10

DIESEL ENGINES.

This series of Lectures was delivered by Mr. Harry R. Ricardo, F.R.S., before the Royal Society of Arts and is reprinted by courtesy of the Author and the Society.

LECTURE I.

The Diesel engine even as we know it to-day is still in its infancy, for it was born only in the closing stages of the last century. New conditions call for new developments to satisfy them, and the particular new condition which gave birth to the Diesel engine was the rapid development of the petroleum industry during the last half of the last century. During that period there had sprung up suddenly a world-wide demand for kerosene oil for lighting, heating, etc. This kerosene was obtained by fractional distillation from crude petroleum, a process which left behind a large proportion of heavy oils for which, at first, no use could be found, and which remained for a time as a rapidly accumulating drug in the market.

As you are all aware, crude petroleum as taken from the ground consists of a heterogeneous mixture of liquid hydrocarbons ranging from light volatile fractions, such as petrol and kerosene, to heavy residues such as asphalt. Intermediate between these extremes lies a wide range of oils of high potential heat value, but so unstable chemically and of so high a boiling point that they cannot be burnt either in a lamp or in any internal combustion engine depending on external vaporisation. These oils could, of course, be burnt under boilers for steam raising, but this is, or was, an extravagant use. The need therefore arose for some means whereby these otherwise waste products could be converted into power by the more efficient method of internal combustion in the cylinder of an engine—hence the Diesel engine.

We are too fond, I think, of crediting a few particular individuals with a monopoly of inventive genius. The world is well stocked with men of scientific knowledge and wide imagination, and it is with no disrespect to the late Dr. Diesel that I suggest that, had he never existed, an equally suitable engine to deal with these heavy oils would none the less have been developed and that at about the same time. Once the incentive is established a way can always be found. Ripe seeds of invention everywhere abound, and it awaits only a certain combination of need, of circumstances, and above all, of chance, to decide which shall germinate. It is perhaps a little ironical that in this case the particular seed which sprouted turned out a hybrid, for Dr. Diesel had intended to cultivate a coal dust engine, but when its petals unfolded, there appeared a very pretty heavy oil engine.

Prior to the Diesel engine, all internal combustion engines had relied upon gaseous fuels, for liquid fuels could be utilised only after they had first been vaporised to a gaseous state. The heavier petroleum oils, by reason of their high boiling point and their chemical instability, cannot be vaporised completely without what is known as "cracking" taking place; that is to say, a chemical change whereby a portion of the fuel, instead of merely vaporising as a whole, splits up into components, some gaseous, others solid. The latter soon chokes up the vaporiser or cylinder, as the case may be.

The essential principle of the Diesel engine is the compression of the air within the cylinder to so high a temperature that the liquid fuel, when injected into this air, is either burnt, or is at least fully alight, before it has had time to reach to and deposit upon the relatively cold walls of the cylinder or piston; under these conditions it may "crack" to its heart's content, for the solid matter is burnt in mid-air and has no chance to make itself a nuisance. Again, prior to the Diesel engine, all internal combustion engines in practical use drew into the cylinder a mixture of air and fuel, so that the fuel was present during the compression stroke. The presence of a combustible mixture during this period set a limit to the ratio of compression and therefore of expansion which can be employed. The actual limit thus set depends upon the chemical stability, and the self-ignition temperature of the fuel. In the case of petroleum oils the chemical stability and the self-ignition temperature tend to decrease as we go up the scale, with the result that these heavier fractions which we call Diesel oils, even if they could be wholly vaporised, could be used only in engines of low compression and therefore of low efficiency. In the Diesel engine, air alone is compressed—to a pressure of about 450 lbs./sq. in. and to a temperature of the order of 600° C. Into this highly compressed and highly heated air the fuel is injected in the form of a fine spray at just such a rate that it shall, by its burning, maintain the pressure more or less constant during the first portion of the outward stroke, after which the supply of fuel is cut off and expansion proceeds in the usual manner. The crux of the whole problem lies in the introduction and distribution of the fuel.

