DEVELOPMENT AND APPLICATION OF INTERNAL-COMBUSTION ENGINE

A Dissertation submitted to the
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in partial fulfilment of the requirements for
the Degree of Master of Engineering in
Applied Thermodynamics (Power Engineering—Steam & I.C.E.)

by
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CERTIFICATION

It is certified that Shri I.S. Rau has prepared this dissertation entitled "DEVELOPMENT AND APPLICATION OF INTERNAL COMBUSTION ENGINE". He has satisfied the minimum requirement of his three months residence at this University in connection with his dissertation.

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Dated

ACKNOWLEDGMENTS

I was asked to write a dissertation on the subject ... "The Development of the Design and Application of Internal-Combustion Engines", for the award of the Master's Degree in Applied Thermodynamics (Power Engineering- Steam and I.C.E.). My first thought was that I would not be able to do full justice to the subject as it was a very vast one. On deliberating over it, I decided to go through the catalogues of books and publications on the topic, available in the University Library. After some weeks of study of these books and publications, I could sketch the outlines. This to some extent persuaded me to make an intensive study. After a couple of months of study, I found that I would not be able to present a continuous chain of events in the historical development.

I approached my Professor Shri M.V. Kamlani and put before him my work of the past months and the difficulties that I was experiencing. He was quick to see the handicaps I was labouring under and gave me the necessary encouragement to persevere. He was very generous to give me access to his personal library. He spared no pains to help me at every step and gave me valuable suggestions. I am very highly indebted to him for his precious advice and guidance without which this dissertation would not have seen the light of day in the form it is now presented. I take this opportunity to express my immense gratitude to him.

I owe my grateful thanks to my Associate Professoor Dr. Shankar Lal for his useful advice.

My gratitude is also due to Dr. J.P. Srivastava, Reader in Mechanical Engineering, for permitting me to use his valuable books and I thank him for his good suggestions.

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CONTENTS

INTRODUCTION

In an internal-combustion engine of to-day, we see the fulfilment of the creative effort of man in its progress towards modern civilization which has attained a high level of industrial economy. It can hardly be denied that the internal-combustion engine has played a very important role in the harnessing of energy to a variety of applications, which have accelerated the development of industrial life and helped the world to share its benefits amongst nations, through vastly improved movement of men and material. Indeed, the internal-combustion engine has had a checkered career, with a keen competitor, in the steam engine, during its infancy and adolescence. It has had to struggle hard to establish its superiority over the steam engine and finally gain its rightful place in the field of transport with a substantial share in other fields of application.

The life history of the internal-combustion engine makes an interesting study. It has taken nearly two centuries to gain its full maturity and only very recently given birth to the gas turbine, which, shows promise of taking over the

CHAPTER I

ORIGIN AND DEVELOPMENT OF THE INTERNAL-COMBUSTION ENGINE

Contrary to popular belief, the conception of the internal-combustion engine is older than that of the steam engine. The principle of burning fuel inside an engine cylinder dates back to the early experimental period when gunpowder was first tried as fuel in a "heat motor". In fact, the first gunpowder engine was developed in its primitive form by the Dutch physicist Christian Huyghens (1-4)* in 1680. But, about this time, the power of steam and its simpler ~~devices~~ forms of application began to draw the attention of scientific men, and their efforts ~~of~~ were, naturally, diverted to the development of steam engine. In this, the application of the explosive properties of fuel was well-nigh forgotten. It was not until the last years of the eighteenth century that, interest was again roused in Huyghens contrivance of a "heat motor". An application of gas as fuel, burnt inside the "motor" cylinder, occupied the attention of scientific men once again. In the initial stages, ignition of the compressed gas inside the cylinder was achieved by periodic application of an external flame, but, with the invention of electric

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* For these and subsequent citations see References at the end.

entire field of power generation ranging from small portable power units for variety of applications, to large capacity power units for land, air and marine transport, and for generation of electricity. In this last application, it may even gain superiority over the steam turbine, which stands unchallenged to-day.

An attempt has been made to trace this life history of the internal-combustion engine in this dissertation, and, take a closer view of the important features which have developed in its course. These have added to the scope and range of the activities covered by this power unit in its matured form.

There are three important episodes which deserve a detailed review and the dissertation presents this review in the following plan:

1. History of the internal-combustion engine and the development of its specific features.
2. Internal-combustion engine applications.
3. The gas turbine.

Apology is made for making only a brief mention of the gas turbine developments. Although it has entered the field of motive power recently, it cannot be given full justice in this dissertation without making the dissertation voluminous and without pushing the reciprocating type of internal-combustion engine, the main theme of the dissertation, into the background.

The published material available in this country is not sufficiently abundant to cover the various aspects minutely, but it is hoped that, the life review of the internal-combustion engine presented in the dissertation would form the basis for an enlarged review which may be attempted at a later stage. Attempt has, however, been made in chapter 6, to high light the important features of the development of the internal-combustion engine; and also indicate the problems calling for immediate attention for further improving the versatility of this type of power unit, both in regard to the variety of fuels which may go to improve its economics, and ~~to further~~ the scope of its applications, which would go to widen the field of its usefulness. And if the dissertation helps in showing the importance of these problems to the scientist, engineer and research worker, it will have well served its purpose.

spark ignition, the gas engine technique progressed at a very rapid rate bringing in its train the application of light oils in place of gaseous fuels. This marked the beginning of petrol engine as a motive power unit. Improvements which followed in the devices for vaporising and intimately mixing the highly volatile light fuel oils with air (carburation), and in spark ignition devices, stimulated the progress in the design of petrol engine during the period of next fifty years. The need for using cheaper (and safer) heavy fuel oils in the type of engine then developed also received attention, resulting in the introduction of compression-ignition principle for proper application of heavy fuel oils. The type of engine developed for heavy fuel oils is now popularly known as Diesel engine because of the important contribution made by Dr. Rudolf Diesel (3-6) in this direction, although Herbert Ackroyd- Stuart (3-6) is acclaimed as the originator of the compression-ignition engine. It must be noted that, in the internal -combustion engine field, the petrol engine has completely revolutionised the mode of road travel and has been solely responsible for the advent of aeroplane.

On the other hand, the Diesel engine tended to develop mainly in its application for generation of electricity in stationary power plants and marine propulsion, effectively replacing the reciprocating type of steam engine in the two fields. Further, during recent years, the high speed Diesel engine has been successfully developed employing compression ratio as high as nineteen, with the result that the position of petrol engine in the field of transport is now becoming precarious with the Diesel engine as its keen competitor. In fact, petrol engine is now being hardly used for road transport power units exceeding 100 hp, its place being completely taken up by the Diesel engine on account of the latter's higher performance efficiency.

The reciprocating type of steam engine has shown its limitations and the steam turbine has already taken over from the steam engine for generating power beyond a few hundred horse power. Gas turbine operating on the internal-combustion principle is developing fast to follow the same trend regarding Diesel and petrol engines.

An interesting account of the development of the internal-combustion engine is presented in a chronological order in Tables 1.1, 1.2 and 1.3.

TABLE 1.1 - HISTORY OF EXPLOSIVE POWDER AND GAS ENGINES.

Table 1.2. History of oil engines

Table 1.3 History of Petrol engines

POWDER AND GAS ENGINES

ACHIEVEMENTS

Conceived of a device for producing motive power from gunpowder as fuel, but he did not give it any practical shape.

Independently developed the same idea and actually built a crude internal-combustion engine using gunpowder as fuel (Fig. 1.1)(See next page)

Scientific men and inventors diverted their attention to the study of steam with the result that further development of gunpowder internal-combustion engine was checked.

Toyed with the idea of internal-combustion gas turbine and constructed a crude model using gas derived from wood, coal, or oil as fuel.

Applied the established reciprocating mechanism of steam engine to internal-combustion engine and introduced flame-ignition arrangement for gas drawn into the engine cylinder; developed the first gas engine working model. (Fig. 1.2)(See next page)

Worked theoretically on the possibility of electric spark ignition for compressed gas-air mixture. His ideas were much in advance of time as the machines and tools required for precision work were not then available.

The beginning of the nineteenth century was marked by the introduction of new machines and tools which considerably improved the design and manufacture of steam engine and helped in the adaptation of new techniques to the development of internal -combustion engine.

Steam engine showed its limitations as a power unit for the road vehicle; Rivaz and Cecil (independently) tried to develop a simple internal-combustion engine to replace the steam engine in this field.

TABLE 1.1 - HISTORY OF EXPLOSIVES

PERIOD OR YEAR	PERSON OR AGENCY.	NATIONALITY OR COUNTRY.	PROFESSION OR TRADE
1678	J.D.Haute-feuille	Frenchman	Scientist
1680	Christian Huyghens	Dutch	Physicist.
1680-1790			
1791	John Barber	Englishman	Engineer-Scientist.
1794	Robert Street	England	Engineer
1799	Philippe Lebon	Frenchman	Engineer
1800-1820			
1807 1820	Rivaz W.Cecil	Englishman	Engineer

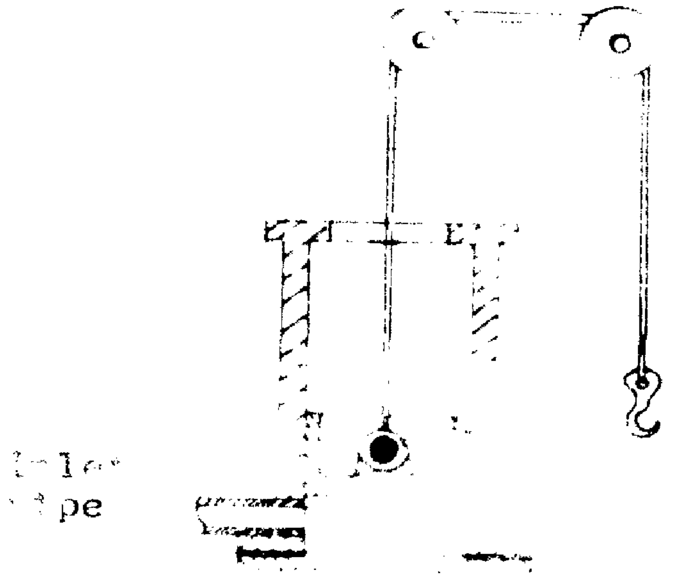
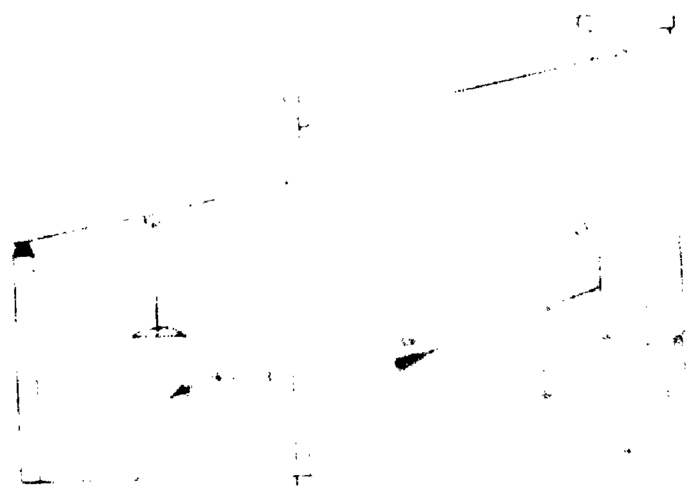


Fig.1.1 Huyg[illegible] (1680)



ACHIEVEMENTS

Barnett also developed the idea of compressed gas-air mixture (presumably independent of Lebon), and gave it a practical shape by introducing separate air and gas pumps in his design of "gas motor", and application of flame for ignition of the mixture with the piston at the dead centre. Unknown to him, in his gas motor, he had well approached the actual working conditions of gas in a modern gas engine. (Fig. 1.3) *(See next page)*

Many patents were taken for commercial applications in England and France but without practical designs being put into service.

Borrowing ideas from steam engine developments he produced a reliable internal-combustion engine. He introduced spark ignition for gas-air mixture, at atmospheric pressure. The engine however showed signs of overheating and excessive consumption of gas. (Fig. 1.4) *(See next page)*

This defect was partially overcome by M. Hugon who introduced a device for injecting a fine spray of water into the cylinder during explosion of ignited gases. But there was hardly any improvement in efficiency due to lack of compression of gas-air mixture at the time of ignition.

He made a theoretical study of the experimental engines then available, and defined the four-stroke cycle, indicating the possibilities of the gas-air mixture being compressed inside the cylinder before the occurrence of spark ignition. This basic conception of cycle operations taking place in the internal combustion engine cylinder has continued to stay till this day with necessary improvements

PERIOD OR YEAR..	PERSON OR AGENCY.	NATIONALITY OR COUNTRY.	PROFESSION OR TRADE
1838	William Barnett	Englishman	Engineer.
1838-1860			
1860	J.J.E.Lenoir	Frenchman	Engineer
1862	M.Hugon	France	Engineer
1862	Beau de Rochas	Frenchman	Designer

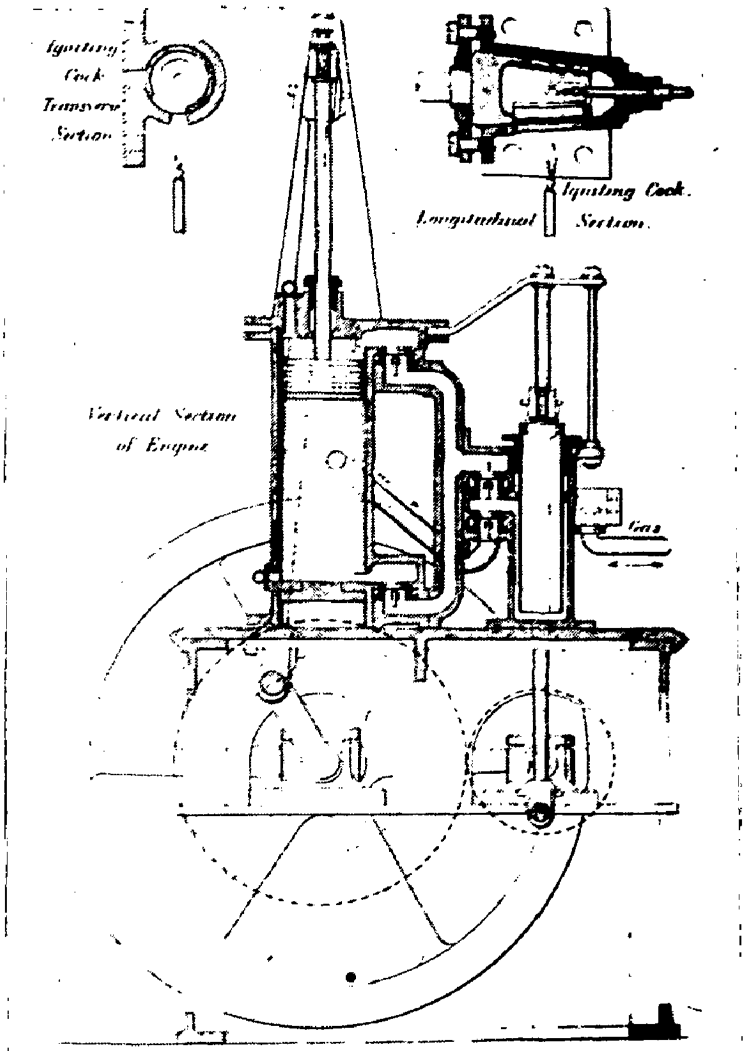


Fig 1·3 Compression engines were described in a patent of 1838 by William Barnett. They made use of special flame-ignition cocks.

