentials and violent gas vibration known as knocking (diesel knock), and is evidenced by audible knock. The phenomenon is similar to

That in the SI engine However, in SI Engine knocking occurs Near the end of combustion whereas in CI engine, Knocking the occurs near the beginning of combustion.



Delay period is directly related to Knocking in CI engine. An extensive delay period can be due to following factors:

- A low compression ratio permitting only a marginal self ignition temperature to be reached.
- A low combustion pressure due to worn out piston, rings and bad valves
- Low cetane number of fuel
- Poorly atomized fuel spray preventing early combustion
- Coarse droplet formation due to malfunctioning of injector parts like spring
- Low intake temperature and pressure of air

METHODS OF CONTROLING DIESEL KNOCK

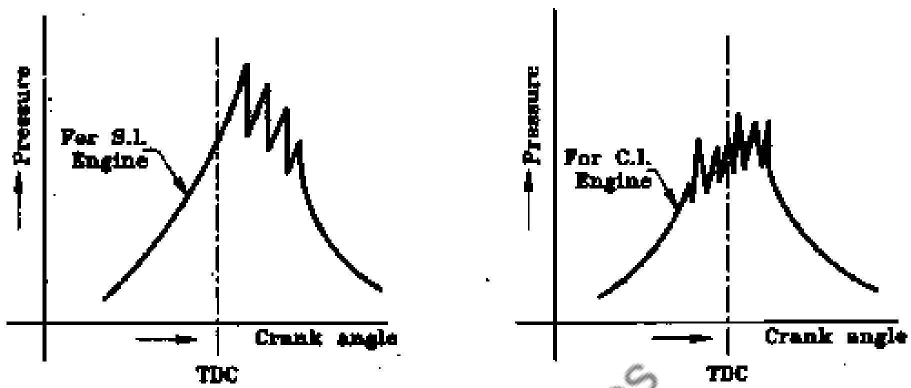
We have discussed the factors which are responsible for the detonation in the previous sections. If these factors are controlled, then the detonation can be avoided.

- Using a better fuel. Higher CN fuel has lower delay period and reduces knocking tendency.
- Controlling the Rate of Fuel Supply. By injecting less fuel in the beginning and then more fuel amount in the combustion chamber detonation can be controlled to a certain extent. Cam shape of suitable profile can be designed for this purpose.
- Knock reducing fuel injector: This type of injector avoid the sudden increase in pressure inside the combustion chamber because of accumulated fuel. This can be done by arranging the injector so that only small amount of fuel is injected first. This can be achieved by using two or more injectors arranging in out of phase.
- By using Ignition accelerators: C N number can be increased by adding chemical called dopes. The two chemical dopes are used are ethyl-nitrate and amyl –nitrate in concentration of 8.8 gm/Liter and 7.7 gm/Liter. But these two increase the NO_x emissions
- Increasing Swirl: Knocking can be greatly reduced by increasing swirl (or reducing turbulence). Swirl helps in knock free combustion.

COMPARISON OF KNOCK IN SI AND C ENGINES

It may be interesting to note that knocking in spark-ignition engines and compression- ignition engines is fundamentally due to the auto ignition of the fuel-air mixture. In both the cases, the knocking depends on the auto ignition lag of the fuel-air mixture. But careful examination of knocking phenomenon in SI and CI engines reveals the following differences:

1. In spark ignition engines, auto ignition of end gas away from the spark plug, most likely near the end of combustion causes knocking. But in compression engines the auto ignition of charge causing knocking is at the start of combustion.



(a) S.I. engine (b) C.I. engine

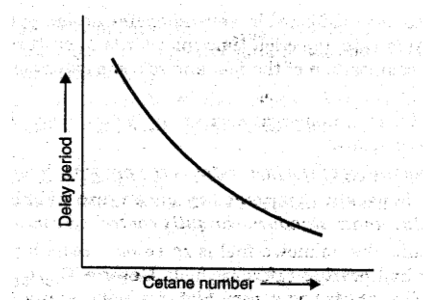
2. In order to avoid knocking in SI engine, it is necessary to prevent auto ignition of the end gas to take place at all. In CI engine, the earliest auto –ignition is necessary to avoid knocking
3. The knocking in SI engine takes place in homogeneous mixture, therefore, the rate of pressure rise and maximum pressure is considerably high. In case of CI engine, the mixture is not homogenous and hence the rate of pressure is lower than in SI engine.
4. In CI engine only air is compressed, therefore there is no question of Pre-ignition in CI engines as in SI engines.
5. It is lot more easily to distinguish between knocking and non-knocking condition in SI engines as human ear easily finds the difference. However in CI engines, normal ignition itself is by auto-ignition and rate of pressure rise under the normal conditions is considerably high (10 bar against 2.5 bar for SI engine) and causes high noise. The noise level becomes excessive under detonation condition. Therefore there is no definite distinction between normal and knocking combustion.
6. SI fuels should have long delay period to avoid knocking. CI fuels should have short delay period to avoid knocking.

<u>Knock rating of CI fuels (CETANE NUMBER)</u>

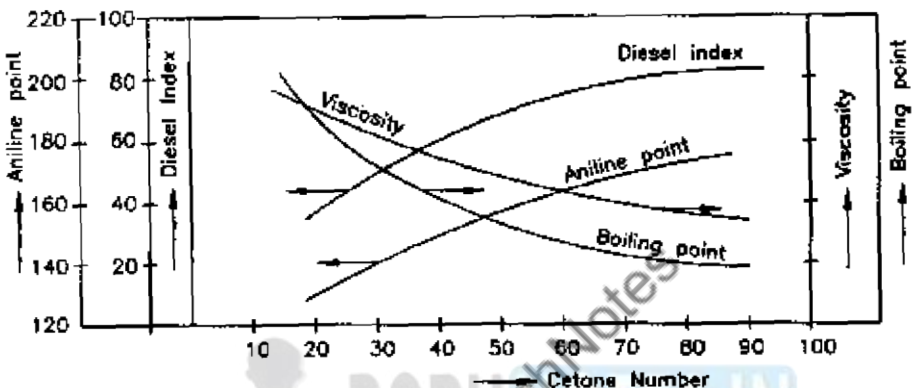
The cetane number is a numerical measure of the influence the diesel fuel has in determining the ignition delay. Higher the cetane rating of the fuel lesser is the propensity for diesel knock. The cetane number of a diesel fuel is a measure of its ignition quality.

The cetane number of a fuel is the percentage by volume of cetane in a mixture of cetane [$C_{16}H_{34}$] and -methylnaphthalene [$C_{10}H_7$ CH_3] that has same performance in the standard test engine as that of the fuel. Cetane is arbitrarily assigned a number 100 and originally -methylnaphthalene was given a number 0 but now reference fuels is heptamethylnonane (HMN) which is given a value of 15. HMN is used because it is more stable compound and has slightly better ignition quality.

The relation between the cetane number and delay period is shown in adjacent figure
Cetane number 40 means a mixture containing 40 % cetane and 60 % of heptamethylnonane (HMN) by volume
Which gives same ignition delay as tested fuel for high sped engine?
Cetane number of 50 is required, for medium speed engine about 30.
High octane number implies low cetane number. In other words good CI engine fuel is bad CI engine fuel.



The following graph shows relationship of other properties of fuel with CN



To reduce knocking Diesel oil should have low self ignition temperature and short time lag, whereas petrol should have high self ignition temperature and a long ignition lag.

In SI engine knocking occurs near the end of combustion, where as in CI engine this occurs in the beginning of combustion. Because of this dissimilarity in the time of starting of knock in SI and CI engines. The conditions which reduce the knock tendency in SI engine will increase the knocking tendency in CI engine.

Diesel has a high cetane number (40-60) and low octane number (30) and petrol has high Octane number (80-90) ad low cetane number (20).

Figure shows typical indicator diagram of a diesel engine with sharp pressure oscillating during the combustion caused by shock waves when using petrol

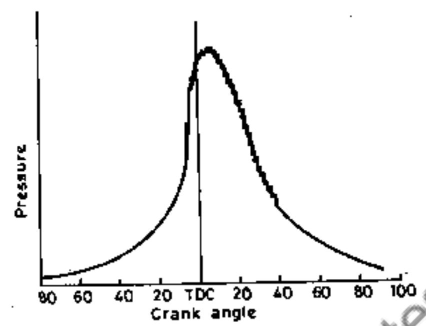
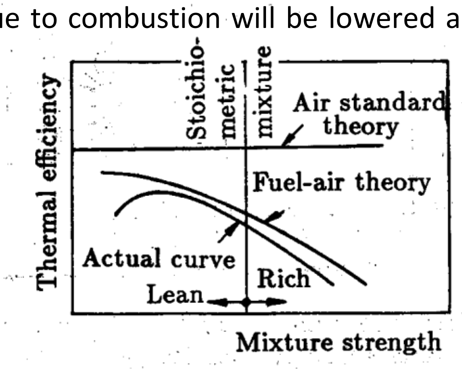


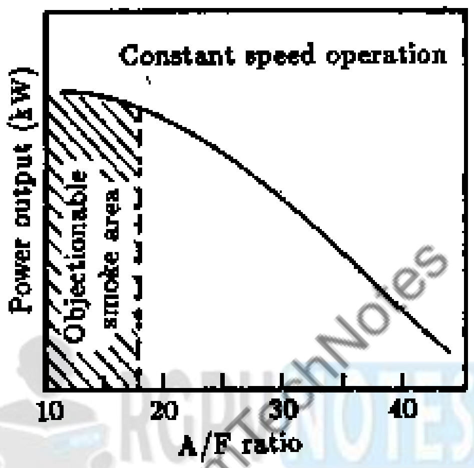
Fig. 6.11. Indicator diagram of diesel engine when using petrol.

Weak mixture gives better efficiency in CI engine

As the mixture is made lean (less fuel) the temperature rise due to combustion will be lowered as a result of reduced energy input per unit mass of mixture. This will result in lower specific heat. Further, it will lower the losses due to dissociation and variation in specific heat. The efficiency is therefore, higher and, in fact, approaches the air-cycle efficiency as the fuel-air ratio is reduced as shown in adjacent figure.



Thermodynamic analysis of the engine cycles has clearly established that operating an engine with a leaner air-fuel ratio always gives a better thermal efficiency but the mean effective pressure and the power output reduce. Therefore, the engine size becomes bigger for a given output if it is operated near the stoichiometric conditions, the A/F ratio in certain regions within the chamber is likely to be so rich that some of the fuel molecules will not be able to find the necessary oxygen for combustion and thus produce a noticeably black smoke. Hence the CT engine is always designed to operate with an excess air, of 15 to 40% depending upon the application. The power output curve for a typical CI engine operating at constant speed is shown in Fig. given below. The approximate region of A/F ratios in which visible black smoke occurs is indicated by the shaded area.