In all the earlier Diesel engines, and in some few of the larger present-day examples, the liquid fuel is sprayed into the cylinder by means of highly compressed air. It will be apparent that in order to provide rapid burning we must break the fuel up into very fine particles. It will be apparent also that we must contrive to distribute these particles as uniformly as possible throughout the air in the combustion chamber, in order that each, in the short time available, may find sufficient oxygen for its complete combustion. With the help of compressed air this is comparatively easy, for the air can then be used both to pulverise the fuel and to distribute it, as in a scent spray. There are, however, very serious practical objections to the use of air injection, foremost of which is the cost and complication of the air compressor; in addition, the compressor itself absorbs a very considerable amount of power, of the order of 10 per cent. of the total output of the engine, while its own constitution is none too robust and it is liable to nervous disorders. In nearly all modern Diesel engines the use of injection air has been abandoned and its place taken by high pressure " solid " injection; that is to say, the fuel is injected by a suitably timed valve or pump under a pressure so great that it can be both pulverised and distributed by its passage, at high velocity, through the injection nozzle without the help of air. At first sight, this much simpler method would seem obvious, but the problem is not so simple as it may appear, for one is between the devil and the deep sea. Air at a pressure of some 30 atmospheres is a surprisingly dense medium through which the small particles of liquid have the greatest difficulty in shouldering their way, unless escorted by more air at a still higher pressure. We can see to it that each particle has a good kick-off from the nozzle—the higher the pressure the harder the kick—but we cannot ensure that it will reach its goal. Our ideal is to divide the fuel into the largest possible number of the smallest possible particles and to distribute these uniformly throughout the combustion chamber, but, the smaller the particle, the sooner it loses its impetus, and is borne down by the stolid resistance of the air. Without the aid of air, thorough pulverisation and adequate penetration are incompatible and we are compelled to fall back on compromise. In most of the large low-speed, and in nearly all the small high-speed engines, distribution and, in some cases, pulverisation also, is assisted by setting the air within the cylinder in violent motion, on the principle that it is easier for the air to find the fuel than for the fuel to find the air. In all cases, of course, the combustion air is in a more or less turbulent state, due to the velocity it has acquired while entering the cylinder, but in the case of solid injection engines, it is usual either to supplement this turbulence by forcing it through a restricted passage during compression, or to exchange the general rough and tumble turbulence for an orderly rotational flow. The former appears to be the more favoured method where poppet valves are used and the latter when the air is admitted to the cylinder through ports, as in the case of sleeve valve or two-cycle engines. Whatever method we use, our main objective is always to keep the relative motion between the burning fuel particles and the air as rapid as possible, in order to save the former from suffocation.