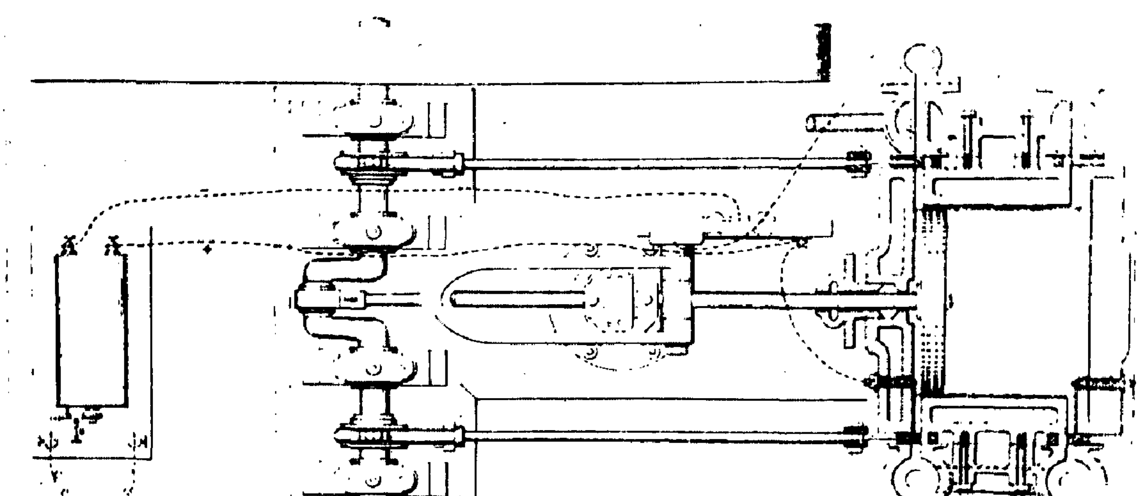


Fig ·4 Slide-valves of steam-engine pattern and sparking plugs were features of a gas engine patented in 1860 by J. J. E. Lenoir. Of horizontal double-acting design, it is thought to be the first internal combustion engine to work with reliability. Delayed ignition, however, caused the piston to move too slowly

ACHIEVEMENTS

It is claimed that he evolved the four-stroke -cycle independently of Rochas and produced a satis- -factory design of gas engine eliminating roughness and noise in its operation. It is for this reason that the four-stroke cycle is known as "Otto Cycle."

Following the development of the Otto cycle which has the disadvantage of one working stroke in two revolutions, Clerk, developed the mechanism for two-stroke operation giving one working stroke per revolution, thereby, nearly doubling the power of the engine.

OIL ENGINES.

ACHIEVEMENTS

Due to high cost of fuel gas he was the first to experiment with fuel oil in a four-stroke gas engine. The device he developed enabled air under pressure to break up the jet of oil into a fine spray and produce thereby air-gas mixtures resembling the normal gas conditions before entry to the cylinder. The experiment did not prove a great success due to erratic behaviour of fuel-air mixture and low ignition temperature of fuel oil.

He developed a combustor for burning gas or oil and used the burning gases attaining high pressure and temperature for working his engine in the same way as the steam engine, an idea which has in the recent past, been introduced in the gas turbine. Strictly speaking Brayton's engine was an external-combustion engine using combustion gas as a working agent.

He worked on a novel idea of producing air-fuel mixture by utilising the heat of exhaust gases in a regenerator unit. The arrangement provided for the heating of the regenerator elements by the passage of exhaust gases through them during the exhaust stroke and utilisation of the heated element to evaporate oil dropped thereon. Siemens ingenuity in this novel approach germinated the idea of waste heat recovery which has, in later years, been well applied to heat requirements for industrial applications.

ACHIEVEMENTS

He is known for improving the mechanical workability of engines developed on "Otto cycle" principle with a view to application of light oils as fuel, for which he followed the idea developed by Hock. This objective was partly achieved due to crude mechanism for carburation.

The honour of developing a satisfactory oil engine goes to Priestman by virtue of the fact that he improved the device for oil-air mixture by spraying oil under pressure into an air jet, and carrying the mixture into a chamber heated by exhaust gases. This combustible mixture so formed was used in the same way as in a gas engine. He developed a small handy power unit manoeuvrable in the fields for agricultural work. For the design of the unit and its application he was awarded the silver medal of the Royal Agricultural Society.

Theoretical studies had clearly indicated the advantages of increased compression pressure in the engine cycle, but attempts in this direction did not meet with success due to erratic ignition conditions with normal carburised air (fuel-air mixture). He was the first to depart from the then existing practice of compressing carburised air, by trying high compression with pure air in the engine cylinder, and introducing a suitable mechanism for injecting fuel-oil into the cylinder at the end of compression. He did not however succeed in reaching the required compression pressures to cause self-ignition of the injected fuel-oil. Hence his work could be considered as an important step in the development of the compression-ignition engine.

ACHIEVEMENTS

Since the development so far, had not led to self-igniting operation in the oil engine cycle, all earlier types of non-spark-ignition engines required a starting flame and in many cases a cyclic flame contact for ignition. With the work of Steurt as the basis, Diesel improved on the mechanism of compression and fuel injection to achieve compression ignition conditions. Although credit for the compression- ignition engine goes to Diesel, the foundation work in this direction can be safely credited to Steurt whose name should indeed have been linked with the compression-ignition engine popularly known as Diesel engine to-day.

Diesel had the advantage of close association with manufacturing concerns, namely M.A.N. and Krupp, and this enabled him to develop different types of working models culminating in the development of air blast fuel injection system as distinct from solid fuel injection system.

PETROL ENGINES.

ACHIEVEMENTS.

His contribution to the development of internal-combustion engine is marked by two features:-

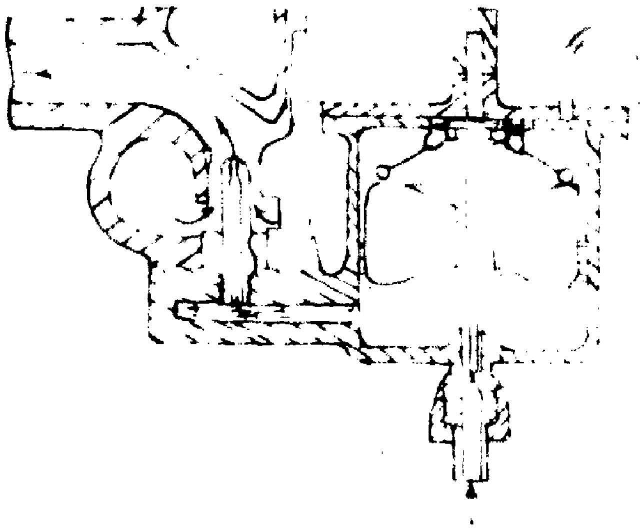
1) improved design of the device for producing fuel vapour-air mixture called the carburettor and

2) the design of high-speed motor which involved difficult balancing problems of reciprocating components; this led him to the adoption of Vee type twin-cylinder engine unit for the purpose. Attention to these two features has been responsible for satisfactory design of petrol engine. In fact, in the earlier motor cars and launches, petrol engines were largely of the Vee-twin-cylinder type developed by Daimler.

A contemporary of Daimler, who was responsible for commercial development of the manufacture of four-stroke petrol engine and for the application of induction coil system, of spark ignition as a substitute for magneto ignition.

Originator of the float type of carburettor on which practically all the designs of modern carburettors are based. (Fig. 1.5) (See next page)

Improved the design of the high speed motor first developed by Daimler and achieved from it working speeds upto 1500 rpm as against the earlier Daimler and Benz engine speeds of 600-700 rpm. This increased the horse-power per unit weight of the engine and made it more suitable for the motor car.



[illegible] carburettor

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SPECIFIC FEATURES AND FURTHER DEVELOPMENTS

Tables 1.1, 1.2 and 1.3 give a good historical sketch of the earlier developments which established the internal-combustion engine as an appliance for production of mechanical energy directly from fuels. Its increased application to different purposes led to the development of specific features which have been responsible for improving its reliability, operational efficiency and power weight ratio. These specific features make an interesting study and they are presented in this chapter.

2.1 CARBURATION

The success of the petrol engine has solely depended upon the development of the well-known device known as the carburettor. This device is intended to discharge into the air stream, the desired quantity of liquid fuel, atomize it, and, produce a homogeneous air-fuel mixture.

The idea of carburation dates back to the latter part of the nineteenth century. Siegfried Marcus (5), in 1864, is reported to have used a carburettor for a petrol engine developed by him which employed a revolving brush to spray the fuel into the air induction pipe. However, it was not till 1883, that the carburettor took a proper shape, Wilhelm Maybach (3) patented a float-feed carburettor which was similar to the modern carburettor based on the fuel jet spray principle. This carburettor which was then used on all Daimler engines, is shown in Fig. 1.5. Petrol was fed either by pressure or by gravity into a chamber containing a float. A tube leading from the chamber terminated into a jet located at a suitable point in the inlet pipe of the engine. Here, the air drawn in during the suction stroke got mixed with a fine spray of petrol coming out of the jet, resulting in a combustible gas. The float in the chamber controlled a needle valve regulating the admission of petrol from the tank, thus maintaining the level of petrol in the chamber at the correct height.

Petrol engines operating under variable speed and load conditions which obtain in aircraft propulsion and land transport call for the following requirements in the design of the carburettor:

1. Ease of starting, particularly at low ambient temperatures.
2. Ability to give full power quickly after starting the engine.
3. Smooth operation at varying loads and speeds with good fuel economy, and absence of racing at idling speeds.
4. High torque at low speeds giving good acceleration.

Since the operation of the petrol engine depends primarily on the quality and quantity of the fuel-air mixture delivered to its cylinders, the above requirements can be summed up in one statement: A good carburettor must automatically produce the desired air-fuel mixture over the whole range of speeds and loads.

For engines used in road transport or aircraft propulsion, it is necessary to obtain full range of power at any given speed of travel. There is, however, one economic speed in the rpm of the engine for each position of the throttle. The necessary condition for varying load requirements at a given speed of travel is satisfied by means of a suitable gearing and transmission system. Accelerating periods generally occur in the low speed range, -and here, it is necessary to develop power by larger opening of the throttle giving a richer mixture irrespective of economy. At normal running speeds of travel, economy in fuel is an important consideration, and, the air-fuel mixture has to be of a ratio conducive to this condition. The carburettor has therefore to meet the requirements of air-fuel ratio, a) for maximum economy at sustained speeds, and b) for maximum power during acceleration. Fig.2.1 presents values... established experimentally with carburettors of modern design... of air-fuel ratios in relation to load for the two specified conditions of operation, and also indicates limits of lean and rich mixtures for the respective conditions which should not be exceeded in normal practice.

From the above data, it is clear that the desired air-fuel mixture for maximum economy at sustained high speeds and loads ranging from 50 to 80 per cent of that normally met in operation is of the order of 16.5, and about 12 to 12.5 for developing 60 to 100 per cent during acceleration periods. The carburettor should be capable of manipulating these ranges of air-fuel ratios under the required conditions of operation.

A simple jet carburettor has the characteristic of increasing the richness of the charge (air-fuel mixture) with the increased opening of the throttle. As for developing the required power, larger throttle opening is necessary both at high speeds and during accelerating periods, this carburettor does not meet the varying requirements of air-fuel mixture for the two well defined conditions of operation. To achieve this, the following additional features have been incorporated in the carburettor now developed:

1. An auxiliary air valve that automatically admits additional air as the mixture flow increases (Fig.2.2)

2. A compensating jet that allows an increasing flow of air by discharging lean mixture into the inlet pipe. (Fig. 2.3) By properly proportioning the two jets, a mixture which may remain constant, either becoming leaner, or richer with increase in load, can be achieved.

3. A tapered metering pin (that reaches into the

fuel nozzle) which is lifted or lowered, thus changing the quantity of the fuel drawn into the air charge. (Fig. 2.4).

4. A combination of a variable air passage and a tapered metering pin, controlled by the air valve to give the desired mixture.

<u>Idling Jet</u>: The idling - and low-load jet discharges the air-fuel mixture at the edge of the throttle plate, Fig. 2.5. With the throttle closed, the manifold depression may rise to 200 inches of water, but the depression at the idling jet will be considerably smaller because of the admission of air through the idling adjustment and because of a certain airflow past the edge of the throttle plate. The desirable idling air-fuel ratio is obtained by adjusting the idling screw provided.

The manifold depression decreases as the throttle is opened until, at a wide-open throttle and low speed, the depression may drop to about 5 inches of water or less. As the depression decreases the amount of fuel delivered by the idling jet gradually decreases to practically zero.

<u>Acceleration:</u> With a partial throttle opening, the pressure in the intake manifold is appreciably reduced and the fuel is vaporized quite readily. At low speeds of travel, when the throttle is wide open to accelerate the engine, the heavier fractions of petrol will begin to condense and collect on the walls of the intake manifold, forming a fuel film. When the wall film is built up, the mixture returns to the desirable air-fuel ratio. With a sudden acceleration of the engine the mixture would become so lean that firing back in the carburettor or failure of the mixture to ignite would result, unless extra fuel is furnished for acceleration.

The following devices to provide this extra fuel may be used:

1. A damped air valve.
2. An accelerating well.
3. A displacement pump operated by the throttle.
4. A displacement pump operated by suction.

<u>Choking:</u> Petrol consists of a number of fractions of which the heavier ones are not easily vaporised when the engine is cold. Therefore a very rich air-fuel mixture which provides a larger quantity of the vaporiseable lighter fractions is required to start the engine from cold particularly in cold weather; this is induced by choking.

A choke is an additional butterfly valve located in the intake before the venturi to throttle the air supply and also simultaneously increase the depression in the venturi, both leading to an increased supply of fuel in the mixture. Choking should be limited to the minimum necessary to warm up the engine. If continued the unvaporised heavier fractions of gasoline will wash off the lubricating oil from the cylinder walls, and the contaminated lubricant will then run down to the crankcase, causing quick deterioration of the lubricating properties of the oil.

In modern high powered automobiles, a spring-loaded choking device is operated by a bimetallic thermostat of the vacuum piston type shown in Fig. 2.6. As soon as the engine starts, the manifold vacuum causes the vacuum piston 'p' to partially open the choke 'c'. Exhaust gases heat the thermostat, bimetallic spring and its casing, which then allow the choke to assume a wide-open position. Thus at starting, with the engine cold the choke comes into operation causing the necessary air throttling effect; with the engine warming up, the throttling effect vanishes completely.

<u>Aircraft-engine carburettors</u>: Aircraft engines operate at high altitudes. The relation between the atmospheric pressure 'p' (psia) and the altitude 'h' (feet) above the sea-level is expressed as

$$h = 122.86 \ T_m \log_{10} \left(\frac{14.7}{p} \right) \qquad (7)$$

where T_m is the absolute mean temperature between the sea-level and the altitude referred in degrees Rankine.

Also $t = t_s - 0.003566\ h$, small t's denoting ^{o}F units.
(7)

The density of air is directly proportional to its pressure and inversely proportional to its temperature. The effect of pressure on air density is, however, relatively greater than that of the temperature with the result, that the air becomes lighter (less dense) as the altitude increases.

Thus, in a naturally aspirated aircraft engine, there is a reduction in the amount of air drawn into the cylinder as the aircraft rises in altitude. Special provisions have therefore to be made to prevent the formation of rich air-fuel mixtures in the aircraft engine at high altitudes, leading to wastage of fuel.

The main consideration here is, to admit more air or less fuel to the induction system of the engine, in order to compensate for the altitude effect. The measures usually adopted are:

1. Provision of an auxiliary air valve or port for regulating air supply as shown in Fig. 2.7.

2. Provision for varying the position of the venturi relative to the jet for regulating fuel supply as in Fig. 2.8.

3. Provision of a fuel metering orifice with a needle valve for regulating fuel supply.

4. Provision of a by-pass valve between the air space of the float chamber and the venturi to reduce pressure

differential for flow of fuel through the jet and regulate thereby fuel supply as shown in Fig.2.9

The first three devices can be controlled manually if required. Normally all the four devices are set and adjusted for automatic compensation according to altitude requirements of flight.

<u>Ice formation:</u> The evaporation of the fuel in the venturi and intake manifold, is effected by heat taken from the incoming air and containing walls of the passages. As a result, air is cooled below the dew point and the water vapour in the air freezes on the throttle plate, choking the air flow through the carburettor which, often proves disastrous.

Tests have shown that this phenomenon of ice formation is pronounced when the temperature in the venturi falls by about 9° F below the dew point with the atmospheric temperature at about 32°F, and also with rich mixtures and highly volatile fuels.

A remedy for this trouble has been found in the preheating of the air or the introduction of alcohol into the system which absorbs the water vapour and lowers the freezing point of the alcohol-water vapour thereby inhibiting the tendency for ice formation on the throttle plate.