Unit-4 Engine Systems

Fuel injection system

Diesel engines are a compression ignition type of internal combustion engine. It is well known technology in achieving major improvement in fuel economy and heavy duty task presently. Diesel engines are commonly used in heavy duty application vehicle such as constructional vehicles, trucks and Lorries. But now it is widely implemented in light vehicle such as cars and vans. Diesel engines can double the fuel economy than spark ignition engines in light vehicles.

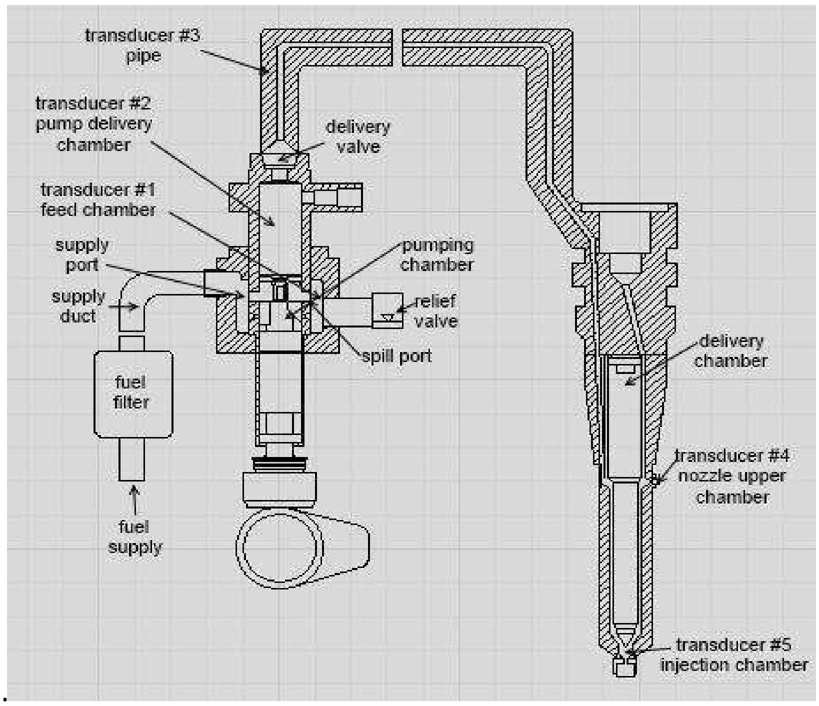
Diesel engines use fuel injection system. The fuel injection system is a system used to supply fuel into internal combustion engine which replaced carburetor function to supply the fuel into the engine. Fuel injector atomizes the fuel by forcibly pumping it through a small injection nozzle under high pressure. It is because diesel engine ignites the fuel by the high temperature created by the compression of air and fuel mixture.

Diesel engines have many advantages such as high fuel efficiency, reliability and durability. The performance of diesel engines depends on many parameters. One of the important parameters which influence the performance of diesel engines is fuel injection pressure. Fuel injection pressure plays an important aspect of power performance of the engine to obtain combustion treatment.

Fuel Injection System

Fuel injection is a technology that is being used in most of cars and other automotive transportation these days. The technology is used to eliminate the need for carburetors. The technology helps the engine to supply fuel directly to the cylinder in the intake manifold, eliminating the use if carburetor to much extent. Overall, the fuel injection is required to supply fuel directly to the engine.

The system works by the fuel is directly supplied to the cylinder in the intake chamber. Sensors located in such engines will regulate the flow of fuel injected and maintains it to appropriate levels. As long as the sensors which are usually electronic are working properly, the possibilities of breakdown and choke are immensely reduced



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Fuel injection system

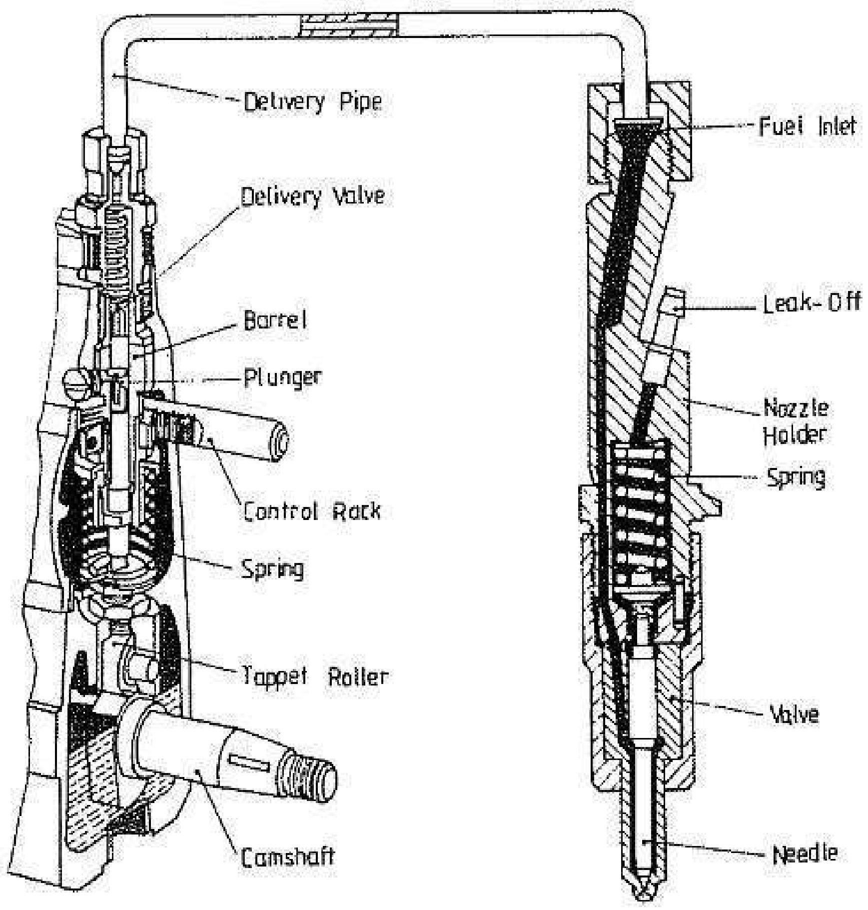
There are a great variety of diesel engine designs for wide range of applications, such as car, truck, locomotive, marine vessel and power generation. The diesel engine is more efficient than the petrol engine because it is fuel efficient in present diesel engines, fuel injection system designed to obtain higher injection pressure. It is aimed to decrease the exhaust emissions by increasing efficiency of diesel engine. It is because when the fuel injection pressure is low, fuel particle diameters will enlarge and ignition delay period during the combustion will increase.

There are several functions of fuel injection such as to filter the fuel, to meter or measure the correct quantity of fuel to be injected, control timing of fuel injection, to control the rate of fuel injection, to atomize or break up the fuel to fine particles and to properly distribute the fuel in the combustion chamber. Though the functional objectives for different types of fuel injections vary, the main task is to supply fuel to the combustion process. The objectives of a fuel injection are fuel efficiency, reliability, emission performance, output power, to accommodate alternative fuels, smooth operation, basic cost, maintenance cost, diagnostic capability and environmental operation. It is practically impossible for a single system to have all these objectives as certain combinations are conflicting. But all the systems try to supply most of these objectives. There are many benefits of fuel injection including, smoother and dependable engine response during quick transitions, easier and faster engine starting, better operation at a high or low ambient temperature, increased fuel efficiency and increased maintenance intervals. Modern electronic fuel injections help in maintaining accurate fuel metering and help in producing less air pollutants. The fuel injection system in a direct injection diesel engine is to achieve a high degree of atomization in order to enable sufficient evaporation in a very short time and to achieve sufficient spray penetration in order to utilize the full air charge. The fuel injection system must be able to meter the desired amount of fuel, depending on engine

speed and load, and to inject that fuel at the correct time and with the desired rate. Further on, depending on the particular combustion chamber, the appropriate spray shape and structure must be produced. Usually, a supply pump draws the fuel from the fuel tank and carries it through a filter to the high-pressure injection pump. The fuel injection pressure in a standard diesel is in the range of 200 to 1700 atm. According to Shimada et al. (1989), low pollution and low fuel consumption are the most important demands imposed on engines and these requirements are becoming ever more stringent, year after year. To satisfactorily reduce smoke and exhaust emissions and also reduce fuel consumption, which generally is adversely affected when lowering pollutant levels, an increase in the fuel injection pressure of direct injection type diesel engines has been conventionally adopted as an overall solution. The effect of high pressure fuel injection was investigated with in-cylinder fuel spray observation and single cylinder engine to reduce exhaust emission and fuel consumption. It is based on spray impingement on the cavity wall which promotes mixing with air and reduction on the nozzle area thus extends the wall impingement as result of increasing both fuel injection and injection period.

Modifying injection rate of fuel pump and nozzle area will increase injection pressure, and also improves smoke and fuel consumption at low and medium speeds in particular. To extend these effects of high pressure injection, more optimized combustion system and minimized injection equipment drive torque required. To resolve the problem of high pressure injection such as higher combustion noise and increase in emissions, the combination with pilot injection can be an effective method.

However, the relationship between fuel injection characteristics and exhaust emissions or fuel consumption performance, such as how the optimum injection pressure or injection duration should be, can hardly be said to have been sufficiently clarified. Therefore, the authors proceeded by first observing fuel spray, which is the basis of diesel combustion, and examining the relationship between fuel injection pressure and engine performance using high pressure fuel injection equipment and a single cylinder engine.



Diesel fuel injection system

ELECTRONIC FUEL INJECTION SYSTEM:

The operation cycle of electronic fuel injection system is as follows:

i. Air enters the engine through the air induction system where it is measured by the air flow meter. As the air flows into the cylinder, fuel is mixed into the air by the fuel injector.

ii. Fuel injectors are arranged in the intake manifold behind each intake valve. The injectors are electrical solenoids which are operated by the Electronic Control Unit or known as ECU.

iii. The ECU pulses the injector by switching the injector ground circuit on and off. When the injector is turned on, it opens, spraying atomized fuel at the back side of the intake valve.

iv. As fuel is sprayed into the intake airstream, it mixes with the incoming air and vaporizes due to the low pressures in the intake manifold. The ECU signals the injector to deliver just enough fuel to achieve an ideal air/fuel ratio of 14.7:1, often referred to as stoichiometric.

v. The precise amount of fuel delivered to the engine is a function of ECU control. The ECU determines the basic injection quantity based upon measured intake air volume and engine rpm.

vi. Depending on engine operating conditions, injection quantity will vary. The ECU monitors variables such as coolant temperature, engine speed, throttle angle, and exhaust oxygen content and makes injection corrections which determine final injection quantity.

ADVANTAGES OF FUEL INJECTION SYSTEM

There are many advantages of fuel injection system.