The full-blooded Diesel engine depends upon the compression of air in a cold cylinder to a temperature well above the self-ignition temperature of the fuel. To ensure starting at once from cold and to provide the necessary margin of excess temperature involves a compression pressure of the order of 450 lbs. per sq. in., with the risk of pressures far in excess of this in the event of an accidental early injection or other derangement. These high normal working pressures, and still higher fortuitous ones, involve necessarily a somewhat heavy and costly engine and call for a high standard, both of workmanship and of maintenance. It is natural, therefore, that attempts should have been made to produce a cheaper and lighter version by using a much lower compression pressure of the order of 150 lbs. per sq. in., and obtaining the necessary high temperature for ignition by the help of heated surfaces in the combustion chamber. Such engines, known variously as hot bulb, semi-Diesel, or surface ignition engines, had at one time a great vogue. In these, the combustion chamber, either the whole or a part, is left uncooled and is allowed to reach a high temperature, sometimes a full red heat. Against this heated surface the fuel is directed in a fairly coarse spray; on striking the hot surface the particles are both "cracked" and set alight. The solid carbon left behind by the partial cracking process will not readily adhere to a very hot surface, but, for the most part, falls away into the cylinder and passes out through the exhaust. At first sight this system looks attractive, but it will not bear close analysis. As compared with the full Diesel, the efficiency is of course reduced, in part by the much lower ratio of expansion and in part by the fact that combustion is partial only, for an appreciable proportion of the carbon in the fuel has been reduced by cracking to an indigestible form. Low efficiency can, however, be tolerated in cheap and relatively small engines, but there are serious practical objections also. In the first place, the temperature of the uncooled surfaces is dependent upon the amount of fuel burnt within the cylinder, and varies, therefore, as the load or speed are varied; it varies too, in the wrong direction, for the heavier the load the higher the temperature and the earlier the ignition, while on light loads the surface is apt to cool off to such an extent that ignition may fail entirely. Again, such engines are necessarily very sensitive to the self-ignition temperature of the fuel, which varies widely, depending upon its source. Various expedients have been adopted to get over these difficulties. In some cases water is injected into the cylinder at heavy loads, in order to cool the hot surface; in others external lamps are employed to maintain the surface temperature on light loads; in yet others, means are provided for deflecting the spray from a hot to a cooler surface or *vice versa*. About 20 years ago the surface ignition engine was in extensive use for all purposes where first cost was of more importance than subsequent fuel economy. The lack of flexibility as regards speed or load, the rough running due to the uncertain time of ignition, recurring trouble due to the deposition of carbon, and the liability of uncooled combustion chamber walls to crack, led engine builders gradually to abandon the surface ignition. Little by little the ratio of compression has been raised and the area or temperature of the uncooled surface reduced. An intermediate stage was reached, when such engines depended no longer on surface ignition, but became air ignition engines; the air being heated, in part, by moderately high compression of the order of 300–350 lbs. per sq. in., and, in part, by its passage over hot surfaces. This marked an improvement in smoothness of running, in flexibility and in economy, but the weight and cost approached more nearly that of the full-blooded high compression engine, while such engines still require preheating before they can be started.

The actual process of combustion inside the cylinder of an internal combustion engine is still largely a matter of speculation. Engineers and physicists are raising the curtain inch by inch, but it will be long yet ere we can hope to have a full view of the stage.

I have alluded already to the self-ignition temperature of the fuel, and so far as its use in a Diesel engine is concerned, this is the most important consideration of all. The burning of a hydrocarbon fuel in air is an oxidation process pure and simple: it may be intensely rapid or it may be excessively slow. In the latter case we are accustomed to describe it as oxidation rather than burning. If we expose oil fuel to air at ordinary temperatures, it will oxidise, but only very slowly; as the temperature of the air is raised the process speeds up. Some of the constituents will oxidise more rapidly than others. Owing to the extreme complexity of these heavy hydrocarbon molecules, the process of oxidisation is excessively complicated. At ordinary temperatures it may take years to oxidise only a portion of the fuel; at, say, 200° C., it will be a matter of days, at 250° C. of minutes, perhaps, and so on, but in all such cases the rate of rise of temperature due to oxidation is less than the rate at which heat is being dissipated by conduction, etc. Ultimately, as we continue to raise the temperature, a critical stage is reached where heat is being generated by oxidation at a greater rate than it is being dissipated. The temperature then proceeds to rise automatically, this in turn speeds up the oxidation process and therefore the evolution of heat; events then proceed to move rapidly, and what we describe as ignition takes place and a flame is established. If now, instead of heating the fuel and air together, we drop cold oil through air already heated well above its ignition point, what will happen? On entering the hot air, the extreme outer surface of the droplet will immediately start to evaporate, thus surrounding the core with a thin film of vapour. So soon as this vapour has reached a certain temperature ignition will take place, though the core is still liquid and relatively cold. We have then a core of liquid surrounded by a layer, which is burning as fast as it can find fresh oxygen to keep the process going, and this condition probably continues unchanged until the whole is burnt. Under these conditions, which are substantially those obtaining in a Diesel engine cylinder, we shall have first: (1) A delay period before ignition takes place. The duration of this period will depend clearly upon the excess of air temperature over and above the self-ignition temperature of the fuel. The higher the air temperature or the lower the ignition temperature of the fuel, the shorter will be the delay, but a delay of some sort there must always be. Apart from temperature, pressure also has an important bearing on the duration of the delay, for the higher the pressure the more intimate the contact between the hot air and the cold fuel. In Fig. 1 is shown approximately the variation in air temperature and in the self-ignition temperature of the fuel during the compression stroke of a Diesel engine. The absolute figures are of course approximate only, and are taken from Neumann's experiments. Once the delay period is over and ignition is established, the rate of burning will depend primarily upon the rate at which each flaming nucleus can find fresh oxygen to replenish it; that is to say, it will depend upon the rate at which it is moving through the air or the air is moving past it. In the Diesel engine the fuel is not all fed in at once, but is spread out over a definite period. The first arrivals meet air whose temperature is only a little above their self-ignition temperature, and the delay is more or less prolonged. The later arrivals find air already heated to a far higher temperature by the burning of their predecessors, and therefore light up much more quickly, almost as they issue from the injector nozzle, and get into their stride practically at once, but their subsequent progress is handicapped, for there is less oxygen to find —the milk has been skimmed by the first arrivals.