<u>Petrol injection:</u> Fuel injection system which has attained perfection in the case of Diesel engine has been

adapted to petrol engine with some modification to overcome the disadvantage of the carburettor of which, the most serious ones are ice formation on the throttle plate, and float chamber troubles arising from aircraft manoeuvres. In the injection system applied to the aircraft, petrol is injected in a finely atomized state either into the intake manifold or directly into the cylinder. The real advantage gained lies in the facility of control of the air-fuel ratio to suit a wide range of operational and performance requirements. It is because the fuel injection system is a device of high precision and loses its reliability if not satisfactorily maintained that it has not come into extensive application.

REFERENCES*: 3, 4, 7 - 10.

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* For these and subsequent citations see References at the end.

2.2 FUEL INJECTION (COMPRESSION-IGNITION ENGINES)

In a Diesel engine, the fuel injection system is of paramount importance, as the operation and performance of the power unit is primarily controlled by it. This equipment requires a high standard of design and manufacturing technique to ensure satisfactory functioning over long periods of service. Its adjustment and testing also call for considerable care and skill. (11)

Atomization and Penetration: Atomization is the breaking up of material (solid or liquid) to a high degree of fineness and the dispersion of the fine particles into air or gaseous medium; in other words, it is the production of a fine mist in the air medium, resulting in a combustible gas of homogeneous composition.

In the case of compression-ignition engine, the problem is to achieve perfect atomization of the liquid fuel injected into engine cylinders, so that, complete combustion is effected during the combustion phase of the cycle, the period of which is nearly 1/10 to 1/5 of the working stroke. If the stream of injected fuel oil consists of fine particles they do not gain sufficient momentum due to air resistance at the instant of injection, to quickly disperse into the combustion space over the piston head. On the other hand, if it consists of large droplets, a bullet flow is produced due to high penetration momentum, but this hinders the dispersion of the fuel particles necessary for intimate mixing of fuel with oxygen. In both cases, there are delayed ignition and

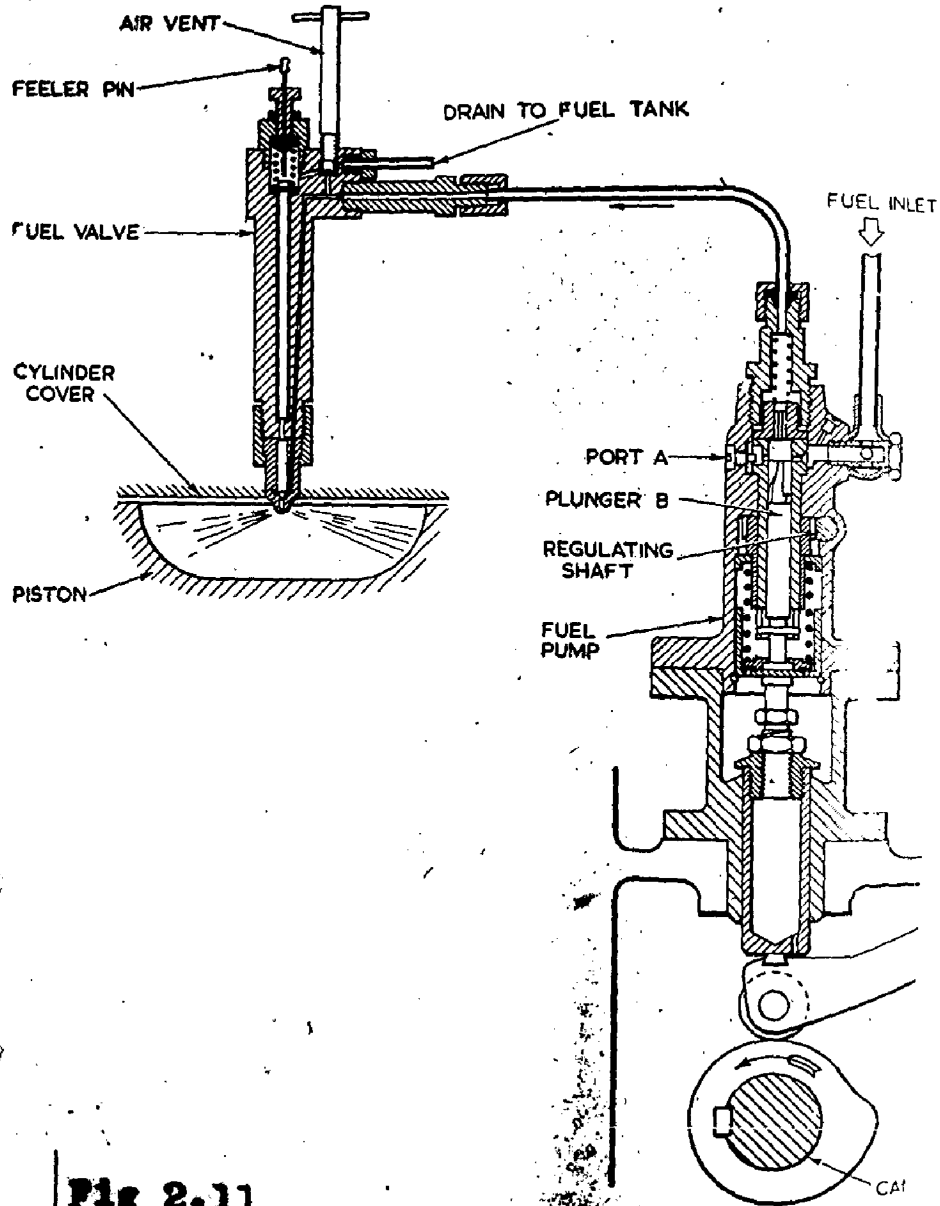

Fig 2.11 —Typical Fuel-injection Arrangement.

detonation troubles. Thus, there is an optimum magnitude of the fuel particle penetration momentum relative to the resistance offered by air. Dispersion or intermixing of the fuel with air is the maximum achievable for this optimum in practice, within the momentary period of combustion phase.

Fig. 2.10 shows, diagrammatically, the essential components of a fuel injection system for a multi-cylinder engine. The diagram is self-explanatory. In a multi-cylinder engine, the fuel pump contains as many plungers as there are engine cylinders, i.e., each plunger element delivers fuel to the injector, or pair of injectors, on the cylinder to which it is connected.

Fig. 2.11 shows a typical sectional arrangement of fuel pump and injector. The pump plunger 'B' is thrust upward, on its delivery stroke, by a tappet arrangement which is operated by the engine camshaft. As the plunger 'B' moves through its stroke the port 'A' is closed; thereafter the fuel line, ~~as far as~~ the fuel injector, is under compression. Continued movement of the plunger increases the pressure in the system until a point is reached where the nozzle valve lifts and injection begins. The pressure in the system, throughout the injection period, is determined by the cross-sectional area and speed of movement of the fuel pump plunger and the aggregate cross-sectional area of the holes in the nozzle.

To regulate the amount of fuel delivered to the engine cylinder, it is necessary to vary the effective stroke of the pump plunger. Over the years, various arrangements have been tried but the simplest arrangement is that in which the plunger stroke is constant and fixed, and variation of effective stroke is obtained by a spill port cut in the plunger. This is done by the engine governor through a medium of regulating rod, rack and pinion.

When the upward injection stroke is completed, the cam recedes, port 'A' is uncovered, and the pump plunger is returned downward to the end of its suction stroke by an internal spring, and the cycle starts again.

When the pump plunger moves upward, compression of the fuel in the line begins, and a pressure wave is propogated throughout the fuel column as far as the fuel valve. The speed of propogation is approximately that of sound in the contained fluid.

The pressure wave travels along the fuel pipe until it reaches the nozzle, where it may or may not be reflected; i.e., the fuel valve may or may not open. The effect of the impulse will depend upon the relation between the fuel-valve spring pressure and the magnitude of the impulse. If resonant waves are set up in the pipe-line, the fuel valve may be lifted more than once.

Actuation of the plunger by a mechanical "punch" is the most satisfactory method for generating the pressure wave by which the charge of the fuel is carried. Without the pressure wave the system is purely hydraulic, and the fuel consumption can be appreciably affected. The speed of the fuel discharge through the atomizer holes may be 850 to 1,000 fps. The fuel valve is set to open at, approximately, one-half of the injection pressure.

The size and cost of the air compressor, along with the power required for operation (about 10 per cent of that of the engine) has made air-injection system obsolete. The basic systems of fuel-injection in common use are i)common rail system, ii) jerk pump system, and iii) Gas compression system.

<u>Conclusion:</u> The problem for the future would be to design the fuel-injection system to handle low grade oils. This would call for considerable fuel spray research and experimentation.

REFERENCES; 7, 9, 11 & 12.

2.3 COMBUSTION CHAMBERS.

TABLE 2.1 - COMBUSTION CHAMBERS

TYPE OF COMBUSTION CHAMBER.	YEAR.	FIG. NO.
Flat type used in side-valve engines.	1914	*2.12
Turbulent head used in side-valve engines.	1919	2.13
Bath tub type used in overhead valve engines.		2.14

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* For figures see next two pages.

(FOR SPARK-IGNITION ENGINES)

FEATURES

Advantageous from manufacturing and maintenace point of view. However, excessively prone to detonation, and extremely sensitive to ignition timing, because, it did not produce the required turbulence. This disadvantage made it inferior to the type of combustion chamber developed for overhead valve engines with the necessary turbulence effect.

The above defect was overcome by bringing (1) that portion of the head which lay over the farther side of the piston into as close a contact as possible with the piston crown, thus reducing the effective length of flame path and, 2) by positioning the main body of the combustion chamber over the valves, leaving a slightly restricted passage-way communicating with the cylinder, thus creating additional turbulence and speeding up the second stage of combustion.

Simple and mechanically convenient compromise with good all-round performance; other advantages are:

1) high volumetric efficiency because of large inlet valve or valves,

2) short flame path, and

3) additional turbulence (squish) provided by the flanks of the oval which overhang the cylinder bore.

REFERENCES: 7, 9, & 13.

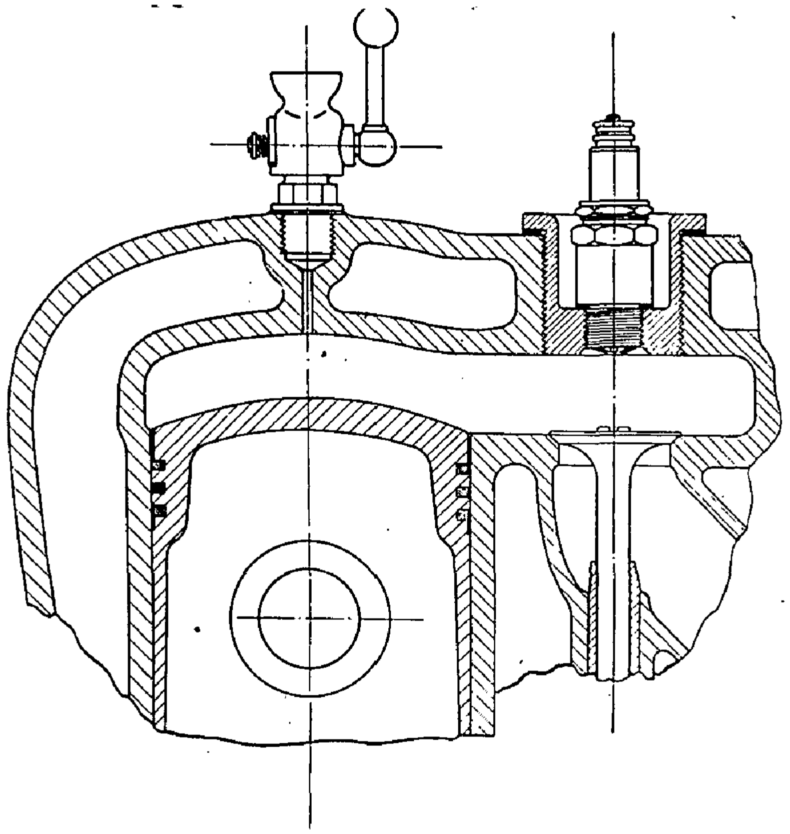


Fig 2·12.—Typical side-valve combustion chamber (1914)

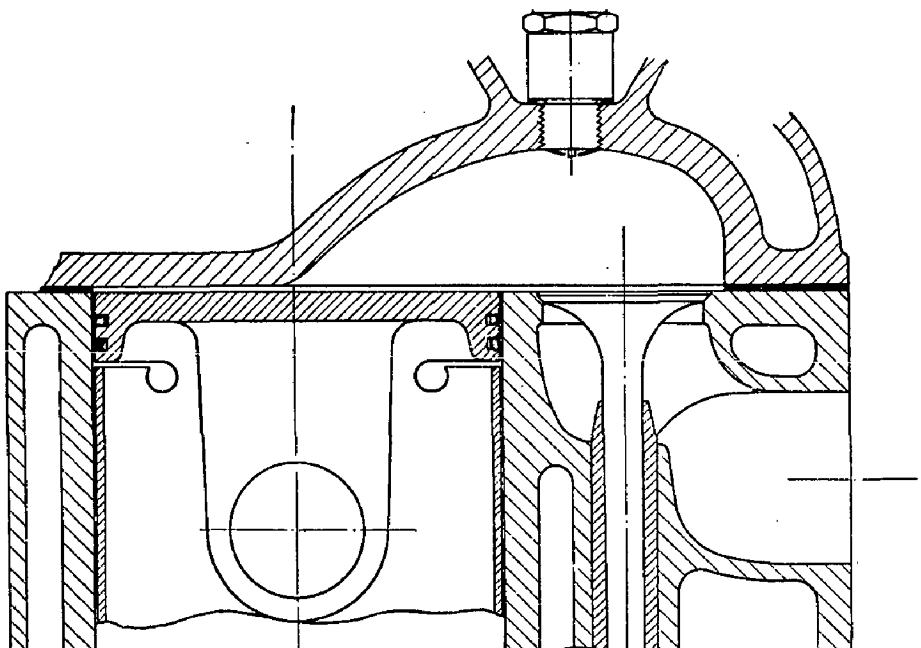


Fig 2·13—Typical turbulent-head design (1919)

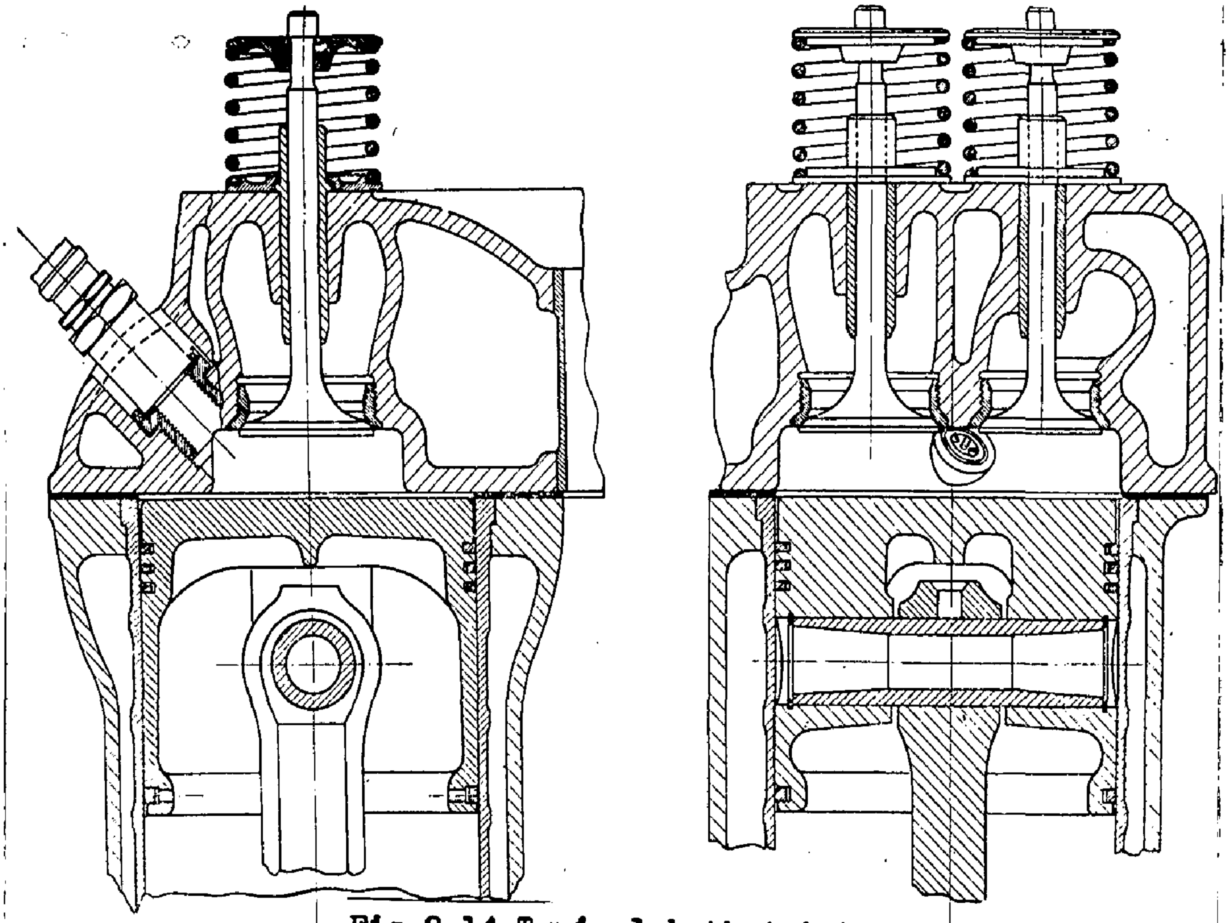


Fig 2.14 Typical bath-tub head

(FOR COMPRESSION-IGNITION ENGINES)