First is uniform air/fuel mixture distribution; each cylinder has its own injector which delivers fuel directly to the intake valve. This eliminates the need for fuel to travel through the intake manifold, improving cylinder to cylinder distribution.

Second is high accurate air/fuel ratio control; throughout all engine operating conditions electronic Fuel Injection or EFI supplies a continuously accurate air/fuel ratio to the engine no matter what operating conditions are encountered. This provides better drive ability, fuel economy, and emissions control.

Third is superior throttle response and power; by delivering fuel directly at the back of the intake valve, the intake manifold design can be optimized to improve air velocity at the intake valve. This improves torque and throttle response.

Fourth is excellent fuel economy with improved emissions control; cold engine and wide open throttle enrichment can be reduced with an EFI engine because fuel puddling in the intake manifold is not a problem. This results in better overall fuel economy and improved emissions control.

Fifth is improved cold engine start ability and operation; the combination of better fuel atomization and injection directly at the intake valve improves ability to start and run a cold engine. And the last is simpler mechanics, reduced adjustment sensitivity; the EFI system does not rely on any major adjustments for cold enrichment or fuel metering. Because the system is mechanically simple, maintenance requirements are reduced.

Function of the fuel injection pump

The fuel injection pump is also called the high pressure fuel pump; it is the most important part in the fuel system. The function of the fuel injection pump is to improve the pressure of the fuel, and according to the requirement of working conditions of the diesel engine, gushing out the fuel of a certain amount the combustion chamber within accurate time.

The requisition for the fuel injection pump is:

(1) The amount of fuel supported of the fuel injection pump should meet the need of the diesel engine under various kinds of working conditions, namely the amount of oil supply increases when load is big, the amount of oil supply reduces when load is small. We should guarantee the amount of oil supply to every jar and be equal at the same time.

(2) According to the requirement of diesel engines, the fuel injection pump should be guaranteed supplying the fuel of every jar begin constantly to be the same, namely every jar is for the fuel to advance the angle unanimously, should be guaranteed to be for the fuel to extend time the, and is for the fuel to meet an urgent need and begin rapidly, it should be agile rapidly to stop the oil, avoid dripping the fuel phenomenon.

(3) It is different methods according to the form of combustion chamber and mixed air, the fuel injection pump must offer the fuel of enough pressure to the fuel injector so as to ensure good atomized quality.

We have a look at the work animation of the fuel injection pump first before studying the fuel injection pump.

The structure of the fuel injection pump

The structure of the fuel injection pump

The fuel injection pump can be divided into mono-pump and the synthesized pump according to its ensemble architecture (the whole pump).

1. Mono-pump [Assemble the animation to demonstrate] [The synthesized pump virtual model]

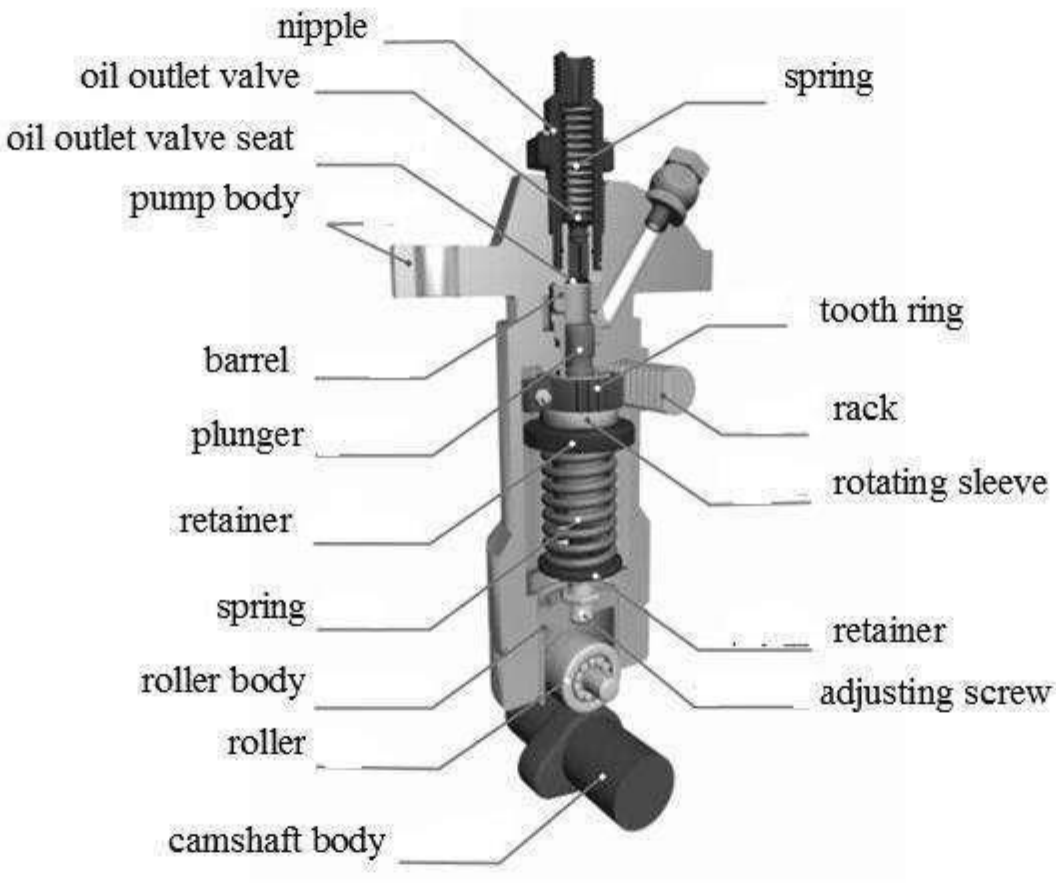
Mono-pump is formed by one plunger and barrel mainly, itself don't bring camshaft and some even don't bring roller transmission part.

Because this kind of mono-pump is easy to be fixed up in the position close to cylinder head, making high pressure fuel pipe shorten greatly, it is applied to the cylinder bore diameter above 200mm of the high-power medium-speed low-speed diesel engine at present.

2. The synthesized pump

The synthesized pump (Example pictures) [The whole pump virtual model]is installed that cylinder numbers are equal to the plunger and barrel assembly in the same pump body, every jar has a group of fuel injection component , by every corresponding cam drive of the camshaft in the body of the pump.

Among the synthesized fuel injection pumps, we take out the synthesized fuel pump group to explain now. The structure chart is as follows:



Its major parts are as follows, the camshaft, roller body, plunger and barrel, plunger return spring, rotating sleeve and tooth ring, oil outlet valve and valve seat, compressing tightly and connecting pipes etc..

Barrel and plunger is a pair of main accurate matching parts in the fuel injection pump, they are processed, ground and mixed each other carefully, their diameter interval is 0.001-0.003mm only, this pair of parts can only be changed in pairs, can't be changed alone .

There are two bores on the barrel, which making barrel inside cavity communicate with oil pipes, there are vertical troughs on the right oil bore place, among them stretching into the screw, which making barrel fixed and can't be rotated in pump body.

The top of plunger has an annular trough, it communicates with terminal surface on plunger with the vertical trough. The spiral hypotenuse begins from the vertical trough and is used to regulate the amount of oil supply.

Plunger under part has two protruding shoulders and flanges. The protruding shoulder of plunger is inserted in the notch of rotating sleeve.

Rotating sleeve is installed on barrel freely. Tooth ring of opening is put with screw in the rotating sleeve to fasten and clenching the teeth by rack.
Rack is put in the vertical bore of pump body and linked with governor gear shift. While rack is moving to the axial direction under the function of gear shift and governor, rotating sleeve and plunger of every oil pimp will turn certain angle thereupon. Retainer of the plunger return spring is equipped on plunger flange. Spring retainer is supported on pump body. The function of spring is to make plunger fall. Cam on camshaft acts on plunger through roller body, which making that go up. Roller body is the transmission body among cam and plunger, it bears side thrust and makes plunger only receive axial force by itself. Equipped with roller on roller body under part axle, it is mounted on rolling needle bearing, twisting the adjusting screw and insurance nut on roller body.

The operation principle of the fuel injection pump

The operation principle of the fuel injection pumps

1. The course of sucking the oil and pressing the oil

Sucking the oil and pressing the oil of the fuel injection pump, is finished by plunger reciprocating motion in barrel. When plunger lies in the under part position, two oil bores on barrel are opened, the inside cavity of barrel communicates with oil passageway in pump body, the fuel is filled with the oil chamber rapidly.
When cam is carried on roller of roller body, plunger rises. Upward movement begins from the plunger to the oil bore and terminates before blocking from top surface of the plunger. Within these periods, because of movement of plunger, the fuel is pushed out of the oil chamber, flows into the oil passageway. So this section lift is called the advance stroke. When plunger blocks the oil bore, it begins to press the oil course. When plunger goes up, the indoor oil pressure rises sharply. When the pressure exceeds out spring elasticity of oil valve and top oil pressure, carrying and opening the oil valve, the fuel is pressed the oil pipe and sent to fuel injector.
The moment is called the initial point of supplying oil in theory when oil inlet bore of plunger is totally blocked by the top surface of plunger. When plunger continues upward movement, supplying the oil continues all the time too, the pressing oil course is not over until the spiral hypotenuse of plunger gets out of the way the oil return bore of barrel, as the oil bore is opened, the high-pressure oil flows back to the oil passageway in pump body from the oil chamber through the vertical trough and the oil return bore of barrel. The oil pressure of oil chamber in barrel is reduced rapidly at this moment; oil outlet valve falls in the valve seat within the function of spring and oil pressure in high-pressure oil pipe, fuel injector stops gushing out the oil immediately. Though plunger still continues up going at this moment, but the oil already stopped. The moment is called the end point of supplying oil in theory when oil return bore of barrel is opened by plunger hypotenuse.
Seen from the sucking the oil and pressing the oil course since above-mentioned, in the whole course of plunger upward movement, just a section of stroke is pressing the oil course, this stroke is called the effective stroke of plunger.

2. Oil adjusting

In order to meet the needs of diesel engine load, the amount of oil supply of the fuel injection pump must be regulated in the range from the amount of maximum fuel (full-load) to zero amount of oil supply (park).For the regulation of oil quantity to realize is made all plungers of the fuel injection pump rotate through rack, rotating sleeve at the same time.
Seen from the animation, when plunger is rotated, oil supply time isn't changed, but the oil supply end time alters, because position of plunger hypotenuse to oil return bore of barrel is changed. As angle that plunger turns being different, the effective stroke of plunger is different too, therefore the change thereupon of the amount of oil supply.
The bigger angle what plunger is rotated to not supplying the oil level is, the hypotenuse distance of the terminal surface which is opened to oil return bore of barrel is bigger, the bigger the amount of oil supply is, if angle that plunger rotates relatively little, Disruption of oil supply begins relatively early, the amount of oil supply is too relatively small. It must be interrupted when the diesel engine parks, for this reason; we

can turn into and make the vertical trough on plunger be facing toward on barrel oil return bore. At this moment, in the whole plunger stroke, the fuel in barrel has been flowing back to oil pipes through vertical trough、oil return bore all the time, there is not pressing the oil course, so the amount of oil supply equals zero.