It is clear that the more finely the fuel is divided the greater the

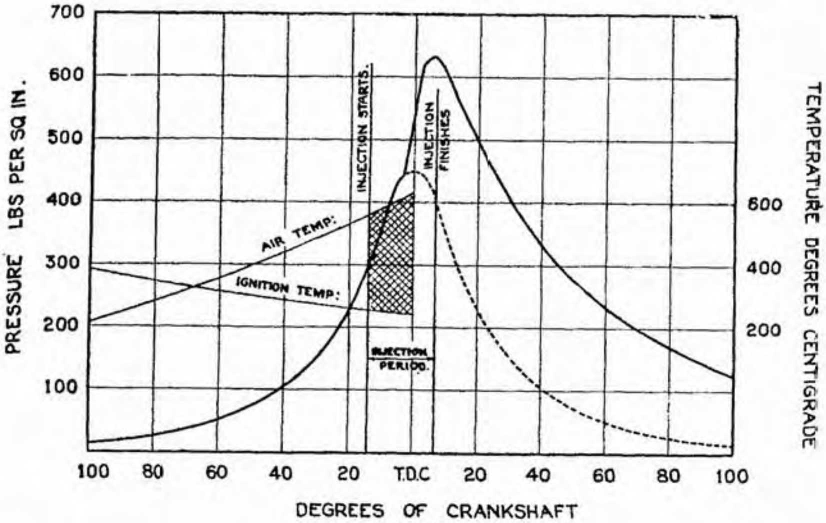


FIG. 1.

area of total burning surface and therefore the more rapid the combustion, once ignition has started; but whether or no the size of the particles has any large influence on the initial delay period is somewhat doubtful. Some influence it no doubt has, for it is certain that when air injection is used the delay period is less, but, in this case, the size of the particles is reduced to quite a different order.

If the air within the cylinder were motionless, it is quite clear that only a small proportion of the fuel would find sufficient oxygen, for it is obviously out of the question to distribute the droplets uniformly throughout the combustion space. We depend, therefore, on some considerable motion of the air as well as the fuel, and in my own experience the best results of all are obtained when, in place of general turbulence, the air within the combustion chamber is directed in a continuous flow at right angles to the stream of fuel.

In the air injection engine, owing to the shorter delay period and extremely rapid burning, we can, if we choose, operate on what is very nearly a constant pressure cycle. Since the rate of burning follows closely the rate of fuel admission, we can so control the latter as to maintain a nearly constant pressure during this period.

In the solid injection engine this is no longer possible, and combustion may be considered as taking place in three distinct stages—first a delay period, during which some fuel has been admitted but has not yet ignited. This is succeeded by a period of very rapid pressure rise following ignition. The rise is rapid because during the delay period the droplets of fuel have had time to spread themselves out over a wide area and they have fresh air all around them. Just how rapid it is will depend, to a large extent, on the relative motion of the droplets and the air, since it is this factor which controls the rate at which they can be replenished with oxygen and cleansed of their combustion products ; that is to say, the rate at which they can burn. At the end of this second stage the temperature and pressure are so high that the later arrivals burn as they enter, and any further pressure rise can be controlled by purely mechanical means. Fig. 2 is a diagrammatic indicator