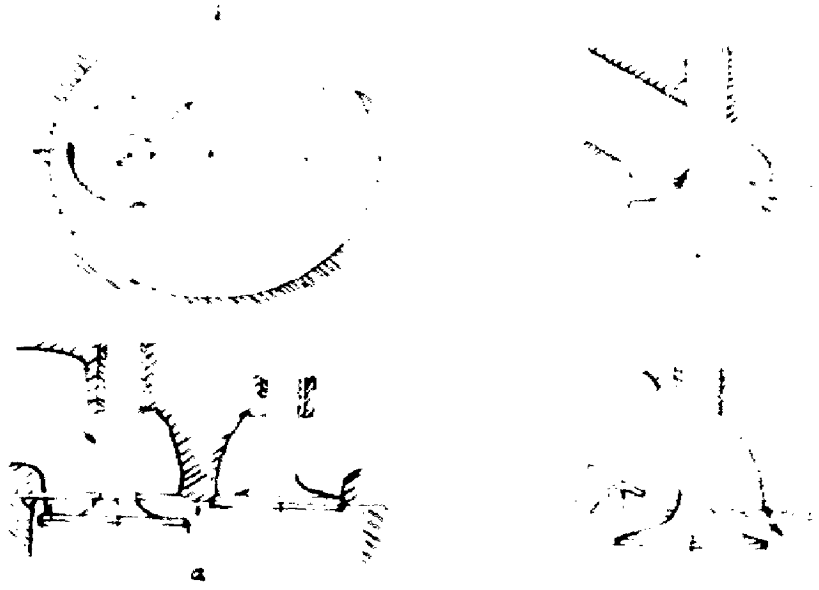
FEATURES

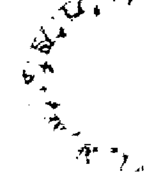
As shown in the figures, suction swirl (cyclonic effect of air admitted into the cylinder) is obtained as a) by masking one side of the inlet valve so that air is admitted in a desired direction around a part of the periphery of the valve, b) by sloping the sides of the inlet port in the desired direction, and c) by casting a lip over one side of the inlet valve. The masking of the inlet valve is the more common method, as it permits the finding of the best tangential direction by turning the valve about its centre line.

A tangential arrangement of the scavenge ports creates a strong air swirl in the exhaust gases and this swirl is transmitted to the fresh air sucked in simultaneously.

An ante chamber communicates with the cylinder space through an orifice tangentially disposed to the cylinder. During compression stroke air enters the ante chamber with a cyclonic flow which continues after compression is completed; and this cyclonic flow is completely disturbed by injection of fuel, producing the required turbulence and instantaneous combustion. Figure shows the different variations. a) A compact ante chamber suitable for high speeds and high outputs. b) Comet double swirl combustion chamber. c) Same as (a) but with large passage to ante chamber which gets throttled as the piston approaches the end of the stroke thereby intensifying the swirl effect which sustains during the fuel injection period resulting in vigorous turbulence and instantaneous combustion.

The thinning of the clearances of the circumference of the cavity, with the piston approaching the dead-centre, causes a violent radial flow of air as it is being squeezed and induces greater turbulence in the air mass contained in the cavity. This squish effect has the advantage of being well tuned with the injection of fuel to produce instantaneous or explosive combustion.





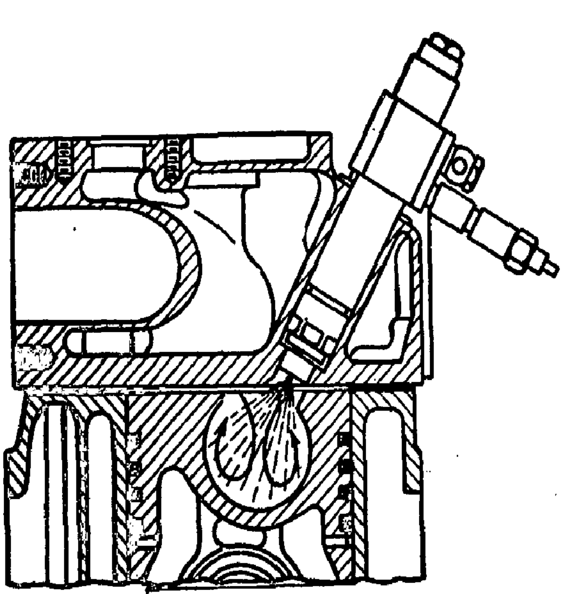


Fig 2·17(a)

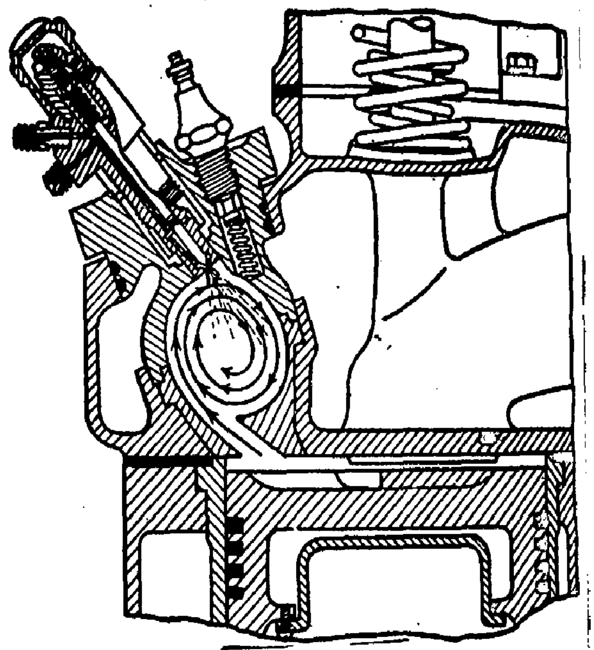
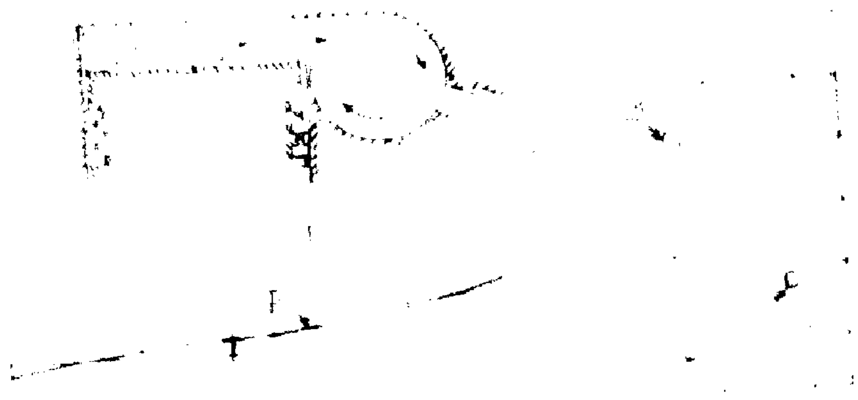


Fig . ·7 b

Fig 2·17(a) **MAN antechamber engine with very high turbulence.**

Fig 2·17(b) **Waukesha Comet Diesel engine with** highly turbulent antechamber and **depressions in piston head.** Clearance volume in cylinder equals swirl-chamber volume. [*J. B. Fisher, Development of a Combustion Chamber for Medium and High-speed Diesel Engines, SAE Jour.*, **57**, 59 (*May*, 1949).]



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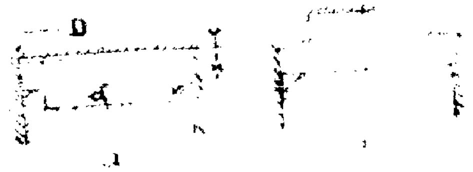

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FEATURES.

The pre-combustion chamber is a small air pocket on a side of the cylinder communicating with the main cylinder space through a narrow orifice. With the compression of the air charge, air fills this pocket at the compression pressure attained in the main cylinder, and, with fuel injection into this pocket, partial combustion first takes place in the air pocket. This causes an instantaneous blow of the partially burnt gas into the main combustion chamber where, with the turbulence produced by the blow, instantaneous combustion occurs.

The Lanova combustion chamber has two air chambers. Fuel is injected across the main chamber, some entering and igniting in the first auxiliary chamber. This raises the pressure in the auxiliary chambers, and the burning mixture is discharged into the main chamber which is designed to produce a double swirl. The use of two auxiliary chambers and a starting valve that can shut off the main air chamber makes possible a higher compression ratio for easy starting.

Air-cell combustion chambers are designed to produce smooth combustion processes with low maximum pressures. The result is some loss of efficiency, since the smoothness is usually accomplished by having more than the optimum amount of combustion during the expansion stroke of the engine.

REFERENCES: 7, 9, 12-14.

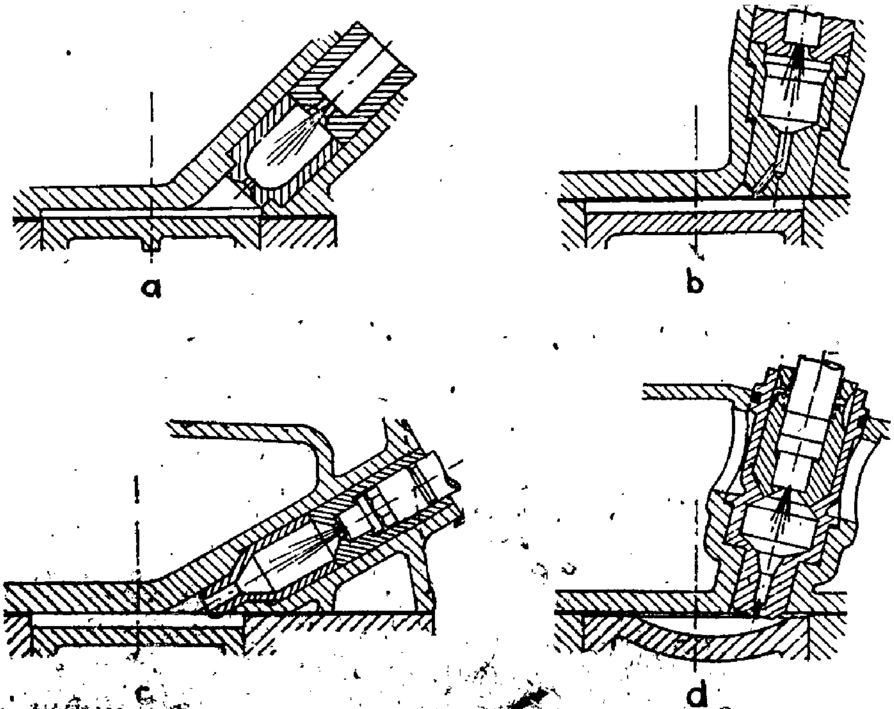


Fig. 2·19 Precombustion chambers of American engines.

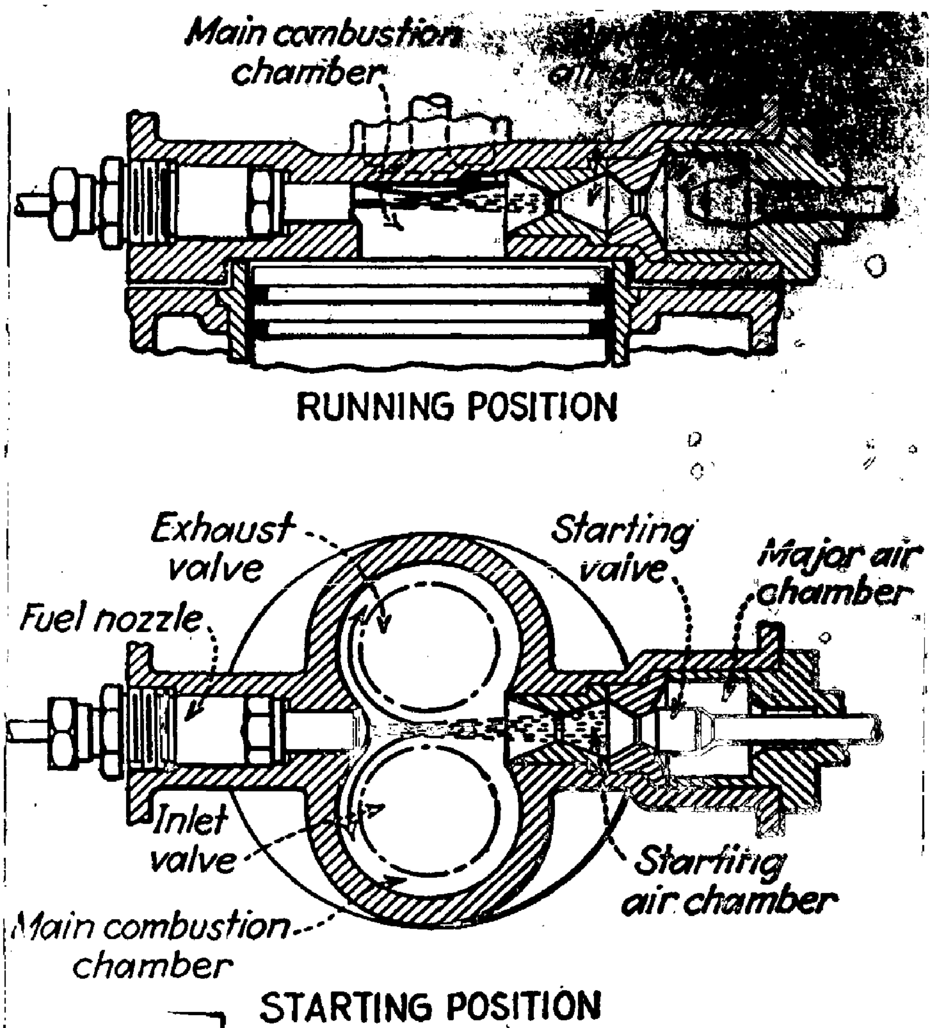


Fig. 2·20 Lanova air-cell combustion chamber.

2.4 SCAVENGING (TWO- STROKE ENGINES)

The process of emptying the cylinder of an internal - combustion engine of its exhaust gases is generally referred to as "Scavenging". This applies specially to a two-stroke engine where exhausting of ~~gases occurs~~ over a very short period of the cycle and is closely followed by the filling of the cylinder with the air or gas charge. As proper scavenging is a difficult proposition with a two-stroke engine, it needs thorough examination.

The scavenging of the exhaust would be completely effected in a four-stroke engine qith separate exhaust and suction strokes. With a two-stroke engine, however, both exhaust and inlet occur towards the end of the stroke, and, for a period the exhaust and inlet valves remain simultaneously open. In a naturally aspirated two-stroke engine, exhaust release is sufficiently advanced so as to cause a blow of the burnt gases through the exhaust valves instantaneously producing slight vacuum in the cylinder when the inlet valve opens, and freely admits air or gas. In a super charged two-stroke engine the exhaust can be made to occur very nearly at the n end of the stroke and the burnt gases are actually blown out by the air entering the cylinder. Here, the burden of scavenging rests on the inlet charge.