Therefore, as plunger rotates, we can regulate the amount of oil supply by changing the terminal point of oil supply, this kind of method is called for oil supply terminal point to regulate the law.

Changing the position of the hypotenuse on plunger, we can receive other regulating methods. The plunger hypotenuse shapes of three kinds of regulating method of oil supply are shown in the following diagram.

（a） Regulate the law of oil supply terminal point for above-mentioned, it is suitable for applying to the diesel engine that the rotational speed does not change and applying to the ship supercharged diesel engine too.

（b） Regulate the law for some of supply beginning. Because the spiral hypotenuse slopes upwards, the oil supply initial point isn't changed, but oil supply terminal point is changed while rotating plunger amount of oil regulated. This adjustment method was once thought that it would be suitable for driving the propeller directly on the diesel engine, when it runs according to the promoting performance, load increases with rotational speed, fuel injection advance angle should be increased. But it is unfavorable when it works for low load in fact, so higher turbocharged engines are already few application of marine diesel, we still hope to adopt the first kind of regulation to oil supply terminal point method.

（c） Method to change for initial point and end point of oil supply at the same time . This kind of plunger meets the requirement of reducing the amount of oil injection by properly moving backward initial point and end point ahead of time; therefore, it can control the whole combustion process and go on near the top dead centre no matter in low, high load. This kind of regulating method is suitable for the marine diesel engine that is in high pressurization and changed in rotational speed and load.

In the regulating mechanism of oil supply of the fuel injection pump, besides above-mentioned rack type oil amount controlling organizations, there is a kind of shift fork type oil amount controlling organization. There is one adjusting arm in plunger under part, one of ball head's ends of adjusting arm is put in the trough of adjusting fork, adjusting fork is fixed on pull rod by locking screw, moves pull rod, adjusting fork drives plunger to rotate, so as to achieve the goal of changing oil supply. Its advantage is processing simply, easy repair, oil pump is small in external dimension, and the serial pumps of our country No. 2 adopt this kind of controlling organization.

In above-mentioned the fuel injection pump, the most key part is plunger. There are a lot of structure forms of plunger, but its basic structure is like the Fig:

The form has helix type (b and d) and straight line type (a and c) in the chute (the oil edge) on plunger. The chute of straight line type plunger returns oil through centre bore, processing the advantage such as being simple, and the serial pumps of our country No. 2 adopts plunger of this form.

Spiral troughs or straight line chutes on plunger, according to its slope direction, we can divide it into dextrorotation (c and d) and Left deviation fastened (a and b). The trough direction of the spiral can be judged with the tactics of controlling. The fastening of spiral trough turning towards direction relates to control the movement direction of the tooth pole or arrangement. Spiral trough that dextrorotation turned towards, oil supply reduces when rotating left, it is applied to the fuel injection pump that the whole pump installs governor in the right side. And the fuel injection pump installing governor in the left side fastens the spiral trough with the left.

Cooling system

Need for cooling system

During the process of converting thermal energy to mechanical energy high temp are produced in the cylinder of the engine as a result of the combustion process. A large portion of the heat is transferred to the cylinder head and walls, piston and valves. Unless this excess heat is carried away and these parts are adequate cooled, the engine will be damaged. A cooling system must be preventing damages to vital parts of the engine, but the temperature of these components must be maintained within certain limits in the order to obtain maximum performance from the engine. Hence a cooling system is needed to keep the engine from not getting so hot as to cause problems and yet to permit it to run hot enough to ensure maximum efficiency of the engine. The duty of cooling system, in other word, is to keep the engine from getting not too hot and at the same time not to keep it too cool either.

Characteristics of efficient cooling system

The following are the two main characteristics desired of an efficient cooling system

1) It should be capable of removing about 30% of heat generated in the combustion chamber while maintain the optimum temp of the engine under all operating conditions of engine.
2) It should remove heat at a faster rate when engine is hot. However during starting of the engine the cooling should be minimum, so that the working parts of engine reach their operating temperature in short time.

Type of cooling system

In order to cool the engine a cooling medium is required. This can be either air or a liquid accordingly there are two type of systems in general use for cooling the IC engine. They are

1) Liquid or indirect cooling system
2) Air or direct cooling system

Liquid cooled systems

In this system mainly water is used and made to circulate through the jackets provided around the cylinder, cylinder-head, valve ports and seats where it extracts most of the heat.

It consists of a long flat, thin-walled tube with an opening, facing the water pump outlet and a number of small openings along its length that directs the water against the exhaust valves. The fits in the water jacket and can be removed from the front end of the block.

The heat is transferred from the cylinder walls and other parts by convection and conduction. The liquid becomes heated in its passage through the jackets and is in turn cooled by means of an air-cooled radiator system. The heat from liquid in turn is transferred to air. Hence it is called the indirect cooling system. Water cooling can be carried out by any of the following five methods

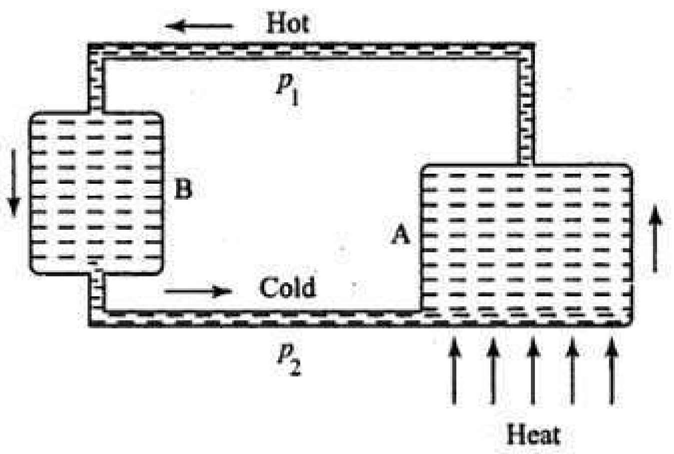
1) Direct or non-return system
2) Thermosyphon system
3) Forced circulation cooling system
4) Evaporative cooling system
5) Pressure cooling system

Direct or non-return system

This system is useful for large installation where plenty of water is available. The water from a storage tank is directly supplied through the inlet valve to the engine cooling jacket. The hot water in not cooled for reuse but simply discharged.

Thermosyphon system

The basic principle of thermosyphon can be explained with respect to fig. heat is supplied to the fluid in the tank A. because of relative lower density, the hot fluid travel up, its place is being taken by comparatively cold fluid from the tank B through pipe p2.



Principal of thermosyphon system

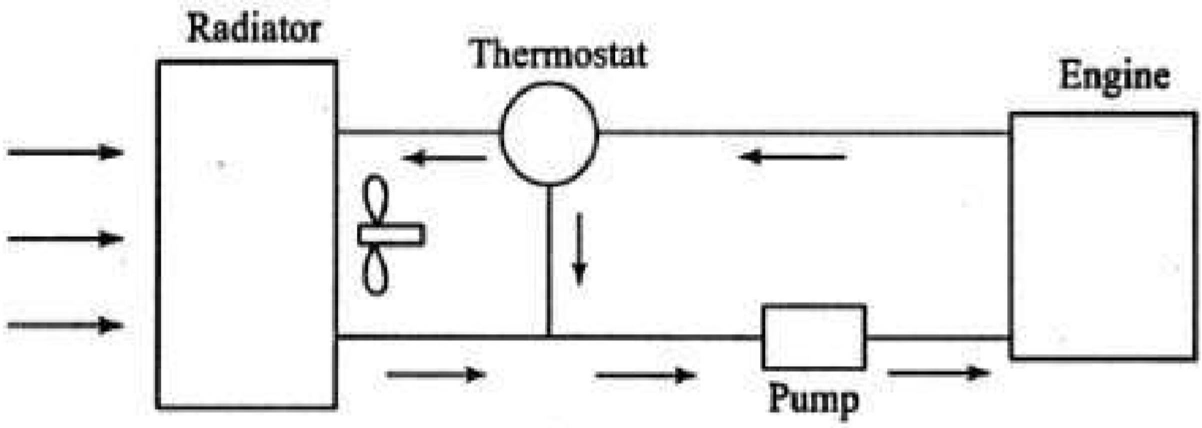
The hot fluid flow through the pipe p1 to the tank B where it get cooled. Thus the fluid circulates through the system in the form of convective current.

For engine application the tank a represent the cylinder jacket while tank B represent a radiator and water act as a circulating fluid. The main advantage of this system is its simplicity and automatic circulating of the cooling water.

Forced circulating cooling system

This system is used in large number of auto-mobile like cars, buses and even heavy trucks. Here, flow of water from radiators to water jacket is by convection assisted by pump.

The main principle of this system is explained with the help of block diagram as shown.

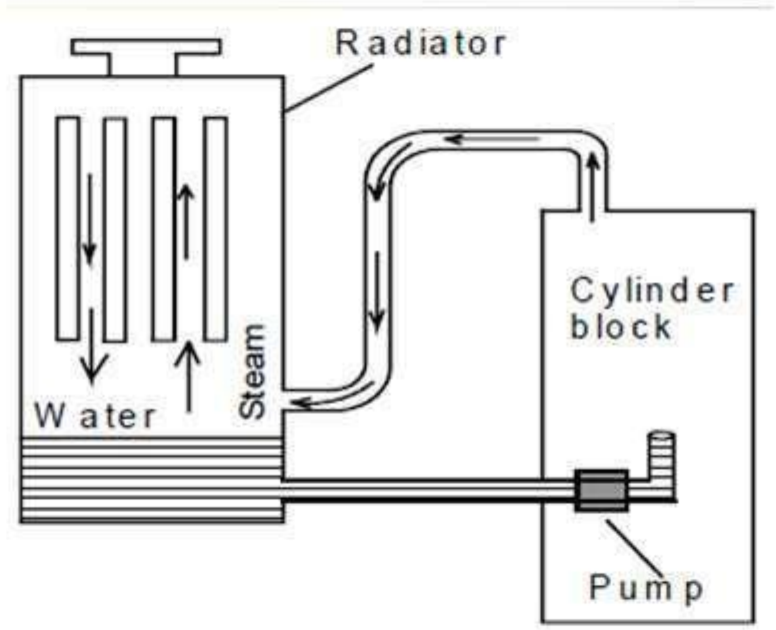


Principal of forced circulation cooling system using thermostat

The water or coolant is circulated through jacket around the part of engine to be cooled, and is kept in motion by a centrifugal pump which is driven by the engine. The water is passed through the radiator where it is cooled by the air drawn through the radiator by a fan and by the air draft to the forward motion of the vehicle. A thermostat is used to control the water temperature required for cooling. It consist mainly four component radiator, fan water pump and a thermostat.