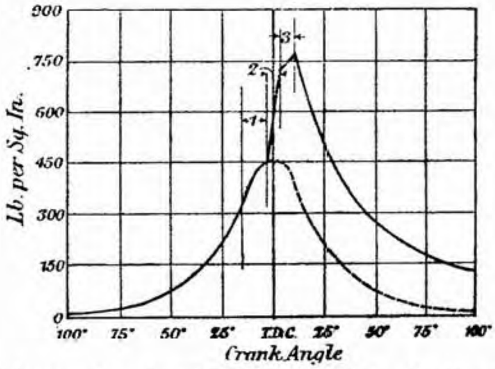
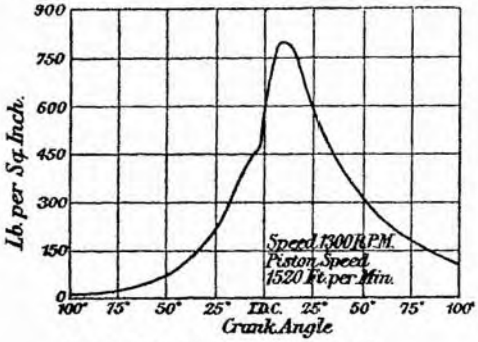


FIG. 2.—Diagram showing Three Phases of Combustion Process in Compression Ignition Engine.

diagram showing the three stages as quite distinct, while Fig. 3 shows an actual indicator diagram taken from a high-speed solid injection Diesel engine in which the three stages, though merged together, are quite distinguishable. It will be obvious that, for any given injection timing, the pressure reached during the second stage will depend upon the duration of the delay period ; the longer the delay, the more rapid and the higher the pressure rise, since more fuel will be present in the cylinder before the rate of burning comes under direct control. Some control can, however, be exerted by admitting the fuel slowly at first, thus ensuring that only a little has entered before ignition starts. In all cases we must aim to keep the delay period as short as possible, both for the sake of smooth running and in order to maintain control over the pressure changes.



Single Cylinder Bore 5½" Stroke 7"
Speed 1300 R.P.M.
B.M.E.P. 90 Lb. per Sq. In.
I.M.E.P. 112 " " "
Fuel Consumption per B.H.P. Hour 0·36 Lb.
" " " I.H.P. " 0·29 Lb.

FIG. 3.

And now to compare the process of combustion in a Diesel and petrol or gas engine. In the latter the air has already been carburetted or intimately mixed with fuel vapour before its entry to the cylinder. It is then subjected to compression, but in this case a relatively low compression only, for we cannot afford to heat the mixture too much or detonation followed by premature ignition may occur. Towards the end of the compression stroke a single intensely high temperature spark passes across the electrodes of the plug, leaving behind it a thin thread of flame. From this thin thread combustion spreads slowly at first, until there has been built up a substantial nucleus of flame. Under the conditions of indiscriminate turbulence which obtain to a greater or lesser extent in any practical engine, the flame, once fully established, is torn and spread throughout the combustion chamber with the result that the whole of the mixture is inflamed with a rapidity many times in excess of that which would occur under stagnant conditions. The combustion process in a petrol or gas engine may be regarded as taking place in two stages—first, a delay period following the passage of the spark, and second, a period of rapid pressure rise while the flame is being spread throughout the working fluid. The duration of the first stage, or delay period, depends primarily on the proportions of the mixture constituting the initial nucleus and its immediate surroundings, for this determines the flame temperature and therefore the rate of flame propagation. The duration of the second stage depends upon the amount of movement within the combustion chamber, that is to say, upon the degree of turbulence. If now we compare the two, we find that in both the Diesel and the petrol or gas engine we have first a delay period followed by a period of rapid burning; these two complete the process so far as the petrol engine is concerned, for the whole of the fuel is present and ready mixed. In the Diesel engine, however, there is yet a third stage while more fuel is entering the cylinder and is burning as it enters.