From the above, it is clear that in a two-stroke petrol engine some of the combustible mixture which serves as a scavenging medium will naturally escape through the exhaust ports along with the burnt gases, increasing thereby the specific fuel consumption of the engine. This is a positive disadvantage in the case of large size power units. The position is, however, different in the case of two-stroke Diesel engine, as air escapes with the burnt gases through the exhaust ports, and this is of no material disadvantage. It is for this reason that the two-stroke cycle has been more extensively used in large size Diesel engines than in petrol engines.

Proper combustion and in turn the power output of a two-stroke engine would in no small measure be governed by the effectiveness of scavenging, i.e., upon the purity of the air-fuel mixture or air inside the cylinder, before the commencement of the compression stroke. Thus a major problem in the design of a two-stroke engine is to ensure complete scavenging by adopting simple means, with little or no fuel loss.

So far three systems of scavenging have been developed and commonly applied to two-stroke engines viz.,

a) Cross- scavenging

b) Loop scavenging

c) Uniflow scavenging.

Table 2.3 gives a brief description of these types of scavenging.

TABLE 2.3 - SCAVENGING SYSTEMS OF TWO-STROKE ENGINES.

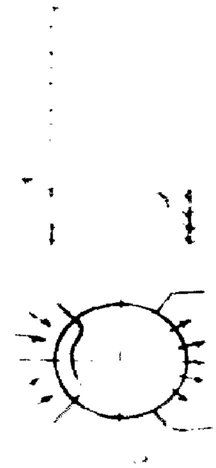
OF TWO-STROKE ENGINES

DESCRIPTION

Probably, the most common, particularly in petrol engines. There is usually a deflector-head type of piston, which helps to avoid short-circuiting by directing the air flow upwards; cross-scavenging is found to be very effective and results in a lower mep. But its simplicity and low cost are often useful factors in the design of low capacity power units.

Provides a longer path for the scavenge charge, and various designs have been successfully developed. A scavenge efficiency of 90 per cent is now claimed. The arrangements described in the above figures are indicative of a simple cylinder construction with a cylinder head of a suitable shape to sustain high thermal stresses without damage. Further, mep's of 80 to 85 psi have been achieved in engine cylinders using the system since 1943.

In this arrangement, the exhaust gases and the inlet charge flow in the same direction thus minimising the mixing (turbulence) of the inlet charge with exhaust gases. The figures shown describe three systems of uniflow scavenging. Because of a larger cross-sectional area for flow, both admission and exhaust are free ensuring good breathing characteristics. Further, the loss of fuel in the case of petrol engines is well avoided in the uniflow system. However, this system necessitates the provision of independent valves in a two-stroke engine complicating thereby the design with repercussion on costs. The consequential increase of the specific output of the engine offsets the above disadvantage.



Fi . .21 Cross scavengin .

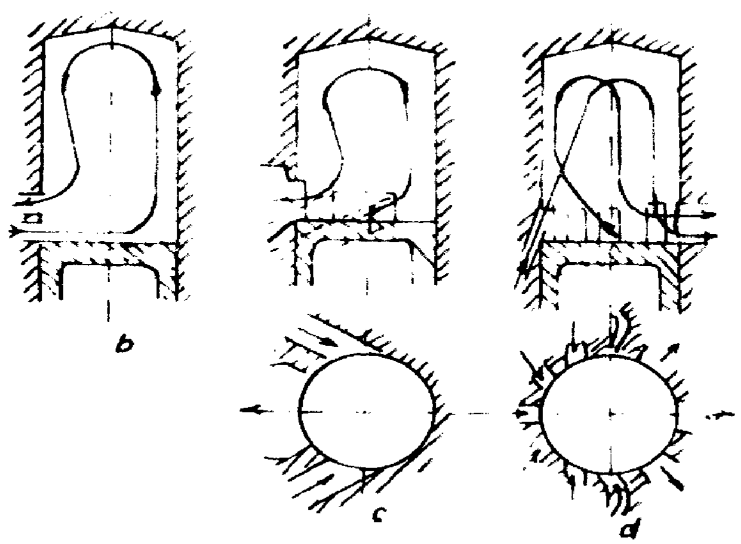
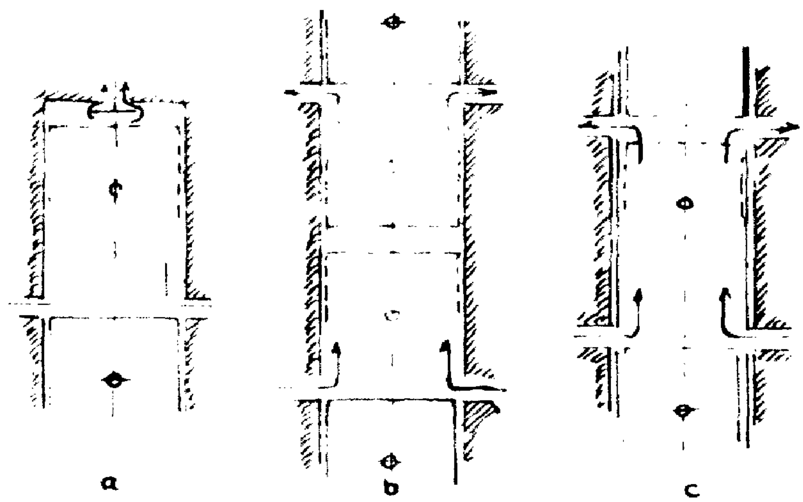


Fig.2.2 Schemes of lo p scaven ing.



. .3 Schemes of uniflow sc v nging

develop inside the engine cylinder while the exhaust gases are still in motion in the escape from cylinder space; and the occupancy of the cylinder space with a fresh charge is complete before the escape motion of the exhaust gases reduces to zero, producing a return wave to destroy the depression. This is exactly what seems to be understood by proper timing between the instant of depression in the cylinder and admission of charge.

Design developments on the basis of this conception would call for a) good deal of experimentation to study the pressure characteristics inside the cylinder during the exhaust and admission phases under varying conditions of loads and speeds, and proportions of admission and exhaust passages, and b) detailed analysis of prescure wave phenomena connected with gas flow conditions obtaining in the internal-combustion engine. This is a fruitful field for research in future.

REFERENCES : 7, 11 & 13.

<u>Kadenacy Scavenging:</u> The name of Kadenacy (11) has been identified with some original work on two-stroke engine scavenging. As stated by Professor S.J. Davies, Kadenacy claims: "Immediately on opening rapidly the exhaust ports of an engine during the expansion stroke, there is within the first interval of time of a few thousands of a second, an urge or impulse in the gases within the cylinder, to escape very rapidly from the cylinder leaving behind them a <u>depression.</u> By suitable timing of the admission valve or port the new charge is arranged to enter the cylinder behind the retreating gas. These actions are found to occur with suitable port design and timing; no scavenging pumps, inlet pipes or exhaust pipes are necessary to enable such an engine to run and deliver power."

His further claim in support of his observation of the scavenging operation is, that the burnt gases were discharged from the cylinder "as a mass, in an interval of time shorter than that required for the burnt gases to expand down to the ambient pressure by adiabatic flow."

It would appear from the above statements that the exhaust from the internal-cumbstion engine cylinder has an explosive character which enables vacuum conditions to arise for extremely short duration in the first blast to atmosphere. This does suggest that the right time for admission of air or air-fuel mixture is when the depression (vacuum) begins to develop inside the engine cylinder while the exhaust gases are still in motion in the escape from cylinder space; and the occupancy of the cylinder space with a fresh charge is complete before the escape motion of the exhaust gases reduces to zero, producing a return wave to destroy the depression. This is exactly what seems to be understood by proper timing between the instant of depression in the cylinder and admission of charge.

Design developments on the basis of this conception would call for a) good deal of experimentation to study the pressure characteristics inside the cylinder during the exhaust and admission phases under varying conditions of loads and speeds, and proportions of admission and exhaust passages, and b) detailed analysis of pressure wave phenomena connected with gas flow conditions obtaining in the internal-combustion engine. This is a fruitful field for research in future.

REFERENCES : 7, 11 & 13.

2.5 SUPERCHARGING

The heat of charge per stroke in the cylinder of an engine is given by

$$H = n_v \cdot \frac{\pi}{4} D^2 \cdot L \cdot \frac{1}{V_a} \cdot \frac{1}{A_f} \cdot C$$

where H is the heat of charge,
n_v is the volumetric efficiency,
D is the diameter of the cylinder ,
L is the length of the cylinder,
V_a is the specific volume of air,
A_f is the air-fuel ratio,
and C is the calorific value of the fuel.

Therefore for an engine of given proportions, a given quality of fuel and any specified air-fuel mixture, the above equation may be rewritten as

$$H = K \left(\frac{n_v}{V_a}\right) \text{ where } K \text{ is a constant.}$$

As the power output of an engine depends upon the heat of charge, increasing the value of n_v / V_a will increase the IHP developed. This is obtained by feeding the cylinder with air of greater density (higher pressure) which improves its volumetric efficiency nv and reduces the specific volume V_a. The process involved in this, is rightfully known as "supercharging", in contrast to natural aspiration which latter is the normal case when an air is drawn in directly from the atmosphere during a suction stroke of the engine. Supercharging is also known as "boosting" because of its boosting effect on the power developed.

The idea of supercharging dates back to 1895 (15) when it was first applied to gas engines, but its attractiveness was lost due to inherent difficulties then presented. About the middle of the first world war (1916), however, the aero-engine forced its application on account of the need of maintaining power at high altitudes, and due to war emergency intensive efforts could be directed to develop the necessary devices for supercharging irrespective of cost. With this achievement, progress towards commercial application of the device became possible and during the last forty years superchargers have been increasingly applied to land and marine power units.

Briefly speaking, supercharging has been applied to internal combustion engines to achieve the following advantages:

1. At high altitudes the air is rarefied. This has adverse effect on the power out-put of an air-craft engine or in stationary engine installed in a mountainous region. Supercharging overcomes this effect.

2. To reduce the bulk and weight of the engine per horsepower developed by supplying ample quantity of air per engine stroke and maintaining the required air supply at high engine speeds.

Evidently the two advantages of supercharging were applicable not only to the new designs but also to the older engines in order to increase their power rating upto a limit beyond which operation troubles would arise.

Supercharging has enabled successful development of high-speed engines reducing the specific weight of the engine from 2.5 lb. per bhp in 1916 to 1 lb. per bhp to-day, in the aircraft field.

Although the power output tends to increase with a greater quantity of air inhaled per cycle, the following points need consideration when supercharging is applied to spark-ignition engines. (13)

1. The increased density of air and its consequential increased temperature (the latter depending upon the degree of intercooling) tend to speed up the combustion process by reducing the delay period and accelerating the rate of speed of the flame. The effect is similar to that produced by another factor known as turbulence. Since, in most modern high-duty petrol engines, the degree of turbulence is already adequate for efficient combustion, supercharging would overdo the turbulence effect, rendering the engine more sensitive to air-fuel mixture, thereby limiting the range of the mixture ratio over which the engine may produce power at a high efficiency. For best results, the degree of turbulence in a supercharged engine should be lower than in aim a naturally aspirated engines.

2. The further effect of increased density and temperature resulting by supercharging is, the tendency for detonation and pre-ignition which restricts the degree of supercharge for satisfactory operation of a petrol engine.

Here, fuel characteristics play an important part as ignition of some fuels is more sensitive to temperature and others more sensitive to pressure; even the fuel rated for the same octane number would seem to respond differently to a given degree of supercharge.

3. It has been experimentally established that if the heat of charge is doubled by increasing the supercharged intake of air to approximately two atmospheres, the losses to the cooling medium is increased only by about 70 per cent. Although reduced cooling losses have an advantage in that the thermal efficiency is increased, the components within and near the combustion space tend to become over-heated affecting reliability of operation and maintenance, and increasing the tendency of detonation. The thermal efficiency is also improved by virtue of rigorous turbulence resulting from increase of high pressure air with supercharging in engines where combustion chambers are specially designed for this purpose, and fuel is properly treated to inhibit the tendency for detonation. For the above reasons, the degree of supercharging is limited; the increase in the power rating with satisfactory cooling system does not exceed 40 to 50 per cent. It may be pointed out that an intercooling system either in the form of a heat exchanger or water-injection has been added to the normal cooling system to satisfactorily control temperature conditions inside the engine cylinders and inhibit the tendency for detonation so as to achieve such

hi h power ratings. Normally supercharging is provided for increasing the power rating upto 20 per cent.

4. Supercharging, effects an improvement in scavenging of exhaust, as air admission pressure is sufficiently high to drive out the residual exhaust gases from the engine cylinders.

5. The addition of a supercharger to the system, increases the frictional losses, but, due to considerable increase in power, the overall mechanical efficiency of the engine shows improvement.

So far as spark-ignition engines are concerned, supercharging has been applied to large capacity aircraft engines, and the centrifugal or axial flow type of supercharger has been found to give satisfactory service in these engines.

In the case of compression-ignition (C.I.) engines, the conditions for detonation and pre-ignition become less pronounced with supercharging. Experiments indicate that, greater the density of air, shorter is the delay period and in consequence smoother and more complete is the combustion. This is in contrast to the conditions obtained in spark-ignition engines.

Another advantage is that with the increase in the presence of the intake air, propensity of the fuel to diesel knock (cetane number) is reduced due to suppression of volatility. This enables fuels of a wider range of cetane numbers being used in a supercharged engine. This advantage is of a maximum degree when the supercharged pressure is steadily maintained over the full range of operation relating to loads and speeds.

With a supercharged spark-ignition engine, it may become necessary to reduce the compression ratio in order that maximum pressures developed as a result of combustion, practically at constant volume, may not exceed the design limits. This condition hardly applies to a supercharged C.I. Engine, as combustion takes place practically at constant pressure during a part of the working stroke and the maximum pressure developed show less variation with increased pressure of the intake air. This enables higher degree of supercharging being applied to C.I. engine with the resulting advantage of higher power rating and therefore a higher mechanical efficiency as compared to a supercharged spark-ignition engine, in spite of the higher frictional losses of the heavier C.I. engine mechanism.

However, design considerations have imposed a limit on supercharging which is determined by the maximum cylinder pressure of about 1200 psi achievable with the intake air pressure of about 30 psi (2 atmospheres) and a compression ratio of the order of 15:1, giving a final compression pressure of about 450 psi. Against this, a naturally aspirated engine can be designed for a compression ratio of 19:1 with the final compression pressure attaining a value of only about 280 psi.

These design limitations are intended to avoid: (1) excessive scuffing of the piston and heavy liner wear, (2) Overloading of the bearings, and, (3) leakage of the cylinder joints, due to springing of the cylinder-head bolts. With these limitations, increase in power rating of about 40 to 50 per cent is obtained in a supercharged C.I. Engine with a more efficient cooling system than is necessary for a supercharged spark-ignition petrol engine, where the maximum permissible increase in rating is about 10 to 15 per cent.

Conclusion: From the above observations relating to the application of supercharging to spark-and C.I. engines (petrol and Diesel), it would be clear that the main purpose of supercharging in petrol engines would be to avoid loss of power due to intake of rarefied air at high altitudes... a very important consideration for an aircraft engine... whereas, in the case of C.I. engines, the main purpose of supercharging would be to enhance the rating of the power unit, thereby, reducing its specific weight.

There are special cases of spark-ignition engines being supercharged for increased power output, but in such cases fuels of octane number (performance number) higher than 100 can alone be satisfactorily used apart from the need for a more effective cooling arrangement.

REFERENCES: 7, 13, & 15.