Evaporative cooling system

This is predominately used in stationary engine. In this the engine will be cooled because of the evaporation the water in the cylinder jackets into the steam. Here the advantage is taken from the high latent heat of vaporizing of the water by allowing evaporating in the cylinder jackets. If the steam is formed at a pressure above atmospheric the temperature will be above the normal permissible temperature.



Evaporative cooling with air cooled condenser

In fig. evaporative cooling with air cooled condenser. In this case water is circulated by the pump A and when delivered to the overhead tank B part of it boils out. The tank has portion C. The vapors rise above the portion C and because of the condensing action of the radiator tube D, condensate flow into the lower tank E from which it is picked up and return to the tank B by the small pump F. the vertical pipe G is in communication with the outside atmosphere to prevent the collapsing of the tank B and E when the pressure inside them due to condensation fall below the atmosphere.

Pressure cooling system

In pressure cooling system moderate pressure, say up to 2 bar, are commonly used. As shown in fig a cap is fitted with two valves which are loaded by a compression spring and a vacuum valve. When the coolant is cold both valve are shut but as the engine warm up the coolant temperature rises until it reaches a certain pre-set value corresponding to the desired pressure when the safety valve open. But if the coolant temperature falls during the engine operation the valve will close again until the temperature rises to equivalent pressure value. When the engine is switched off and the coolant cool down vacuum being to form in the cooling system but when the internal pressure fall below atmosphere the vacuum valve is opened by the higher outside pressure and the cooling system then attains atmosphere pressure.

Air cooled system

In the air cooled system a current of air is made to flow past the outside of the cylinder barrel, outer surface area of which has been considerably increased by providing cooling fin as shown in fig. this method will increased the rate of cooling. This method is mainly applicable to the engine in the motorcycles, small cars, airplanes and combat tank where motion of the vehicle gives a good velocity to cool the engine. The value of heat transfer coefficient between metal and air is appreciably low. As a result of this the cylinder wall temperature of the air cooled cylinder are considerably higher than those of water cooled type.

Cooling fins

Comparison of liquid and air cooling system:

In view of the wide spread use of these two alternative cooling system for petrol as well as diesel engine it is of interest to summarize the respective advantage and limitation of these system.

Advantage of liquid cooling system

(1) Compact design of engine with appreciably smaller frontal area is possible.

(2) The fuel consumption of high compression liquid cooled engine is rather lower than for air cooled ones.

(3) Because of the even cooling of the cylinder barrel and due to jacketing makes it possible to reduce the cylinder head and valve seat temperature.

(4) In case of water cooled engines, installation is not necessarily at the front of the mobile vehicle, aircraft etc. as the cooling system can be conveniently located wherever required. This is not possible in case of air cooled system.

(5) The size of engine does not involve serious problem as far as the design of the cooling system is concerned. In case of air cooled engines particularly in high horsepower range difficulty is encounter in the circulation of requisite quantity of air for the cooling purpose.

Limitation

(1) This is a dependent system in which water circulation in the jackets is to be ensured by additional.

(2) Power absorbed by the pump for water circulation is considerable and this affects the power output of the engine.

(3) In the event of failure of the cooling system serious damage may be caused to the engine.

(4) Cost of the system is considerably high.

(5) System requires considerable maintenance of its various parts.

Advantage of Air-cooling System

- The design of the engine becomes simpler as no water jackets are required. The cylinder can have identical dimensions and be individually detachable and therefore cheaper to renew in case of accident etc.

- Absence of cooling pipes, radiator, etc. makes the cooling system thereby minimum maintenance problems.
- No danger of cooling leakage etc.
- The engine is subjected to freezing troubles etc., usually encountered in case of water coolant engines.
- The weight of the air-cooled engine is less than that of water-cooled engine, i.e., power to weight ratio is improved.
- In this case, the engine is rather a self-contained unit as it requires no external components like radiator, header, tank etc.
- Insulation of air-cooled engines is easier.

Limitations

(1) Can be applied only to small and medium sized engines.
(2) In places where ambient temperature are lower.
(3) Cooling is not uniform.
(4) Higher working temperature compared to water-cooling.
(5) Produce more aerodynamic noise.
(6) Specific fuel consumption is slightly higher.
(7) Lower maximum allowable compression ratios.

Lubrication:-

Lubrication is an art of admitting a lubricant (oil, grease, etc.) between two surfaces that are in contact and in relative motion. The purpose of lubrication in engine is to perform one or several of the following function:-

1) To reduce friction and wear between the moving parts and thereby the energy loss and to increase the life of engine.
2) To provide selling action e.g. the lubrication oil helps the piston rings to maintain an effective seal against the high pressure gasses in the cylinder from leaking out into the crankcase.
3) To cool the surface by carrying away the heat generated in engine components.
4) To clean the surface by washing away carbon and the metal particles caused by wear.

Of all these function, the first function is considered to be the most important one. In internal combustion engines, the problem of lubrication become more difficult because of the high temperature experienced during the combustion process and by the wide range of temperature encounter throughout the cycle. So the energy losses from the friction between different components of the engine can be minimized by providing proper lubrication.

Lubrication of engine component

In the reciprocating engine there are many surfaces in the contact with each other and therefore they should be lubricated to reduce friction. The principal friction surfaces requiring lubrication in an internal combustion engine are:-

1. Piston and cylinder
2. Crankshaft and their bearings
3. Crank pin and their bearing

4. Wrist-pin and their bearing
5. Valve gear

Type of Lubrication system

The function of lubrication system is to provide sufficient quantity of cool, filtered oil to give positive and adequate lubrication to all the moving parts of an engine. The various systems used for internal combustion engine may be classified as:-

1) Mist lubrication system
2) Wet sump lubrication system
3) Dry sump lubrication system

Mist lubrication system

This system is used where crankcase lubrication is not suitable. In two stroke engine, as the charge is compressed in the crankcase, it is not possible to have the lubrication oil in the sump. Hence mist lubrication is used in practice. In such engine, the lubrication oil is mixed with the fuel, the usual ratio being 3% to 6%. The oil and fuel mixture is inducted through the carburetor. The fuel is vaporized and the oil in the form of mist goes via the crankcase into the cylinder. The oil which strikes the crankcase walls lubricates the main and connecting rod bearings and the rest of oil lubricate the piston, piston rings and the cylinder. The advantage of this system is its simplicity and low cost as it does not require an oil pump, filter, etc. however there are certain disadvantage which are enumerated are following:

1) It cause heavy exhaust stroke due to burning of lubricating oil partially or fully and also forms deposit on piston crown and exhaust port which are affect engine efficiency.
2) Since the oil come in close contact with acidic vapor produced during the combustion process get contaminant and may result in the corrosion of bearing surfaces.
3) This system call for a thorough mixing if effective lubrication. This requires either separate mixing prior to use or use of some additive to give the oil good mixing characteristics.
4) During closed throttle operation as in the case of vehicle moving down the hill, the engine will suffer from insufficient lubrication as the supply of fuel is less. This is an important limitation of system.

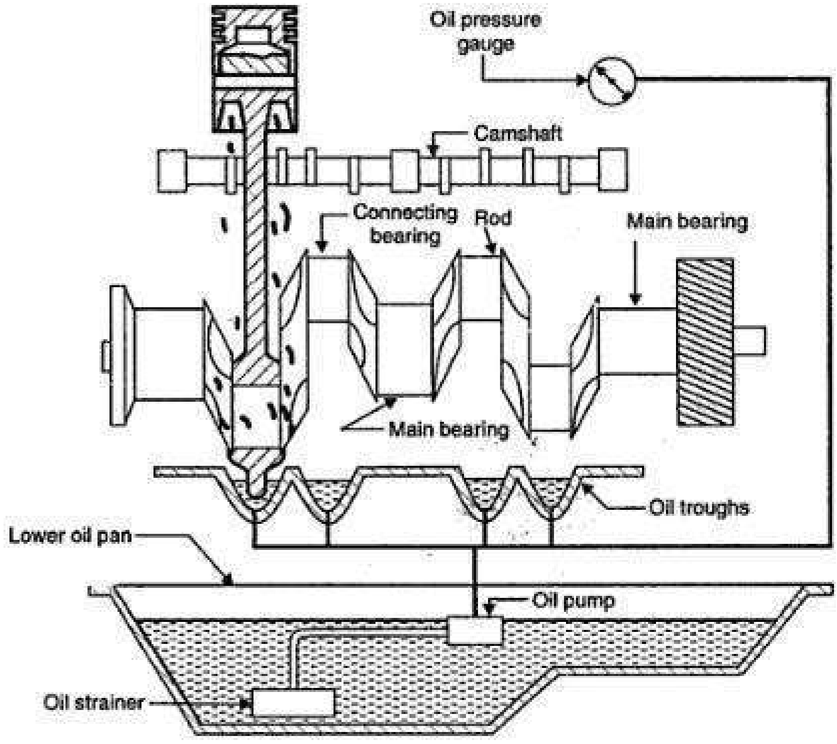
Wet sump lubrication system

In the wet sump lubrication system, the bottom of the crankcase contains an oil pan or sump from which the lubricating oil is pumped to various engine components by a pump. After lubrication these parts, the oil flow back to the sump by gravity. Again it is picked by a pump and recirculated through the engine lubricating system. There are three varieties in the wet sump lubricating system. They are:

1) The splash system
2) The splash and pressure system
3) The pressure feed system

Splash system

This type of lubricating system is used in light duty engine. The lubricating oil is discharge into the bottom of the engine crankcase and maintained at a predetermined level. The oil is drawn by the pump and delivered through a distributing pipe extending the length if the crankcase into the splash trough located under the big end of all the connecting rods. These troughs were provided with overflows and oil in the trough are therefore kept at a constant level. A splashier or dipper is provided under each connecting rod cap which dips into the oil in the trough at every revolution of the crankshaft and the oil is splashed all over the interior of crankcase, into the pistons and onto the exposed portion of cylinder walls. The oil dripping from the cylinder is collected in the sump where it is cooled by the air flowing around. The cooled oil is then recirculated.