It used frequently to be asserted that the combustion process in a Diesel engine must, of necessity, occupy so long a period of time as to render high rotational speeds either impossible or at least hopelessly inefficient. Recent development has, however, shown that this is far from being the case. Although the combustion process in a Diesel engine involves three stages, the first two are very considerably shorter than their counterparts in the petrol engine. The delay period, though it varies greatly under different conditions, is usually only about one-half the duration of that in the petrol engine, while the spread of flame from a vast number of well-distributed burning nuclei is much more rapid than that from a single ignition point. The third stage we cannot compare, because it has no exact counterpart in the petrol engine, but it also is of very short duration. Comparative analysis from actual engines shows that the entire combustion process in a Diesel engine is completed in about two-thirds the time required in a petrol engine of similar dimensions. By entire combustion process, I am reckoning the period from the start of injection, or the passage of the spark, until the pressure has started to fall on the expansion stroke; strictly, of course, this is not the end, for in both engines some after-burning continues while a few oxygen stragglers are being rounded up and devoured.

In the light of present knowledge and so far as combustion conditions alone are concerned, the Diesel engine should be able to run, not only as fast, but even considerably faster than present-day petrol engines. It is mechanical limitations, and mechanical limitations alone, which determine the speed of either type of engine, but owing to the higher maximum pressures and therefore heavier moving parts, the mechanical limitations are greater in the Diesel engine. The belief that the Diesel engine cannot be made to run at high speed prevailed unchallenged for many years, and even now dies hard. I well remember nearly 30 years ago attending a lecture by a well-known physicist in which he deduced from experiments on flame propagation in closed vessels that the limit of speed of any internal combustion engine would be reached at about 300 r.p.m.; almost as he pronounced this conclusion, a motor bicycle roared down the street outside the lecture room—an eloquent commentary.

I do not propose to discuss the theoretical efficiency of Diesel engines at any length, for this is a large subject, and it is one which has been dealt with so fully in lectures and text-books that there is little left for me to say, and I will confine myself rather to considering the effects of deviation from the theoretical cycle.

All practical internal combustion engines at the present day operate, or, shall we say, profess to operate, on either one or other of two heat cycles, known as the constant volume and constant pressure cycles; for brevity let us call them the Otto and Diesel cycles respectively. In practice, no engine operates strictly on either, but the petrol or gas engine sometimes approaches the Otto cycle while the heavy oil engine approaches the Diesel cycle, though it more often hovers midway between the two. In the Otto cycle, since heat is added at constant volume and rejected also at constant volume, the air standard of efficiency is a function of the expansion ratio alone and is independent of the load on the engine. The higher the ratio of compression or expansion the higher the efficiency; but since, in this cycle, fuel is present throughout the compression stroke, the efficiency is in practice limited by the compression which the fuel will stand without detonating. In the Diesel cycle the issue is not quite so simple, for heat is added at constant pressure and rejected at constant volume, and the efficiency varies with the quantity of fuel admitted. For equal compression ratios the Diesel cycle is considerably less efficient than the Otto, as shown in Fig. 4, which shows the excess of work obtained with the Otto cycle from

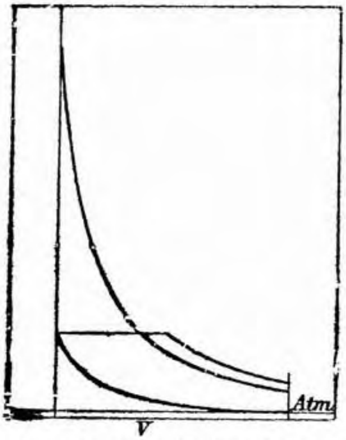


FIG. 4.—Theoretical Diagram. Constant Volume and Constant Pressure Cycles.

the same amount of fuel. In the Diesel cycle, as the load and therefore the quantity of fuel is reduced, so the efficiency approaches more nearly to that of the Otto cycle and in the limit would coincide with it. Against the lower inherent efficiency of the Diesel cycle must be offset the important gain due to the higher ratio of compression possible with this cycle. In an Otto cycle engine, competent to run on any brand of petrol available on the market, the compression ratio must be kept down to about 5·4 : 1 at which ratio the air standard efficiency is 50 per cent. A Diesel cycle engine with a compression ratio of 14 : 1 and consuming 75 per cent. of the available oxygen will have an air cycle efficiency of approximately 56 per cent. Were it possible to employ a ratio as high as 14 : 1 in an Otto cycle engine, the air standard efficiency would be 65·6 per cent.