(See next page for results obtained from supercharging)

2.6 LUBRICATION

It is worth noting that certain advantages of lubrication have been known from the very early times when animal and vegetable oils were freely used to eliminate squeaking sounds produced by surfaces in rubbing contact. Although ideas about friction as we know them to-day, were little understood then, there was sufficient experience with the use of oily liquids to minimise wear and heating on surfaces vigorously rubbing against each other. In modern terminology, oils used for such purposes are called'lubricants.(As said already, early lubricants were animal and vegetable oils and cakes which were readily available and were able to meet the lubrication requirements of primitive machinery. The modern mechanisms and power units cover a wide range of bearing pressures and speeds, environmental and temperature conditions, and demand highly refined lubricants of great adaptability to meet these conditions. Mineral oils have come into the field and often these are specially processed and blended with organic compounds to fulfil the needs of a wide variety of industrial equipment.

It can be well said that it is the development of the science of lubrication comprising advanced knowledge in the field of physics, chemistry and fluid dynamics, and the scientific exploitation of the mineral and organic resources of oils that have contributed materially to the advancement of the internal-combustion-engine and to the versatility of its application. It would be worthwhile to deal briefly with the fundamentals of lubrication before approaching the problem of the lubrication of internal-combustion engines.

Lubricating oils have attained a special significance, the full appreciation of which is obtained through the description of a number of properties which oil possesses and how these properties could be combined to select the lubricant for a particular use. The important properties which an engineer carefully examines in deciding on a lubricant are as follows:-

Chemical properties :

1. Acidity (indicative of corrosion).
2. Oxidation (indicative of sludge formation).
3. Saponification number (indicative of free acid).
4. Carbon residue (indicative of the relative carbon deposit that my form in an engine).

Physical properties :

1. Cloud and pour points (indicative of the temperature limits under which oil will function as a lubricant).
2. Colour tests (indicative of the commercial grades of oils).
3. Flash and fire points (indicative of the tendency for vaporisation).

4. Emulsification.
5. Viscosity.
6. Sediment (indicative of the cleanliness of a lubricant).

Viscosity: The viscosity of a lubricating oil must be given careful consideration in the selection of the proper oil for any internal-combustion engine. One of the primary requirements of a satisfactory lubricating oil is a suitable viscosity-temperature characteristic. The greater the temperature range through which the oil must operate the less should be the relative change in the viscosity of the oil. If the viscosity of the oil is extremely high when the oil temperature is low upon starting the engine, oil flow will be restricted and lubrication will be poor. After the engine and oil have warmed up, the viscosity of the oil must be sufficient to maintain a film thickness that will prevent metal-to-metal contact and resulting excessive wear. While a high-viscosity oil will result in a lower oil consumption, nevertheless considerable power loss results from the increased friction caused by the higher viscosity. In view of the conditions and limitations imposed by the oil viscosity, it is always desirable to use the lowest viscosity oil that will maintain sufficient oil film to prevent metal-to-metal contact at the engine operating temperatures.

Oxidation: Where lubricating oil is used over and over as it is in an internal-combustion engine, it should be relatively free from oxidation difficulties. Admittedly, lubricating oils subjected to the heat of combustion in the cylinder will burn. The major portion of the lubricating oil, however, is not subjected to this intense heat and should not oxidize appreciably at the temperatures encountered in the engine crankcase and in the piston when used for piston cooling.

Dilution by fuel oil: This changes the viscosity characteristics and usually results in undue wear if dilution is considerable.

The amount of dilution primarily depends on the oil temperature, being high when the oil temperature is low, and vice versa. Thus, the dilution tends to reach a maximum under starting and idling conditions and a minimum, under operating conditions. In some cases, it is desirable to predilute the lubricant so that, when oil is changed, the engine does not have to deal with an oil more viscous than that which will exist after a few cold starts.

Charts, based on the viscosity of new and used oil, have been developed to indicate the per cent fuel dilution and the per cent increase in viscosity resulting from too cold and too hot conditions, respectively.

Carbon residue: The carbon formed from the lubricating oil appears to be independent of the oil consumption. It has been found that the volatility characteristics are a better guide as to carbon residue than the conradson carbon-residue test. Thus, if the distillation curve for the heavier ends runs high, the carbon deposition will be high.

Addition Agents: Since lubricating oils are used for widely varying types of service in our industrial world to-day, it is only natural that for certain service conditions it has been found necessary to add various compounds to mineral lubricating oils in order that the lubricant will meet the special requirements desired. These "additives" are generally put into lubricating oils to act as pour point depressants, oiliness carriers and extreme pressure materials, viscosity-index improvers, oxidation inhibitors, and colour improvers.

Oil Reconditioning: Oil circulated in an internal-combustion engine does not wear out or break down but becomes unfit for further use through contamination by solid particles and water, through dilution by liquid fuels and oxidation.

One of the simplest and best methods of reconditioning engine lubricating oil is by means of centrifuges. In larger engines the oil is circulated through the centrifuge all the time; in smaller engines batch purification may be used. Proper purification of lubricating oil not only reduces the oil consumption very materially but also increases the life of the engine through decreased wear.

Oil Cooling: Low-output engines usually have sufficient crankcase surface from which heat can be transferred to the surrounding air to prevent the oil from rising to an undesirable temperature. High-output engines have a comparatively small crankcase area, and in such engines the oil temperature may continue to rise and reduce the viscosity until the connecting-rod bearings are destroyed. Therefore, for preventing the oil-temperature from rising sufficiently to reduce the viscosity to the danger point oil coolers are employed which are constructed of radiator sections using air or water for the cooling medium.

<u>Selection of lubricating Oils:</u> A table for selecting a lubricating oil for a specified service is given in Appendix

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REFERENCES: 7, 9, 11, 16 - 19.

INTERNAL- COMBUSTION ENGINE APPLICATIONS

It cannot be denied that the internal-combustion engine has acquired a singular position in the range of its applications amongst the different forms of power units. The important ones relate to road and rail traction, aircraft and marine propulsion and power generation. These are briefly discussed in this chapter.

3.1 ROAD TRANSPORT

Automobile engineering has had the largest share in the development of spark-ignition internal-combustion engines and ingenious mechanisms for steering, power transmission and sensitiveness of response to traction conditions, etc. A chronological review of the development of the automobile is presented in Table 3.1.

TABLE 3.1 - HISTORY OF THE AUTOMOBILE.

THE AUTOMOBILE

ACHIEVEMENTS

First to conceive the application of petrol engine to road vehicle. He made four attempts to develop his own ideas on carburation, transmission, steering etc., but attained little success. His work, however, inspired other inventors to develop suitable power units and mechanisms.

He brought forth the first (horizontal) petrol engine powered three-wheeled vehicle followed by a four-wheeled vehicle comprising the following features: 1. Vertical crankshaft which was intended to overcome gyroscopic effects affecting the steering. 2. Bevel gear and belt transmission. 3. A rack and pinion steering system. 4. Surface carburettor, and coil-and-battery ignition. Hundreds of cars to his designs were successfully used placing him -as the father of the modern automobile.

He successfully pioneered the development of the light petrol engine of the vertical cylinder type. His commercial ventures both in Germany and England accelerated the development of the automobile finally merging into the Mercedes automobile concern.

An eminent engineer who applied the scientific principles both to power unit and running gear of the crude petrol driven horseless carriage, and developed the first basic automobile, the main features of which continue to exist in the modern vehicle. His work was recognised by an award of a gold medal for his car of 1899, by the Automobile Club of Great Britain.

Following the successful developments achieved by his contemporaries, production models were developed in a large scale for commercial application, improving on the design of water-cooling jackets and air cooling fins (round the radiator). Pneumatic tyres were introduced.

ACHIEVEMENTS

On the basis of European developments in the automobile field, Ford, carried out numerous experiments to develop a reliable petrol driven vehicle. His efforts led to commercial production in America introducing mass production methods for putting into the market popular models.

Starting with his maiden effort on the 1¾ hp., De Dion-Bouton tricycle, he rapidly developed the Renault car comprising the best features of the contemporary designs.

Advanced from the earlier design of two and four-cylinder engines and developed the first six-cylinder petrol engine for automobiles which successfully stood the severe test of covering 1581 miles during a run of 24 hours, giving an average speed of 67 mph, including stoppages. This indicated possibilities of further increase in the number of cylinders for more powerful automobiles developed later.

Introduced a novel design of sleeve valves in place of mushroom valves for inlet and exhaust, but this technical ingenuity did not attain commercial success.

They have earned the credit for incorporating the best features developed by other engineers and inventors in the layout of the car thus helping a long way in the progress of the automobile. These are: 1. Vertical engine with crankshaft running fore and aft, mounted in the front part of the chassis. 2. Universal joints and right angle bevel gear transmission to the driving wheels.

Further developments:

Since the early type of Daimler, Benz, De Dion, Bouton and other pioneers, there has been a progressive development of the automobile engine with the objects of improving its performance, reducing its weight, effecting the maximum economy in fuel consumption, simplifying its controls and operation and, incidentally, in cheapening its cost of production; it has been made extremely reliable to exacting conditions of service, and with a few exceptions, is relatively cheaper simple to maintain in normal working condition.

These improvements, which were to be expected when the very large number of petrol engines constructed since 1895 is considered, have resulted from experiment and experience with previous models and also from researches into the subjects of combustion, carburation, ignition, and metallurgical problems associated with light metals, alloy steels, new bearing metals, etc.

Most of the more recent progress in petrol engine design has been due to the use of higher quality fuels which enable higher compression ratios to be used without detonation effects; to the use of alloy steels and light aluminium and magnesium alloys giving much higher strength weight ratios; to improved combustion chamber design permitting higher 'meps' to be developed from fuels that previously could not be employed, owing to detonation effects;

to improved engine cooling systems; to more efficient and reliable high-pressure lubrication systems; to the achievement of higher volumetric efficiencies due to more effective valve port and manifold design, combined with better designs of carburettor, etc. The general trend has been to obtain higher power outputs from relatively small engines, in the case of motor car and cycle engines, by a general increase in engine speeds and also of meps.

In the larger types of motor vehicles for goods and passenger transport purposes, however, the high-speed compression-ignition (c.i.) engine has to a large extent replaced the petrol engine, for reasons connected with its better fuel economy and the use of cheaper fuels. Similarly, in the field of large stationary power plant, rail coaches, commercial and farm tractors, motor road rollers and small marine craft, the petrol engine has been generally supplanted in more recent designs by the compression-ignition engine.

Where the petrol engine will probably reign supreme for a long period is in applications requiring maximum power output from minimum engine weight as in motor cars, motor cycles, competitive types of high-speed engines for marine and land purposes; also for military and commercial aircraft where power-weight ratio is of primary importance. With the use of high octane fuels, permitting the employment of still higher compression ratios or degrees of supercharging, the fuel economy of the petrol engine approximates more closely to that of the C.I. engine, so that with its lighter weight for a given power output the petrol engine holds a dominating position in the aircraft field.

In the case of the smaller sizes of engines, namely, those below about 20 bhp, the petrol engine is simpler, lighter and cheaper to manufacture than the C.I. engine; more particularly is this the case with the smaller sizes of two-stroke petrol engine. It is unrivalled also for small portable power plant, eg., petrol-electric sets, self-contained road-drills, rammers, motor lawn-mowers, small air-compressure plant, starting engines for large Diesel tractors, etc.

<u>Conclusion</u>: Taking note of the modern trends that have now been acquired, it can be safely stated, that in the final shape of things, compression-ignition engine will completely replace spark-ignition engine in future power units, from the lowest to the highest capacities required in a large variety of applications. One promising field in which the engineer-scientist is now playing a very important role, is the adaptability of compression-ignition engine to a wide range of fuels. Some work has already been done in successfully developing multi-fuel engines using crude petroleum (mineral sources). The scope is widening towards the use of organic fuels such as vegetable oils and towards the development of gas producers of a wide range of outputs using coal and industrial wastes as fuel. It may not be far distant when the fuel problem of the c.i.engine will have been completely solved overcoming the present handicap of high fuel costs. It may be noted that the delivered

price of Diesel oil in this country ranges from R.360/- to 400/- per ton, of furnace oil R.175/- per ton, of charcoal R.40 per ton, and of high grade coke R.60/- to 80/- per ton. The use of vegetable oils and solid fuels for C.I. engines would be an important development, considering the fact, that in this country, petroleum resources are meagre and those of other fuels abundant. Vegetable oils which are to-day used as edible oils are extremely costly as the production is insufficient to meet the country's requirements. But if large scale farming is programmed for cultivation of oil seed crops the switching over to vegetable oils for c.i. engines during hostilities would prove to be a vital defence measure. In India, therefore, research on the development of techniques for adaptation of c.i. engines to a large variety of indigenous fuels is of special importance.

REFERENCES: 2, 3, 4, 14, 20-22.

3.2 AIRCRAFT PROPULSION

It has been possible for the aeroplane to reach its present stage of development because of the petrol engine. This new mode of transport has had a very speedy career and its advancement during the last two decades has been so fast that it has completely revolutionised the design of the petrol engine suited to air flight conditions. Table 3.2 traces the history of the application of petrol engine and the remarkable changes that have been introduced in the design of the petrol engine to meet the exacting demands of aircraft.

TABLE 3.2 - HISTORY OF THE AEROPLANE.

ACHIEVEMENTS

First attempts at flying models were made with the help of light steam power units by John Stringfellow in 1848, Hiram Maxim in 1890, and Laurence Hargrave also in 1890. These attempts achieved indifferent success.

First conceived the idea of light petrol engine for aircraft, but the credit for developing a successful flying model goes to Wright Brothers, who may be regarded as the pioneers of aircraft propulsion, as their efforts established physical possibilities of flying.

Then followed a few enterprises of French engineering firms in the development of aircraft propulsion. A notable enterprise amongst these, consisted in the evolution of rotary engine so called because of the mechanism it provided for rotation of the circular cylinder body round a fixed crankshaft with reciprocating components radially disposed. An ingenious device, which, did not attain much success by virtue of the fact that its development did not proceed further from its initial trials.

Intensive efforts were made to develop petrol engine powered aircraft during the first world war for air attacks. However, with the ending of the war a number of problems relating to body streamlining, design of monoplane, solution of multi-engine machine, problems concerning high altitude, and questions relating to air navigation remained unsolved.

Peace period between 1918-1938 contributed to the solution of the various problems and successful application of the following features which made the petrol engine a light component power unit. 1) Supercharging 2) Air cooling, 3) Improvements in fuel.

Further Developments:

Progressive improvements in fuel with a view to reducing the tendency to detonate have done more than anything else to render possible the high performance of the modern [illegible] engine. Since the realization prior to the 1914 war, that the incidence of detonation set a limit, and in those days a very early limit, to the power output obtainable, research on fuels has been carried on intensively, and the engineer has, at every step, taken full advantage of it, at first to raise his compression ratio and thereby gain in thermal efficiency and, when that had reached the practical limit, to increase further his mep by supercharging. An increase from 66 to 100 in Octane number permits of almost a three-fold increase in mep but at the cost of more than doubling both the maximum gas pressures and the intensity of heat flow. Throughout the last thirty-five years it has been a neck-and-neck race between the chemist and the engineer; at times the chemist has been a-head, and the engineer at frantic pains to stiffen the structure and working parts and improve the cooling of his engine in order to take full advantage of the improved fuel; at others he has taken the lead. From a mechanical point of view, progress has taken the form of strengthening step by step each weak link as it gave way under the ever-increasing strain. At one time exhaust valves were the limiting factor but the introduction of sodium cooling and the use of "Stellite", "Brightray" or other

$$i = \frac{\sqrt{3}\, ei}{xd + x2}$$

$$Td' = \frac{x'd + x2}{xd + x2} \; Td'o$$

in which X2 is the negative sequence impedance of the machine.

For terminal-to-neutral short circuit, the a.c. component of the phase current are given by

$$i'' = \frac{3\, e''i}{x''d + x2 + xo}$$

$$i' = \frac{3\, e'i}{xd' + x2 + xo}$$

$$i = \frac{3\, ei}{xd + x2 + xo}$$

$$Td' = \frac{xd' + x2}{xd + x2 + xo} \; Td'o$$

in which xo is the Zero sequence impedance of the machine.

The subtransient time constant, Td" does not change much with different conditions and, therefore, the single value is used for all conditions. The other components, that is, the unidirectional components are determined in the same manner as used fo finding the unidirectional components of short circuit from load.

The above values of ei, e'i and e"i depend on load conditions.

So some aspects of short circuit analysis have been discussed in the preceding pages by method used by Westinghouse Engineer Mr. C.F. Wagner.