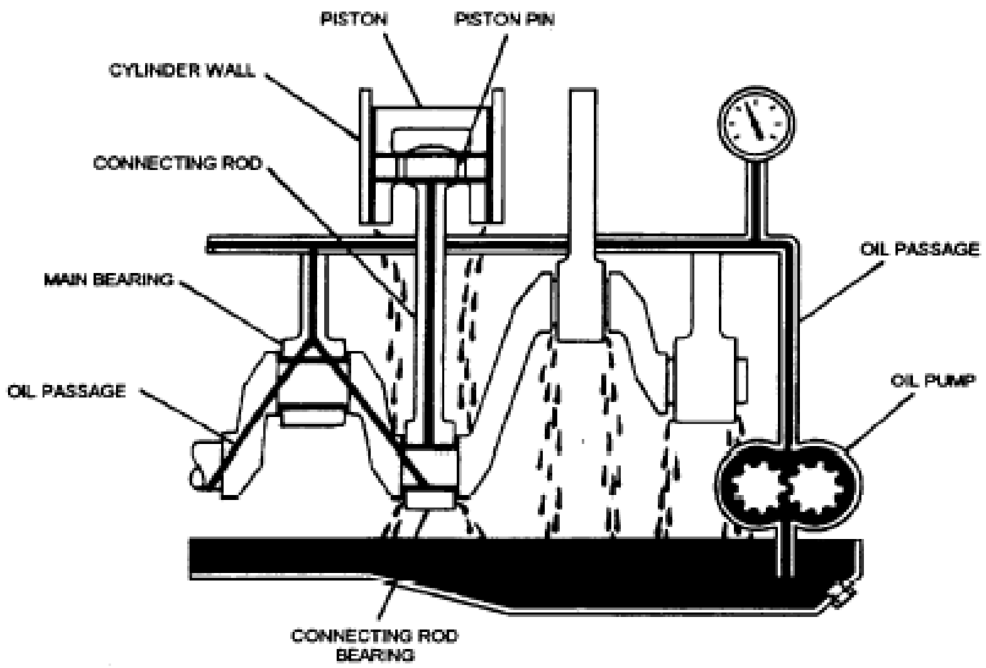
Splash lubrication system

The splash and pressure lubrication system:

In this system, the lubricating oil is supplied under pressure to main and camshaft bearing. Oil is also supplied under pressure to pipes which direct a stream of oil against the dipper on the big end of connecting rod bearing cup and thus the crankpin bearing are lubricated by the splash or spray of oil thrown up by the dipper.

Pressure feed system:

In this system, the oil is drawn in from the sump and forced to all the main bearings of the crankshaft through distributing channels. A pressure relief valve will also be fitted near the delivery point of the pump which open when the pressure in the system attains a predetermine value. An oil hole is drilled in the crankshaft from the center of each crankpin to the centre of an adjacent main journal, through which oil can pass from the main bearing to the crankpin bearing. From the crankpin it reaches piston pin bearing through a hole drilled in the connecting rod. The cylinder wall, tappet roller, piston and piston rings are lubricated by oil spray from around the piston pins and the main and connecting rod bearings. The basic components of the wet sump lubricating system are (1) pump (2) strainer (3) pressure regulator (4) filter (5) breather.



Pressures feed lubrication system

Oil is drawn from the sump by a gear or rotor type of oil pump through an oil strainer. The strainer is a fine mesh screen which prevents foreign particles from entering the oil circulating system. A pressure relief valve is provided which automatically keep the delivery pressure constant and can b set to any value. When the oil pressure exceed that for which the valve is set, the valve open and allow some of the oil to return to the sump thereby reliving the oil pressure in the system.

Dry sump lubrication system

In this system, the supply of oil is carried in an external tank. An oil pump draws oil from the supply tank and circulates it under pressure to the various bearing of the engine. Oil dripping from the cylinder and bearing into the sump is removed by the scavenging pump which in turn the oil is pass through a filter, and is fed back to the supply tank. Thus oil is prevented from accumulating in the base of engine. The capacity of the scavenging pump is always greater than the oil pump. In this system a filter with a bypass valve is placed in between the scavenging pump and the supply tank. If a filter is clogged, the pressure relief valve opens permitting oil to bypass the filter and reaches the supply tank. A separate oil cooler with either water or air as the cooling medium, is usually provided in the dry sump system to remove the heat from the oil.

Properties of lubricants

The duties of the lubricant in an engine are many and varied in a scope. The lubricant is called upon to limit and control the following:

1) Friction between the component and metal to metal contact
2) Overheating of the component
3) Wear of component
4) Corrosion
5) Deposit

To accomplish the above function, the lubricant should have

1) Suitable viscosity
2) Oiliness to ensure adherence to the bearing, and for less friction and wear when the lubrication is in

the boundary region , and as a protective covering against corrosion

3) High strength to prevent the metal to metal contact and seizure under heavy load
4) Should not react with the lubricating surface
5) A low pour point to allow floe of the lubricant at low temperature to the oil pump
6) No tendency to form deposit by reacting with air, water, fuel or the product of combustion
7) Cleaning ability
8) Non foaming characteristics
9) Non toxic and non inflammable

Additives for lubricants

The modern lubrication for heavy duty engines are highly refined which otherwise may produce sludge or suffer a progressive increase in viscosity. For these reasons the lubricant are seasoned by the additive of certain oil soluble organic compound containing inorganic elements such as phosphorus, sulphur, amine additive. Thus oil soluble organic compound added to the present day lubricant to impart one or more of the following characteristics.

1) Anti oxidant and anti-corrosive agent
2) Detergent dispersant
3) Extreme pressure additives
4) Pour point depressor
5) Viscosity index improver
6) Antifoam agent

Unit-5 Supercharging

A **supercharger** is an air compressor that increases the pressure or density of air supplied to an internal combustion engine. This gives each intake cycle of the engine more oxygen, letting it burn more fuel and do more work, thus increasing power.

Power for the supercharger can be provided mechanically by means of a belt, gear, shaft, or chain connected to the engine's crankshaft.

When power is provided by a turbine powered by exhaust gas, a supercharger is known as a turbo supercharger– typically referred to simply as a turbocharger or just turbo. Common usage restricts the term supercharger to mechanically driven units.

In 1848 or 1849 G. Jones of Birmingham, England brought out a Roots-style compressor.

In 1860, brothers Philander and Francis Marion Roots, founders of Roots Blower Company of Connersville, Indiana, patented the design for an air mover for use in blast furnaces and other industrial applications.

The world's first functional, actually tested engine supercharger was made by Dugald Clerk, who used it for the first two-stroke engine in 1878. Gottlieb Daimler received a German patent for supercharging an internal combustion engine in 1885. Louis Renault patented a centrifugal supercharger in France in 1902. An early supercharged race car was built by Lee Chadwick of Pottstown, Pennsylvania in 1908 which reportedly reached a speed of 100 mph (160 km/h).

The world's first series-produced cars with superchargers were Mercedes 6/25/40 hp and Mercedes 10/40/65 hp. Both models were introduced in 1921 and had Roots superchargers. They were distinguished as "Compressor" models, the origin of the Mercedes-Benz which continues today.

On March 24, 1878 Heinrich Krigar of Germany obtained patent #4121, patenting the first ever screw-type compressor. Later that same year on August 16 he obtained patent #7116 after modifying and improving his original designs. His designs show a two-lobe rotor assembly with each rotor having the same shape as the other. Although the design resembled the Roots style compressor, the "screws" were clearly shown with 180 degrees of twist along their length. Unfortunately, the technology of the time was not sufficient to produce such a unit, and Heinrich made no further progress with the screw compressor. Nearly half a century later, in 1935, Alf Lysholm, who was working for Ljungstroms Angturbin AB (later known as Svenska Rotor Maskiner AB or SRM in 1951), patented a design with five female and four male rotors. He also patented the method for machining the compressor rotors.

Types of supercharger

There are two main types of superchargers defined according to the method of gas transfer: positive displacement and dynamic compressors. Positive displacement blowers and compressors deliver an almost constant level of pressure increase at all engine speeds (RPM). Dynamic compressors do not deliver pressure at low speeds; above a threshold speed, pressure increases with engine speed.[7]

Positive displacement

An Eaton MP62 Roots-type supercharger is visible at the front of this Ecotec LSJ engine in a 2006 Saturn Ion Red Line.

Lysholm screw rotors with complex shape of each rotor, which must run at high speed and with close tolerances. This makes this type of supercharger expensive. (This unit has been blued to show close contact areas.)

Positive-displacement pumps deliver a nearly fixed volume of air per revolution at all speeds (minus leakage, which is almost constant at all speeds for a given pressure, thus its importance decreases at higher speeds).

Major types of positive-displacement pumps include:

- Roots
- Lysholm twin-screw
- Sliding vane
- Scroll-type supercharger, also known as the G-Lader

Compression type

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Positive-displacement pumps are further divided into internal and external compression types.

Roots superchargers are external compression only (although high-helix roots blowers attempt to emulate the internal compression of the Lysholm screw).

- External compression refers to pumps that transfer air at ambient pressure into the engine. If the engine is running under boost conditions, the pressure in the intake manifold is higher than that coming from the supercharger. That causes a backflow from the engine into the supercharger until the two reach equilibrium. It is the backflow that actually compresses the incoming gas. This is an inefficient process and the main factor in the lack of efficiency of Roots superchargers when used at high boost levels. The lower the boost level the smaller is this loss, and Roots blowers are very efficient at moving air at low pressure differentials, which is what they were invented for (hence the original term "blower").

All the other types have some degree of internal compression.

- Internal compression refers to the compression of air within the supercharger itself, which, already at or close to boost level, can be delivered smoothly to the engine with little or no back flow. This is more effective than back flow compression and allows higher efficiency to be achieved. Internal compression devices usually use a fixed internal compression ratio. When the boost pressure is equal to the compression pressure of the supercharger, the back flow is zero. If the boost pressure exceeds that compression pressure, back flow can still occur as in a roots blower. Internal compression blowers must be matched to the expected boost pressure in order to achieve the higher efficiency they are capable of, otherwise they will suffer the same problems and low efficiency of the roots blowers.

Capacity rating

Positive-displacement superchargers are usually rated by their capacity per revolution. In the case of the Roots blower, the GMC rating pattern is typical. The GMC types are rated according to how many two-stroke cylinders, and the size of those cylinders, it is designed to scavenge. GMC has made 2–71, 3–71, 4–71, and the famed 6–71 blowers. For example, a 6–71 blower is designed to scavenge six cylinders of 71 cubic inches (1,163 cc) each and would be used on a two-stroke diesel of 426 cubic inches (6,981 cc), which is designated a 6–71; the blower takes this same designation. However, because 6–71 is actually the engine's designation, the actual displacement is less than the simple multiplication would suggest. A 6–71 actually pumps 339 cubic inches (5,555 cc) per revolution (but as it spins faster than the engine, it can easily put out the same displacement as the engine per engine rev).

Aftermarket derivatives continue the trend with 8–71 to current 16–71 blowers used in different motor sports. From this, one can see that a 6–71 is roughly twice the size of a 3–71. GMC also made 53 cu in (869 cc) series in 2–, 3–, 4–, 6–, and 8–53 sizes, as well as a "V71" series for use on engines using a V configuration.