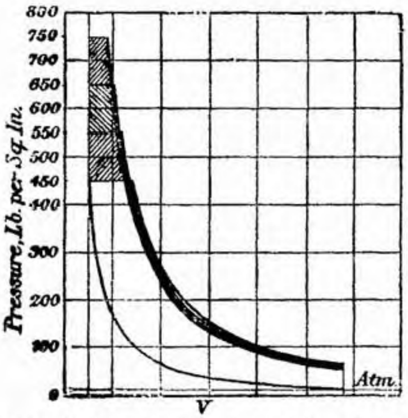


FIG. 5.—Theoretical Indicator Diagrams showing the change in Efficiency when same amount of fuel is burnt at different Maximum Pressures.

In the Diesel engine, as we depart from the constant pressure cycle and approach the Otto cycle, that is, as we allow the pressure to rise, so we gain in efficiency, as shown in diagram Fig. 5.

In the case of large Diesel engines we cannot afford to allow the maximum pressure to rise very much above the compression pressure, or the weight and cost of the engine will become intolerable—on a 30-in. piston the compression pressure alone is 140 tons—but in the case of quite small engines this no longer applies, for the structure is relatively far more rigid and the lightest parts which can be cast or machined are quite adequate to deal with pressures considerably in excess of the compression pressure ; thus on a small engine we can afford to operate on a more efficient heat cycle. By allowing the maximum pressure to rise from the compression pressure of 450 lbs./sq. in. to 550 lbs. we gain approximately 4½ per cent. in power output and in efficiency ; by allowing a further rise to 650 lbs. we gain another 3 per cent., and yet another 2 per cent. if we allow a maximum pressure of 750 lbs./sq. in. On the other hand, the smaller the engine the greater the loss of heat to the cylinder walls; this, however, is offset to a considerable extent by the higher speed at which the smaller engine normally runs. Taking all these factors into account we find that, on balance, the efficiency of the heavy oil engine is independent of size.

The two lowest fuel consumption figures of which I have been able to obtain any authentic records are 0·35 lb. per brake horse-power hour obtained on a very large engine of about 1,000 h.p. per cylinder running at 80 r.p.m. and 0·347 lb. of the same fuel per brake horse-power obtained from a very small engine of only 5½-in. bore running at 1,500 r.p.m., an overall thermal efficiency of approximately 39 per cent. in each case. In the latter case the engine was driving the whole of its auxiliary gear, but I have not been able to ascertain whether this applied in the case of the large engine.

Before concluding, I am going to take the rather unconventional course, in a technical lecture, of asking you to accompany me, in imagination, inside the cylinder of a Diesel engine. Let us imagine ourselves seated comfortably on the top of the piston, at or about the end of the compression stroke. We are in complete darkness, the atmosphere is a trifle oppressive, for the shade temperature is well over 500° C.—almost a dull red heat—and the density of the air is such that the contents of an average sitting room would weigh about a ton; also it is very draughty; in fact, the draught is such that in reality we should be blown off our perch and hurled about like autumn leaves in a gale. Suddenly, above our heads a valve is opened and a rainstorm of fuel begins to descend. I have called it a rainstorm, but the velocity of the droplets approaches much more nearly that of rifle bullets than of raindrops. For a while nothing startling happens, the rain continues to fall, the darkness remains intense. Then suddenly, away to our right perhaps, a brilliant gleam of light appears moving swiftly and purposefully; in an instant this is followed by a myriad others all around us, some large and some small, until on all sides of us the space is filled with a merry blaze of moving lights; from time to time the smaller lights wink and go out while the larger ones develop fiery tails like comets; occasionally these strike the walls, but being surrounded with an envelope of burning vapour they merely bounce off like drops of water spilt on a red-hot plate. Right overhead all is darkness still, the rainstorm continues, and the heat is becoming intense; and now we shall notice that a change is taking place. Many of the smaller lights around us have gone out, but new ones are beginning to appear, more overhead, and to form themselves into definite streams shooting rapidly downwards or outwards from the direction of the injector nozzles. Looking round again we see that the lights around are growing yellower; they no longer move in definite directions, but appear to be drifting listlessly hither and thither;