The improved method used by Mr. Wagner are latest as that of 1942, step by step, simplier and make the calculations of short circuit analysis of synchronous machine easier.

But the methods suggested by M/r. R.E. Doherty and C.A. Nickle in the year 1928 and 1930 are basic, and on the basis of knowledge presented by Doherty & Nickle that further improvement in the field of short circuit analysis of Synchronous machine were suggested by other Engineer. I similar materials for facing the valves and their seatings, banished this limit. Next came bearings, when the intensity of loading exceeded the capacity of ordinary anti-friction linings, and special materials such as copper-lead, cadmium-nickel, or silver-lead, involving new techniques, had to be substituted. Throughout the whole picture the piston itself has always been the weakest link largely because of the high temperature which the pistons attain in aircraft engines; here detailed design in the way of better disposal of material, with a view both to stress distribution and heat dissipation, and the use of oil cooling have done much to improve conditions, but so far as the piston is concerned, the greatest gain of all, in the opinion of Ricardo (13), has been the development, by Napier's some 30 years ago, of the wedge-shaped piston-ring.

<u>Specific weights and outputs:</u> Fig. 3.1 shows the progress made from the past to the present times. Whilst the bhp has rapidly increased after 1940, the upward curve of the specific weight is due to the requirements of modern engine equipment, superchargers, accessories etc.

<u>Air cooling and liquid cooling:</u> From the day the first aeroplane left the ground, controversy has raged as to the relative merits of air and liquid-cooling. To-day it has generally been accepted that, where very high speeds of flight are called for, the liquid-cooled engine with its

much higher performance rating and lower cooling drag because of the shape of the heat dissipating surfaces of the engine, is preferable, despite the objections of vulnerability, plumbing, and freezing; but that for moderate-speedmachines, where a relatively large frontal area and cooling drag can be tolerated, air-cooling is to be preferred. As to overall specific weight, there is but little to choose; on the whole it is claimed that the specific weight of the liquid cooled engine, together with its radiator and cooling liquid is, if anything, the lower.

Compression-ignition engines for aircraft propulsion:

Very shortly after the 1914-18 war the Air Ministry instigated a research into the possibilities, for aircraft propulsion, of the compression-ignition engine using heavy oil, and by 1921 the Royal Aircraft establishment had converted their largest single-cylinder aero-engine unit and succeeded in reaching a power output at a piston speed of 2400 fpm, closely comparable with that of contemporary aero-engines, and that with a fuel consumption as low as the stationary Diesel engine of that date. This really remarkable achievement never received the appreciation or publicity it deserved.

It served, however, to inspire and encourage others to pursue the same aim, and by about 1928 research and development work had reached the stage when several full-sized experimental aero-engines, both air-cooled radial and liquid-cooled V-design, were designed and built. At that time the performance of the contemporary petrol engines were still limited by the low octane number of the fuel available, and the heavy-oil C.I. engines looked like being closely competitive even on the basis of specific weight, and were, of course, immeasurably superior on the score of fuel economy, but by the time these engines were completed and had been nursed through their teething troubles, the octane number of petrol had so much improved, and with it the performance of the petrol engine, that much of the advantage had disappeared.

During the later 1930 s, the rate of increase of the octane number of petrol steepened, with the result that the performance of the petrol engine gained a lead, leaving the C.I. engine far behind the race. With the marked advantage gained by the petrol engine and with the international relations showing signs of hostilities the conditions were not favourable for C.I. engines to take the challenge and has since then lost its position as a power unit for aircraft propulsion.

Temporary Augmentation of Power:

In military usage more especially, it is very desirable to be able, for short periods, to augment the power of the engine for take-off or for combat. At take-off and at relatively low altitudes the supercharger can always provide the engine with more oxygen that it can safely consume, within the limits set by detonation or by thermal considerations, or both. Under such conditions a temporary increase of power can be obtained by the injection of water or of a water-methanol mixture. In this case the high latent heat of the injected liquid serves to provide internal cooling both to the supercharger and to the engine cylinders, while the steam produced serves as a very effective anti-detonant. By such simple means it is possible to augment the power by about 20 per cent without increasing either the heat stresses or the maximum peak pressures.

The addition of methanol, although its latent heat is lower than that of water, confers certain advantages:

1. It serves as an anti-freeze.

2. Its boiling point is much lower than that of water hence it will evaporate more readily and therefore earlier in the cycle.

3. It is itself a fuel, and to this extent is convenient in that its admission has the effect of enriching automatically the mixture strength.

At high altitudes where, even with the supercharger all out, the engine is still starved ~~for lack~~ of oxygen, temporary power augmentation can be achieved only by supplying additional oxygen in some form or other

In the first attempts liquid oxygen was injected into the eye of the supercharger; this achieved the desired result and was used in operational service, but involved difficult supply problems. Moreover owing to increased flame temperature the tendency to detonate was increased. Later nitrous oxide was used in preference to liquid oxygen, for this could be stored and carried as a liquid, in light cylinders. Nitrus oxide proved to be a very effective anti-knock and by its use at high altitudes it was found possible to augment the power by as much as 40 to 50 per cent at a consumption of 5 lb. of nitrous oxide per additional 100 hp per minute. Since the time during which such power augmentation was required was generally a matter of seconds, i.e., in order to close with, or break away from, the enemy, this relatively high consumption was not a serious objection.

The large power augmentation by the use of nitrous oxide was due to:

1. The liberation of free oxygen.

2. The liberation of a large amount of heat by its dissociation into oxygen and nitrogen.

3. The high latent heat of the liquid, the whole of which was evaporated within the supercharger, thus lowering the temperature and increasing the density of the normal supercharge and adding thereby to the supply of atmospheric oxygen.

<u>Conclusion:</u> Although the petrol engine has been well developed for aircraft propulsion, modern requirements

of speed and power are imposing too heavy demands on the power unit. Due to the very inherent limitations in the design of reciprocating engines these requirements cannot be met by this type of power unit and gas turbine is now fast taking over from the petrol engine unit in the high powered aircraft, flying at speeds beyond 400 mph and is breaking the sound barrier.

REFERENCES; 4, 10, 13, 22 - 25.

3.3 MARINE PROPULSION AND POWER GENERATION

One of the most fruitful fields in which Diesel power has been well planted, is marine propulsion. Diesel engines developed to suit power generation in stationary plants, have with necessary auxiliaries been well fitted into the scheme of marine propulsion. In course of time large tonnage vessels were successfully adapted to well designed Diesel-plant capable of 1) smooth operation under varying conditions of propulsion and, 2) reversing quickly from forward to backward drive. The latter is an essential feature of the power requirements in sea faring vessels. A Diesel powered vessel has the advantage of increased payload, maximum cleanliness and fast speeds; it has now become popular with luxury passenger liners.

With the gas turbine developments, there are prospects of steam turbine finding a keen rival, as this new type of power eliminates the use of boilers and other cumbersome equipment.

In the field of stationary power, Diesel and gas engines have been successfully used in pilot generating units on 1) large engineering construction works of power stations, 2) for crude oil exploitation and refineries plant and equipment, 3) for municipal water-works and drainage systems, and 3) for peak load operation in electricity grids. Although internal-combustion thermal stations are highly efficient, the limitations of its reciprocating mechanism have restricted the maximum power rating of a single unit to about 10,000 hp. This has been its major handicap in finding its place amongst modern large capacity installations of central power station systems. In industrial applications where, by-products, liquid and gaseous fuels are available for generation of power, and where heat is required for processing purposes, internal-combustion engine has often proved economical. Here, well designed heat recovery systems have been satisfactorily introduced to obtain very high thermal efficiencies. Power obtained from internal-combustion thermal stations is often more economical than that obtained from the electricity grid.

A brief account of the application of internal-combusion engine to marine propulsion is given in a chronological order in Table 3.3

TABLE 3.3 - HISTORY OF THE MARINE ENGINE.

ACHIEVEMENTS

Gas engine, which had already grown out of infancy when petrol engine was in teething stage had attracted the attention of marine engineers, but, the problem of production of gas in a moving vessel did not help the application of this type of engine to sea-going vessels. However, the possibilities of internal-combustion engine as a marine power unit was continued to be kept in view.

Conceived the idea of applying the crude type of petrol engine then developed for light boats, and, his first experiment consisted in fitting a two-cylinder petrol engine to a launch. This self-propelled vessel indicated the possibilities of internal combustion power in the marine field.

As far as the records go they were the pioneers in introducing gas engine for marine propulsion. They were followed by Messrs. Beardmore and Co., of Dalmuir, whose first experiment in this field was the replacement of tripple -expansion engines by a set of Beardmore-Capitaine gas engines and suction gas plant.

The gas engine did not produce much impression in the marine power field, because of the difficulties and unattractive economies in the production of gaseous fuel in moving vessels. Priestman took over the reins at this stage and developed the crude oil engine which was successfully applied to river craft, laying thereby a solid foundation for the application of large capacity power units of improved performance to sea-going vessels.

Pioneers in the field of Diesel engine development; (Dr. Diesel did most of his early work with Sulzer Bros). They took advantage of the experience gained with crude oil engine as a marine power unit and introduced large capacity Diesel units (two-and four-stroke) to marine propulsion

ACHIEVEMENTS

The main difficulty experienced with the Diesel was its non-reversibility which adversely affected manoeuvrability of the vessels. It was Sulzer Bros., who successfully developed the design of two-stroke reversible engine to overcome this difficulty. This design simultaneously increased the power rating to minimise dead weight carried by the vessel.

Sufficient maturity had been gained in the application of Diesel engine to marine services, to enable numerous manufacturing concerns and ship builders to bring out large tonnage motor vessels. They replaced to a degree, reciprocating steam engines which suffered from the major disadvantage of low efficiency and large non revenue cargo of coal.

Although Diesel powered vessels did not increase in number during the first war period, the turning point came about the year 1923-24 with a magnificient enterprise in the form of a Diesel vessel of 13,000 bhp capacity. The war, however, helped the development of Diesel submarines and fast battle-ships.

Diesel power in marine services has come to stay although it has all along been facing keen competition from the steam turbine.

Most of the recent progress in the design of stationary and marine engines ~~design~~ has been due to

1) Improvement in fuel consumption partly due to the extension of the range of operation of the working medium, and partly to the increased efficiency of combustion and to the reduction of mechanical losses. Formerly the maximum cylinder pressures seldom exceeded 500 psi but to-day pressures even higher than 1000 psi are a common feature.

2) The mechanical injection has replaced the air-injection system thus eliminating the costly and bulky air compressor, and improving the mechanical efficiency. The result of all this is an overall improvement in economy.

3) Utilisation of the heat in the exhaust gases which was a rarity in the earlier days is to-day universal. The earlier two-stroke engines were at a serious disadvantage as regards waste-heat recovery, compared with the four-stroke type, on account of their much lower exhaust temperature. As a result of extensive study of the scavenging process, however, the air quanity in some designs of two-stroke engines has been greatly reduced. This had the two-fold advantage of decreasing the load on the scavenge pump increasing the power rating and thereby the mechanical efficiency, and also of raising the temperature of the exhaust gases, thus increasing the amount of heat recoverable from them.

In the ceaseless endeavour to reduce first cost, which was a serious handicap to the oil engine, as compared with steam machinery, designers directed their efforts to getting more and more power out of a given weight of material. The results of these efforts were in the attainment of higher piston speeds (1500-2000 fps as compared with 700-800 fps in the earlier engines) and higher mean pressures (90 psi).

The progressive reduction in the cost of two-stroke engine installations became a serious matter for the four-stroke fraternity until the position was greatly changed by supercharging. This enabled the mean pressures in four stroke engines to be increased by about 40 per cent. Supercharging, of course, was also adopted in some two-stroke designs, but not to the same extent.

An important development in marine propulsion is the geared Diesel engine. It is the most satisfactory form of indirect drive, reckoned as an alternative to the direct-coupled engine and considered in terms of weight, space occupied, first cost, and so on.

In general terms, the claims made for the geared drive are:

1. Increased reliability, by having more than one engine per screw.

2. One or more of the engines can be shut down when the ship is running light, the others then being operated at their most efficient rating.

3. Easier maintenance, because the engines are of more manageable size.

4. Ease of overhaul of the engines at sea because

of the availability of spare power.

c. Larger scope for standardisation of power units both in regard to the number and size of cylinders in a single unit with advantage to initial cost and replacements.

Diesel -electric drive: As an alternative to the direct -coupled Diesel engine, the claims for the Diesel -electric drive have much in common with those for the geared Diesel drive.

There are certain additional claims which can be made for the Diesel-electric alternating current drive, viz.,

1. Flexibility of power distribution, because any desired number of engines per shaft can be installed.

2. The engines can be located anywhere, the motors being arranged aft, thus eliminating tunnel shafting.

3. Diesel engines are non-reversible.

4. Complete bridge control can be obtained.

5. A quicker turn-round in port can be arranged, based upon a system of running overhaul.

Conclusion: The Diesel engine development has nearly reached its climax as a reciprocating type of power unit, and the only field in which the scope of its application can be widened is its adaptation to a wide range of fuels. In this direction research has already been taken up and the future will indicate how, even solid fuels and industrial wastes can be satisfactorily used for deriving power with the help of this type of power unit. For large capacity installations the Diesel engine is being replaced by gas-turbine power unit which has recently come into commercial application. Therefore there is ample scope for research and investigation to improve the operation and performance efficiency of the gas turbine.

REFERENCES: 2, 11, 26-30

3.4. RAIL TRACTION

The first attempt to apply the internal-combustion engine to a locomotive was made by Daimler, in 1891. His crude locomotive was equipped with a 4 hp petrol engine. (31)

While progress was being made with the internal-combustion engine in the stationary power, marine and automotive field the steam locomotive as a power unit for rail traction was attaining maturity. The internal-combustion engine was beginning to show its superiority over the steam-engine in the above applications and it easily attracted attention as a substitute for steam power,for rail traction. Early attempts dating 1904-19 were made with petrol engine on light shunting locomotives both in U.S.A. and Germany, but due to the high cost of fuel, lower efficiency, and limitations regarding power rating, petrol engine began to be replaced by Diesel engine.

In 1912, Sulzer Brothers introduced the Diesel engine for rail traction. Since the transmission (direct drive) proved to be a failure they switched over to electric transmission in 1914.

The development of Diesel traction was cut short by the first world war. After the war, intensive research on transmissions were carried out. With the solution of the transmission problem and with the advent of the high-speed Diesel engine, the Diesel locomotive progressed at a rapid rate. To-day the Diesel locomotive is a keen competitor to the steam and electric locomotives

Appendix II gives the characteristics of steam and Diesel traction. Table 3.4 gives the factors that are taken into consideration in the design of the Diesel engine for different types of traction duties.

TABLE 3.4 - ENGINE FEATURES FOR DIFFERENT TYPES OF TRACTION DUTIES.

DIFFERENT TYPES OF TRACTION DUTIES

Whether the transmission be electric or hydraulic, engine weight is an important factor.

The tendency has been to incorporate engines of the horizontal type mounted under the floor of the rail-car, so that no useful space is occupied by the power unit.

Although weight per bhp and space occupied are not of the same importance as for rail-car or mainline Diesel-electric locomotives, even here, the tendency is towards more compact units of higher speeds. However, considerable attention has been paid to the production of an engine which is robust and reliable.

Conclusion: As mentioned earlier the Diesel engine development has nearly reached its climax as a reciprocating type of power unit, and the only field in which the scope of its application can be widened is its adaptation to a wide range of fuels. Therefore, research on the development of techniques for adaptation of compression-ignition engines to a large variety of indigenous fuels is of special importance.

REFERENCES; 11, 20, 27, 31-35

THE GAS TURBINE

As steam turbine followed the reciprocating type of steam engine in order to meet the increasing demands for power, the reciprocating type of internal-cumbustion engine is also giving its place to the gas turbine. Gas turbine possesses characteristics similar to steam turbine, that is, in the low power range, its performance efficiency is low, but it meets requirements of a specialised nature. In construction, the gas turbine unit does not materially differ from the steam turbine unit. Both of them use highly energised working fluids, as steam possessing a high content of energy is produced in boilers by burning different kinds of fuel, gas having a high content of energy, is produced in combustors burning different kinds of fuel. The only difference is that the pressure of steam is raised in boilers by compression under static conditions and that of gas is raised under dynamic conditions. It is for this reason that much higher energy conditions can be obtained in steam as working fluid. In the case of gas, the dynamic system used for raising pressure, is a compressor. Pressures beyond 5 to 6 atmospheres cannot be achieved without heavy energy losses. Hence this pressure is taken as an optimum limit. Of course, another advantage possessed by steam is its high specific heat as compared to air or gas, and for the same pressure-temperature conditions, the amount of gas required to produce the same power is nearly twice the amount of steam.