Dynamic

Dynamic compressors rely on accelerating the air to high speed and then exchanging that velocity for pressure by diffusing or slowing it down.

Major types of dynamic compressor are:

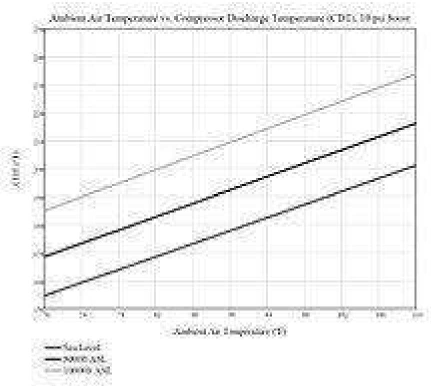
- Centrifugal
- Multi-stage axial-flow
- Pressure wave supercharger

Supercharger drive types

Superchargers are further defined according to their method of drive.

- Belt (V-belt, Synchronous belt, Flat belt)
- Direct drive
- Gear drive
- Chain drive

Temperature effects and intercoolers



Supercharger CDT vs. Ambient Temperature Graph shows how a supercharger's CDT varies with air temperature and altitude (absolute pressure).

One disadvantage of supercharging is that compressing the air increases its temperature. When a supercharger is used on an internal combustion engine, the temperature of the fuel/air charge becomes a major limiting factor in engine performance. Extreme temperatures will cause detonation of the fuel-air mixture (spark ignition engines) and damage to the engine. In cars, this can cause a problem when it is a hot day outside, or when an excessive level of boost is reached.

It is possible to estimate the temperature rise across a supercharger by modeling it as an isentropic process.

For example, if a supercharged engine is pushing 10 psi (0.69 bar) of boost at sea level (ambient pressure of 14.7 psi (1.01 bar), ambient temperature of 75 °F (24 °C)), the temperature of the air after the supercharger will be 160.5 °F (71.4 °C). This temperature is known as the compressor discharge temperature (CDT) and highlights why a method for cooling the air after the compressor is so important.

While it is true that higher intake temperatures for internal combustion engines will ingest air of lower density, this only holds correct for a static, unchanging air pressure. i.e. on a hot day an engine will intake less oxygen per engine cycle than it would on a cold day. However, the heating of the air, while in the supercharger compressor, does not reduce the density of the air due to its rise in temperature. The rise in temperature is due to its rise in pressure. Energy is being added to the air and this is seen in both its energy, internal to the molecules (temperature) and of the air in static pressure, as well as the velocity of the gas.

Inter-cooling makes no change in the density of the air after it has been compressed. It is only removing the thermal energy of the air from the compression process. i.e. the inter-cooler only removes the energy put in by the compression process and does not alter the density of air, so that the air/fuel mixture is not so hot that it causes it to ignite before the spark ignites it, otherwise known as pre-ignition.

Two-stroke engines

For two-stroke engines, scavenging is required to purge exhaust gasses. In small engines this is commonly achieved by using the crankcase as a blower, the descending piston during the power stroke compresses air in the crankcase used to purge the cylinder. Scavenging blowing should not be confused with supercharging, no charge compression takes place. As the volume change produced by the lower side of the piston is the same as the upper face, this is limited to scavenging and cannot provide any supercharging.

Larger engines usually use a separate blower for scavenging and it was for this type of operation that the Roots blower was developed. Historically many designs of blower have been used, from separate pumping cylinders, 'top hat' pistons combining two pistons of different diameter the larger one being used for scavenging, various rotary blowers and centrifugal turbo compressors, including turbochargers. Turbocharging two-stroke engines is difficult, but not impossible, as an exhaust-driven turbocharger does not provide any boost until it has had time to spin up to speed. Purely turbocharged two stroke engines may thus have difficulty when starting, with poor combustion and dirty exhausts, possibly even four-stroking. Some two-stroke turbochargers have a mechanical drive through a clutch, used for starting.

Simple two-stroke engines with ported inlet and exhaust cannot be supercharged since the inlet port always closes first. For this reason, two-stroke Diesel engines usually have mechanical exhaust valves with separate timing to allow supercharging. Regardless of this, two-stroke engines require scavenging at all engine speeds and so turbocharged two-stroke engines must still employ a blower, usually Roots type. This blower may be mechanically or electrically driven, in either case the blower may be disengaged once the turbocharger starts to deliver air.

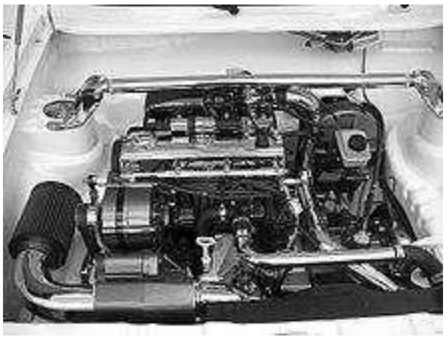
Automobiles

1929 "Blower" Bentley. The large "blower" (supercharger), located in front of the radiator, gave the car its name.

In 1900, Gottlieb Daimler, of Daimler-Benz (Daimler AG), was the first to patent a forced-induction system for internal combustion engines, superchargers based on the twin-rotor air-pump design, first patented by the American Francis Marion Roots in 1860, the basic design for the modern Roots type supercharger.

The first supercharged cars were introduced at the 1921 Berlin Motor Show: the 6/20 hp and 10/35 hp Mercedes. These cars went into production in 1923 as the 6/25/40 hp (regarded as the first supercharged road car) and 10/40/65 hp. These were normal road cars as other supercharged cars at same time were almost all racing cars, including the 1923 Fiat 805-405, 1923 Miller 122 1924 Alfa Romeo P2, 1924 Sunbeam, 1925 Delage, and the 1926 Bugatti Type 35C. At the end of the 1920s, Bentley made a supercharged version of the Bentley 4½ Liter road car. Since then, superchargers (and turbochargers) have been widely applied to racing and production cars, although the supercharger's technological complexity and cost have largely limited it to expensive, high-performance cars.

Supercharging versus turbo charging



A G-Ladder scroll-type supercharger on a Volkswagen Golf Mk1

Keeping the air that enters the engine cool is an important part of the design of both superchargers and turbochargers. Compressing air increases its temperature, so it is common to use a small radiator called an intercooler between the pump and the engine to reduce the temperature of the air.

There are three main categories of superchargers for automotive use:

- Centrifugal turbochargers – driven from exhaust gases.
- Centrifugal superchargers – driven directly by the engine via a belt-drive.
- Positive displacement pumps – such as the Roots, Twin Screw (Lysholm), and TVS (Eaton) blowers.

Roots blowers tend to be only 40–50% efficient at high boost levels; by contrast centrifugal (dynamic) superchargers are 70–85% efficient at high boost. Lysholm-style blowers can be nearly as efficient as their centrifugal counterparts over a narrow range of load/speed/boost, for which the system must be specifically designed.

Mechanically driven superchargers may absorb as much as a third of the total crankshaft power of the engine and are less efficient than turbochargers. However, in applications for which engine response and power are more important than other considerations, such as top-fuel dragsters and vehicles used in tractor pulling competitions, mechanically driven superchargers are very common.

The thermal efficiency, or fraction of the fuel/air energy that is converted to output power, is less with a mechanically driven supercharger than with a turbocharger, because turbochargers use energy from the exhaust gas that would normally be wasted. For this reason, both economy and the power of a turbocharged engine are usually better than with superchargers.

Turbochargers suffer (to a greater or lesser extent) from so-called turbo-spool (turbo lag; more correctly, boost lag), in which initial acceleration from low RPM is limited by the lack of sufficient exhaust gas mass flow (pressure). Once engine RPM is sufficient to raise the turbine RPM into its designed operating range, there is a rapid increase in power, as higher turbo boost causes more exhaust gas production, which spins the turbo yet faster, leading to a belated "surge" of acceleration. This makes the maintenance of smoothly increasing RPM far harder with turbochargers than with engine-driven superchargers, which apply boost in direct proportion to the engine RPM. The main advantage of an engine with a mechanically driven supercharger is better throttle response, as well as the ability to reach full-boost pressure instantaneously. With the latest turbo charging technology and direct gasoline injection, throttle response on turbocharged cars is nearly as good as with mechanically powered superchargers, but the existing lag time is still considered a major drawback, especially considering that the vast majority of mechanically driven superchargers are now driven off clutched pulleys, much like an air compressor.

Turbo charging has been more popular than superchargers among auto manufacturers owing to better power and efficiency. For instance Mercedes-Benz and Mercedes-AMG previously had supercharged "Compressor" offerings in the early 2000s such as the C230K, C32 AMG, and S55 AMG, but they have abandoned that technology in favor of turbocharged engines released around 2010 such as the C250 and S65 AMG biturbo. However, Audi did introduce its 3.0 TFSI supercharged V6 in 2009 for its A6, S4, and Q7, while Jaguar has its supercharged V8 engine available as a performance option in the XJ, XF, XKR, and F-Type, and, via joint ownership by Tata motors, in the Range Rover also.

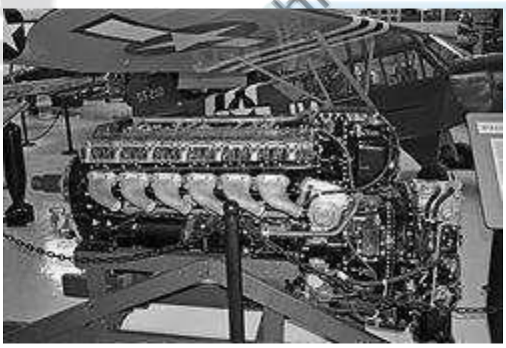
Twin charging

In the 1985 and 1986 World Rally Championships, Lancia ran the Delta S4, which incorporated both a belt-driven supercharger and exhaust-driven turbocharger. The design used a complex series of bypass valves in the induction and exhaust systems as well as an electromagnetic clutch so that, at low engine speeds, boost was derived from the supercharger. In the middle of the rev range, boost was derived from both systems, while at the highest revs the system disconnected drive from the supercharger and isolated the associated ducting.[13] This was done in an attempt to exploit the advantages of each of the charging systems while removing the disadvantages. In turn, this approach brought greater complexity and impacted on the car's reliability in WRC events, as well as increasing the weight of engine ancillaries in the finished design.

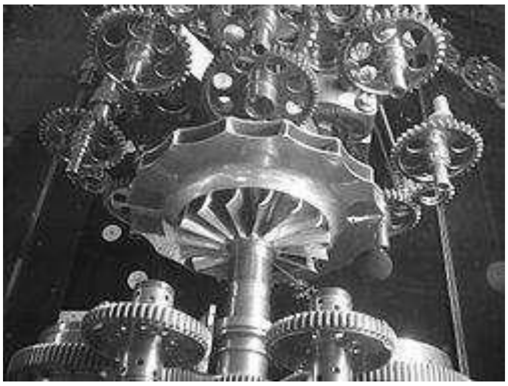
The Volkswagen TSI engine (or Twin charger) is a 1.4-litre direct-injection motor that also uses both a supercharger and turbocharger.

Aircraft

Altitude effects



The Rolls-Royce Merlin, a supercharged aircraft engine from World War II. The supercharger is at the rear of the engine at right



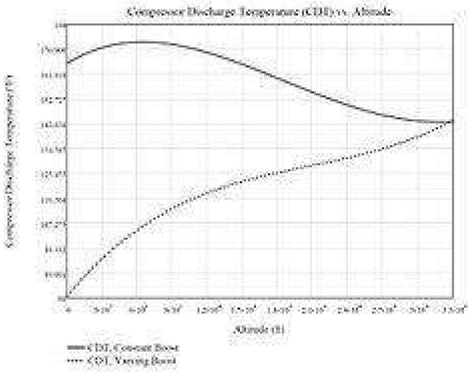
A Centrifugal supercharger of a Bristol Centaurs radial aircraft engine

Superchargers are a natural addition to aircraft piston engines that are intended for operation at high altitudes. As an aircraft climbs to higher altitude, air pressure and air density decreases. The output of a piston engine drops because of the reduction in the mass of air that can be drawn into the engine. For example, the air density at 30,000 ft (9,100 m) is ⅓ of that at sea level, thus only ⅓ of the amount of air can be drawn into the cylinder, with enough oxygen to provide efficient combustion for only a third as much fuel. So, at 30,000 ft (9,100 m), only 1⁄3 of the fuel burnt at sea level can be burnt. (An advantage of the decreased air density is that the airframe experiences only about 1/3 of the aerodynamic drag. Plus, there is decreased back pressure on the exhaust gases. On the other hand, more energy is consumed holding an airplane up with less air in which to generate lift.)

A supercharger can be thought of either as artificially increasing the density of the air by compressing it or as forcing more air than normal into the cylinder every time the piston moves down.

A supercharger compresses the air back to sea-level-equivalent pressures, or even much higher, in order to make the engine produce just as much power at cruise altitude as it does at sea level. With the reduced aerodynamic drag at high altitude and the engine still producing rated power, a supercharged airplane can fly much faster at altitude than a naturally aspirated one. The pilot controls the output of the supercharger with the throttle and indirectly via the propeller governor control. Since the size of the supercharger is chosen to produce a given amount of pressure at high altitude, the supercharger is oversized for low altitude. The pilot must be careful with the throttle and watch the manifold pressure gauge to avoid over boosting at low altitude. As the aircraft climbs and the air density drops, the pilot must continuously open the throttle in small increments to maintain full power. The altitude at which the throttle reaches full open and the engine is still producing full rated power is known as the **critical altitude.** Above the critical altitude, engine power output will start to drop as the aircraft continues to climb.

Effects of temperature



Supercharger CDT vs. Altitude Graph shows the CDT differences between a constant-boost supercharger and a variable-boost supercharger when utilized on an aircraft.

As discussed above, supercharging can cause a spike in temperature, and extreme temperatures will cause detonation of the fuel-air mixture and damage to the engine. In the case of aircraft, this causes a problem at low altitudes, where the air is both denser and warmer than at high altitudes. With high ambient air temperatures, detonation could start to occur with the manifold pressure gauge reading far below the red line.

A supercharger optimized for high altitudes causes the opposite problem on the intake side of the system. With the throttle retarded to avoid over boosting, air temperature in the carburetor can drop low enough to cause ice to form at the throttle plate. In this manner, enough ice could accumulate to cause engine failure, even with the engine operating at full rated power. For this reason, many supercharged aircraft featured a carburetor air temperature gauge or warning light to alert the pilot of possible icing conditions.

Several solutions to these problems were developed: intercoolers and after coolers, anti-detonate injection, two-speed superchargers, and two-stage superchargers.

Two-speed and two-stage superchargers

In the 1930s, two-speed drives were developed for superchargers for aero engines providing more flexibility aircraft operation. The arrangement also entailed more complexity of manufacturing and maintenance. The gears connected the supercharger to the engine using a system of hydraulic clutches, which were initially manually engaged or disengaged by the pilot with a control in the cockpit. At low altitudes, the low-speed gear would be used in order to keep the manifold temperatures low. At around 12,000 feet (3,700 m), when the throttle was full forward and the manifold pressure started to drop off, the pilot would retard the throttle and switch to the higher gear, then readjust the throttle to the desired manifold pressure. Later installations automated the gear change according to atmospheric pressure.

In the Battle of Britain the Spitfire and Hurricane planes powered by the Rolls-Royce Merlin engine were equipped largely with single stage and single speed superchargers. Stanley Hooker of Rolls Royce, to improve the performance of Merlin engine developed two-speed two-stage supercharging with after cooling with a successful application on the Rolls Royce Merlin 61 aero engine in 1942. Horsepower was increased and performance at all aircraft heights. Hooker's developments allowed the aircraft they powered to maintain a crucial advantage over the German aircraft they opposed throughout World War II despite the German engines being significantly larger in displacement. Two-stage superchargers were also always two-speed. After the air was compressed in the low-pressure stage, the air flowed through an intercooler radiator where it was cooled before being compressed again by the high-pressure stage and then possibly also after cooled in another heat exchanger. Two-stage compressors provided much improved high altitude performance, as typified by the Rolls-Royce Merlin 61 powered Super marine Spitfire Mk IX and the North American Mustang.

In some two-stage systems, damper doors would be opened or closed by the pilot in order to bypass one stage as needed. Some systems had a cockpit control for opening or closing a damper to the intercooler/after cooler, providing another way to control temperature. Rolls-Royce Merlin engines had fully automated boost control with all the pilot having to do was advance the throttle with the control system limiting boost as necessary until maximum altitude was reached.

Turbo charging

Main article: Turbocharger

A mechanically driven supercharger has to take its drive power from the engine. Taking a single-stage single-speed supercharged engine, such as the Rolls-Royce Merlin, for instance, the supercharger uses up about 150 hp (110 kW). Without a supercharger, the engine could produce about 750 horsepower (560 kilowatts), but with a supercharger, it produces about 1,000 hp (750 kW)—an increase of about 400 hp (750 - 150 + 400 = 1000 hp), or a net gain of 250 hp (190 kW). This is where the principal disadvantage of a supercharger becomes apparent. The engine has to burn extra fuel to provide power to drive the supercharger. The increased air density during the input cycle increases the specific power of the engine and its power-to-weight ratio, but at the cost of an increase in the specific fuel consumption of the engine. In addition to increasing the cost of running the airplane this has the potential to reduce its overall range. On the other hand, with more engine power the airplane can carry more fuel. In military types, this has often been done using external drop tanks, for example in the American P-38 Lightning, P-47 Thunderbolt, P-51 Mustang, and F6F Hellcat fighter planes.

With their external fuel tanks and supercharged or turbocharged engines, the P-38 and the P-51 could fly from England to Berlin and back, the P-47 could fly from England to the Ruhr and back, and the F6F had the longest range of any fighter based on aircraft carriers of the war. Also, the P-51 could fly even further - from Iwo Jima to Tokyo and back. These ranges were much longer than those of any Nazi German, British, Japanese, Canadian, or Soviet fighter planes of World War II. These American fighters also had excellent fighting performance at high altitudes.

As opposed to a supercharger driven by the engine itself, a turbocharger is driven using the exhaust gases from the engines. The amount of power in the gas is proportional to the difference between the exhaust pressure and air pressure, and this difference increases with altitude, helping a turbocharged engine to compensate for changing altitude.

The majority of high-altitude aircraft engines used during World War II used mechanically driven superchargers, because these had three significant manufacturing advantages over turbochargers. Turbochargers - used by large American aircraft engines such as the Allison V-1710 (used in the P-38) and the Pratt & Whitney R-2800, required additional ducting expensive high-temperature metal alloys in the gas turbine and perturbing section of the exhaust system, but they were very useful in high-altitude bombers and some fighter planes. The size of the ducting alone was a serious problem. For example, both the F4U Corsair and the P-47 Thunderbolt used the same multi cylinder radial engine, but the large barrel-shaped fuselage of the P-47 was needed because of the amount of ducting to and from the turbocharger in the rear fuselage. The F4U used a two-stage supercharger with compact intercooler layout.

Turbocharged piston engines are also subject to many of the same operating restrictions as those of gas turbine engines. Turbocharged engines also require frequent inspections of their turbochargers and exhaust systems to search for possible damage caused by the extreme heat and pressure of the turbochargers. Such damage was a prominent problem in the early models of the American B-29 Super fortress high-altitude bombers used in the Pacific Theater of Operations during 1944–45.

In more recent times most aircraft engines for general aviation (light airplanes) are naturally aspirated, but the smaller number of modern aviation piston engines designed to run at high altitudes use turbocharger or turbo-normalize systems, instead of a supercharger driven from the crank shafts. The change in thinking is largely due to economics. Aviation gasoline was once plentiful and cheap, favoring the simple but fuel-hungry supercharger. As the cost of fuel has increased, the ordinary supercharger has fallen out of favor. Also, depending on what monetary inflation factor one uses, fuel costs have not decreased as fast as production and maintenance costs have.

Effects of fuel octane rating

Until the late 1920s all automobile and aviation fuel was generally rated at 87 octane or less. This is the rating that was achieved by the simple distillation of "light crude" oil. Engines from around the world were designed to work with this grade of fuel, which set a limit to the amount of boosting that could be provided by the supercharger, while maintaining a reasonable compression ratio.

Octane rating boosting through additives was a line of research being explored at the time. Using these techniques, less valuable crude could still supply large amounts of useful gasoline, which made it a valuable economic process. However, the additives were not limited to making poor-quality oil into 87-octane gasoline; the same additives could also be used to boost the gasoline to much higher octane ratings.

Higher-octane fuel resists auto ignition and detonation better than does low-octane fuel. As a result, the amount of boost supplied by the superchargers could be increased, resulting in an increase in engine output. The development of 100-octane aviation fuel, pioneered in the USA before the war, enabled the use of higher boost pressures to be used on high-performance aviation engines, and was used to develop extremely high-power outputs – for short periods – in several of the pre-war speed record airplanes. Operational use of the new fuel during World War II began in early 1940 when 100-octane fuel was delivered to the British Royal Air Force from refineries in America and the East Indies.[19] The German Luftwaffe also had supplies of a similar fuel.

Increasing the knocking limits of existing aviation fuels became a major focus of aero engine development during World War II. By the end of the war, fuel was being delivered at a nominal 150-octane rating, on which late-war aero engines like the Rolls-Royce Merlin 66 or the Daimler-Benz DB 605DC developed as much as 2,000 hp (1,500 kW).