The basic ideas about the gas turbine are more than a century and a half old. It was Hero (36) of Alexandria, who first conceived the idea of a rotary power machine actuated by hot gases. But it was John Barber (2, & 36) an Englishman, who first attempted to use some sort of a gas turbine for developing power in 1791, for which he obtained a patent. The fuel he used for his turbine was gas obtained from coal, wood or oil. He introduced the idea of compressing air by means of a compressor unit run through a chain drive from the turbine shaft. Barber's venture was rewarded by a steady increase in the number of gas turbine patents taken by other aspirants, but none of these patents led to the development of a commercial power unit because of the inefficient designs of the turbine and compressor which consumed practically all the energy derived from fuel. This failure of the earlier inventors of the gas turbine is attributable to lack of adequate knowledge of thermodynamics and aerodynamics, and efforts in the direction of developing gas turbine dropped.

Dr. F. Stolze (36) of France took up the idea of developing a gas turbine towards the end of the nineteenth century and was the first to design a multistage axial-flow compressor directly coupled to a multistage reaction turbine. Tests made on this machine in 1900-1904, clearly showed the inefficiency of the compressor unit thereby indicating the need of a scientific approach to problems of aerodynamics. Attempts of others who followed him also failed for the same reasons.

The modern era of gas turbines begins from 1930's. Brown Boveri was the first to develop an efficient axial-flow compressor and turbine unit, and his valuable experience helped others to design suitable gas turbines. The first gas-turbine power plant for generation of electricity was built by Brown Boveri and successfully tested in 1939. The plant was installed in the city of Neuchatel, giving a net output of 4,000 kw at a thermal efficiency of 18 per cent. Brown Boveri also produced the first gas-turbine locomotive which was successfully run on the Swiss Federal Railways, in 1941.

In U.K., credit is given to Sir Frank Whittle for promoting the development of the jet-propelled plane. He developed an efficient gas-turbine unit using axial and centrifugal compressors for which he obtained a patent in 1930. In Germany, gas turbine was adapted to aircraft propulsion by a young German physicist, Pabst von Ohain in the employ of Ernest Heinkel, and his turbojet aircraft (He 176), had a successful flight in August, 1939.

It is from this point that the gas turbine began to show promise in a wide range of applications; for generation of power, aircraft and marine propulsion and rail traction. As power units of small sizes have not yet found to be reliable in operation and sufficiently efficient... particularly under varying conditions of load... the use of gas turbine in road traction is still in an experimental stage.

Fundamentally, the gas turbine cycle is similar to that of the reciprocating internal-combustion engine, the main events being: compression, combustion and expansion. Thermodynamic analysis of the gas turbine cycle is basically similar to that of the reciprocating internal-combustion engine. Allowances on theoretical efficiencies as determined by this analysis are necessary in order to take account of the deviation of the actual compression and expansion events from the ideal adiabatic conditions. Some of the heat cycles in common use are briefly outlined in Table 4.1

TABLE 4.1 - GAS TURBINE CYCLES.

GAS TURBINE CYCLES

DESCRIPTION

Simplest form of gas-turbine power plant; consists of: 1) Compressor, to raise the pressure of air to about 5 atmospheres; 2) Combustion chamber, to burn fuel and raise the temperature of compressed air under constant pressure conditions; 3) Turbine, to produce work by expansion of gas- air mixture. The maximum practical efficiency of this cycle is approximately 20 per cent. This low efficiency is due to considerable amount of heat lost to exhaust.

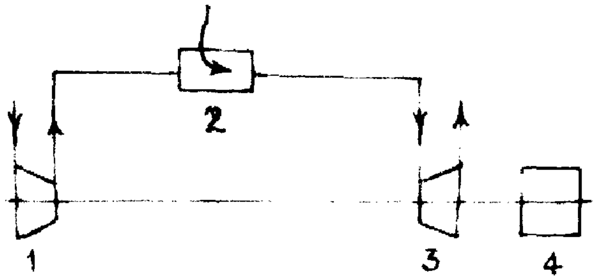
This cycle differs from the simple open cycle, in that a heat exchanger is added to extract heat from the exhaust and pass it to the compressed air before it enters the combustor. The exhaust temperatures are thus reduced, thereby increasing the practical efficiency to 27 per cent.

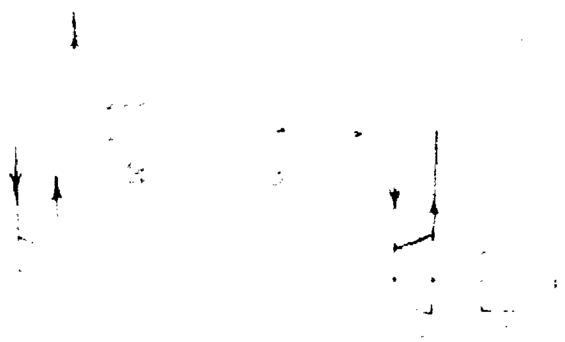
In this cycle only heated air flows through the turbine and combustor; and for this purpose heat exchangers are added to form a separate external loop. This system can be appropriately called exhaust heated external-combustion open cycle. The efficiency of this cycle is same as that of the above one with heat exchanger viz., 27 per cent.

This is a composite system having internal-combustion open cycle on the turbine unit for power generation, and a close external-combustion air cycle on the turbine driving the compressors. This is also known as semi-closed cycle, because of the turbine circuit being close and the other being open. As the amount of air drawn in and combustion gases exhausted is a fraction of a total amount of air used in the system, heat losses to exhaust gases are reduced, increasing the actual efficiency to 32 per cent.

In the close cycle, the working gas recirculates continuously, and combustion gases do not enter the circuit. The power output can be varied by changing the pressure in the circuit. Air is ordinarily used as the working gas, but it has been suggested that helium might give sufficiently improved performance to justify its use. With a full load pressure of 700 psi, a pressure ratio of 10: 1, and a gas temperature of 1200 F at inlet to turbine, an efficiency as high as 35 per cent can be attined. If the temperature at inlet to turbine is increased to 1300 F, efficiency is increased to about 37 per cent.

. ...pr... or
. Combustion ... ber
. Turbine
4. Load





1. Com...essor
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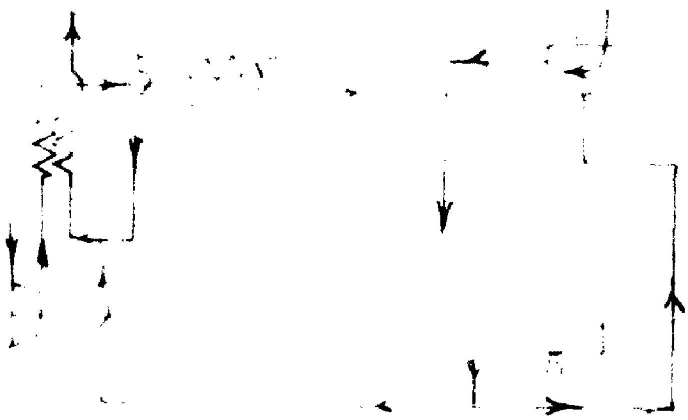

Cycle Refinements:

1. Intercooling is the cooling of compressed air between two or more stages of compression, thus reducing the specific volume of air delivered to the later stages of the compressor, with a corresponding reduction in the work required for compression. Theoretically, the benifit of intercooling increases with the number of stages, but in practice the number of intercoolers is usually not greater than too.

2. Re-heating: This is similar to that used in steam turbines. Dividing the turbine into high and low pressure sections and introducing a second combustion chamber to re-heat the exhaust gas from the high pressure turbine before it enters the low pressure turbine , improves the thermal efficiency of the cycle. But, at low pressure ratios, pressure losses counter-act the gain.Re-heating also complicates the design of the low pressure turbine.

3. Multiple shafts: When the load is subject to wide and abrupt variations, operation is improved by driving the compressor with one turbine and the load with another. A multiple shaft unit does not stall easily with rapidly-applied loads, as the speed of the compressor and heat input to the cycle can be sustained.

Table 4.2 presents the factors that influence the choice of cycle for a gas-turbine power plant.

TABLE 4.2 - FACTORS INFLUENCING THE CHOICE OF CYCLE FOR A GAS-TURBINE POWER PLANT.

OF CYCLE FOR A GAS-TURBINE POWER PLANT

As previously outlined the use of multiple shafts may be considered.

These often limit the choice to a simple, relatively inefficient cycle and especially preclude extensive heat exchange apparatus.

For short operating periods (as for example in stand-by duty), the simplest cycle is usually the choice, because of its lower capital charges.

For part load performance, multiple shaft design may be considered.

Absence of a supply of cooling water in some land installations may prevent selection of compound cycles.

Coal burning turbines have reached only the development stage. Residual petrol fuels have been widely used but with little success. Where distillate fuels are used, the Diesel engine is a serious competitor because of its higher efficiency. It is the fuel cost, therefore, which is leading to the development of the exhaust heated cycle and other designs, that are especially adapted to the use of low grade oils and solid fuels.

Conclusion: As the gas turbine suffers from the handicap of low pressure limitations of the compressor unit, considerable research is necessary to improve the cycle efficiency before it can be said to compare in performance with the steam turbine power unit. The latter is advancing further in the direction of higher efficiencies by utilisation of gas turbine cycles to minimise latent heat losses, which, normally occur with the standard condensate cycle. There is an other direction in which research can bear fruit and this lies in the utilisation of different types of fuels. At present, gas turbines use liquid fuels, such as kerosene, furnace oil, etc., but the use of coal, which is found in abundance in India and many other countries should be a good solution to the fuel problem in this type of power unit. Coal-burning gas turbines have been developed, but now, considerable difficulties are being experienced on account of 1) fly ash entrapped in combustion gases in internal-combustion turbines and, 2) heat exchanger losses in external-combustion gas turbines. Indian coals which are generally inferior in quality, will present a more serious situation in this field of investigation. But it is of vital importance to develop coal burning gas turbines for use in this country so that gas-turbine power can be advantageously applied to central power stations and to the grids located in regions where n low grade coals are in abundance. In rail traction also, use of oil in a gas-turbine power unit is to be deprecated, as indigenous resources of oil are meagre and large scale demands of fuel oil will make the country economically dependent on other countries. Research on coal burning gas turbines can be carried out in the direction of the development of gas producers using coal, coke or other waste products as fuel, or, on heat exchangers which can be successfully applied to exhaust heated cycles.

REFERENCES: 2, 36-38.

CHAPTER 5

MANUFACTURING TECHNIQUES AND PLANNING

We have seen in the historical review presented in the earlier chapters, the important role which the internal-combustion- Engine has played in the field of power and its varied applications. Energy required for industrial purposes is not only obtained in the form of electricity, but also as direct shaft power. Not a small portion of total energy is utilised in the latter form in the electricity grids. To-day, this is a national feature in every industrially advanced countries and, even in countries that are progressing fast towards a high level of industrialisation.

Steam turbine, of course, dominates in the field of large capacity thermal stations connected to the grid system. But in the field of commercial and defence transport, particularly by road, sea and air, internal-combustion power (including gas turbine power) dominates and is not likely to lose its position until nuclear power can be harnessed to attain the degree of flexibility in its applications necessary for the above mentioned services.

It is obvious that no country can advance industrially if the internal-combustion engine is not given its right place in its industrial life. There is no doubt that high engineering standards both in regard to manufacturing techniques and processing of construction materials are required for developing an indigenous industry for production of a wide range of internal-combustion power units (from fractional horse power rating to 10,000-20,000 hp). This is very important to meet satisfactorily the requirements of a well developed national economy. It may be added, that if labour is organised on a large scale to manufacture internal-combustion plant, its capabilities for production of highly complicated engineering equipment are assured. The metallurgical requirements for the supply of high quality metals to with-stand temperature and pressure conditions and complex dynamic forces obtaining in an internal-combustion power unit are no different or of lesser standards than those required for other high quality engineering plant and equipment.

It would be a good approach therefore, to give considerable importance to the manufacture of internal-combustion engines in this country in the planning of the development of heavy industries in the immediate future.

CHAPTER 6

MAIN OBSERVATIONS AND SUGGESTIONS FOR RESEARCH.

The following are the important observations made on the basis of the detailed review of the development of internal-combustion engine presented in the earlier chapters.

1. Diesel engine is replacing petrol engine from the lowest to the highest capacity required for a variety of applications because of its higher performance efficiency and lower fuel costs.

2. Diesel engine development has reached its climax as a reciprocating type of power unit. However, the scope of its application is being widened by its adaptation to a wide range of fuels.

3. Diesel engine is slowly being replaced by the gas turbine in a variety of applications.

4. The gas turbine suffers from the disadvantage of low efficiency. This handicap is being overcome by the development of the exhaust heated cycle and other designs that are especially adapted to the use of low grade oils and solid fuels.

Suggestions for Research:

1. Research on indigenous fuels for Diesel engines on the following lines:

a) Hydrogenation of tar obtained as a by-product of carbonisation process for manufacture of coke.

b) Direct gasification of coal (inferior grade) and synthesis of gases.

2. Research on techniques for the adaptation of Diesel engine to solid fuels and industrial wastes.

3. Research on coal burning gas turbines in the direction of the development of gas producers using coal, coke, or other waste products as fuel.

4. Research on heat exchangers which can be successfully applied to exhaust heated cycles for gas turbines.

5. Research on improvement of manufacturing techniques and processing of construction materials for developing an indigenous industry for production of a wide range of internal-combustion power units.

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APPENDIX I- LUBRICATION CHART FOR DIESEL ENGINES

(Practice of Lubrication, by Thomsen, McGraw-Hill Book Co., Inc., New York, 1937).

CHART FOR DIESEL ENGINES

HORSE POWER PER CYLINDER	GRADE OF OIL RECOMMENDED	VISCOSITY CENTI POISES AT 50 C
Upto 50	Diesel Engine oil, 2c* or 2	8
Above 50	Diesel Engine oil, 3c or 3	10
All Sizes.	Circulation oil, 3	10
Upto 50	Diesel Engine Oil, 2c or 2	8
Above 50	Diesel Engine Oil, 3c or 3	10
All sizes	Diesel Engine Oil, 3 or 4	10 or 13
Upto 60	Diesel Engine Oil,3c or 3	10
Above 60	Diesel Engine Oil, 4c or 4	13
All sizes	Marine Engine oil,1	56
All sizes	Diesel Engine Oil, 2 or 4	8 or 13

* The Numbers 2, 3, 4 refer to viscosity Number of the oils; the addition of letter c means that oil is compounded with fixed oil.

APPENDIX II - STEAM AND DIESEL TRACTION CHARACTERISTICS

(Dynamomoter car report No. 49 (1954) Railway testing and research centre, Lucknow, India.)

TRACTION CHARACTERISTICS

DIESEL

High (on account of the price of diesel locomotive being about 2.5 times that of the steam locomotive).

24 to 28 %

12 to 14

0.3 to 0.6

Equipment more complicated in component design with tighter size and wear tolerances.

High standard of skill required. Maintenance charges generally low in the first 5 years, but increase, later, on account of renewals and replacements of Diesel engine units. R.0.5 to 0.8 per engine mile.

High. Less time is required for inspection and repairs than with steam power.

18

250

1.87

1.2

DIESEL

Comparatively low except in cases of axle hung motors which cause heavy impact on joints.

High, due to oil storage especially in hot weather

Good

Negligible; water is required only for cooling and cleaning purposes.

One mechanic and one driver (main line). One driver (control provided with deadman's handle), for suburban service.

Minimum number of types required as this type of power is adaptable to multiple unit operation and to common designs for goods and passenger services, etc.

10 to 15 % (approx).

Up to 10 % for short periods. Limited by efficiency of cooling system and dynamic stress produced on motor armature.