here and there they are crowding together in dense nebulæ and these are burning now with a sickly smoky flame, half suffocated for want of oxygen. Now we are attracted by a dazzle overhead, and looking up we see that what at first was cold rain falling through utter darkness has given place to a cascade of fire as from a rocket. For a little while this continues, then ceases abruptly as the fuel valve closes. Above and all around us are still some lingering fireballs, now trailing long tails of sparks and smoke and wandering aimlessly in search of the last dregs of oxygen which will consume them finally and set their souls at rest. If so, well and good ; if not, some unromantic engineer outside will merely grumble that the exhaust is dirty and will set the fuel valve to close a trifle earlier. So ends the scene, or rather my conception of the scene, and I will ask you to realise that what has taken me nearly five minutes to describe may all be enacted in one five-hundredth of a second or even less.

LECTURE II.

During the first 30 years of its existence the Diesel engine changed very little. It grew in size and it grew very slightly in speed, but this was normal evolution and no important change was made. Engineers were discouraged from even attempting to produce a really fast-running engine by the belief, which until recently was almost an article of faith, that the combustion process in the Diesel cylinder occupied so long a period of time as to render really high speeds utterly out of the question. Nearly 10 years ago the Royal Aircraft Establishment, on instructions from the Air Ministry, carried out a series of experiments on a large petrol engine strengthened and modified to run as a Diesel. These experiments quickly dispelled the myth that the Diesel engine must not be hurried. Not only were they successful in running the engine at more than double the highest speed which had previously been considered possible, but even at a piston speed of 2,000 feet per minute they obtained an efficiency actually as high as the best that had been obtained at that date by any Diesel engine, large or small. This success (which has never received the acknowledgment it deserves) marks a turning point in the history of the Diesel engine. We are loath to believe in the achievements of our own countrymen, and, as has so often happened before, it was left to Continental engineers to appreciate the significance of this development. Inspired and guided by the experiments at Farnborough, they set to work to produce high-speed Diesel engines, while most English engineers continued in their belief that the thing was impossible. Now that it has been shown, or rather, I should say, reflected from the Continent, that the Diesel engine can be made to run at really high speeds, the interest of the designers of petrol engines has been awakened, with the result that there is being applied to this type of engine all the skill in design, the meticulous attention to mechanical detail, and the superb workmanship which together have made the modern petrol engine the most perfect piece of mechanism in existence.

In my last lecture I pointed out that, in a Diesel engine, the combustion process may be considered as taking place in three stages. First a delay period, followed by a more or less rapid rise of pressure, and lastly, a period during which the fuel is burning as it issues from the jet. Let us consider what is necessary to speed up each of these several stages, and, in particular, the delay period. The duration of the delay period depends primarily upon the excess of the air temperature over and above the self-ignition temperature of the fuel.

We can further raise both the temperature and pressure of the air by increasing the ratio of compression, and this, of course, is the simplest and most obvious way, but in this we are limited, for increase of compression ratio involves a considerable increase in the period during which the bearings, etc., are subjected to high pressure, while, unless we allow the maximum pressure also to rise considerably, we gain very little in expansion ratio and therefore in efficiency. Again, the denser the air, the more difficult it becomes to distribute the fuel and to find the necessary oxygen, with the result that as we raise the compression beyond a certain point, depending on the design of the engine, we gain next to nothing in efficiency, we lose a little in power output, and we increase considerably the strain on the engine generally and on its bearings in particular.

We can reduce the delay period by increasing the movement or turbulence of the air, provided always that we maintain the temperature. In the ordinary course of events, the greater the turbulence the greater the flow of heat to the cylinder walls and, therefore, the lower the compression temperature. Clearly it avails us nothing if we gain movement only at the cost of losing heat. There are, however, ways of increasing turbulence without lowering the temperature of compression, for with skill and care we can arrange to introduce partially insulated and therefore hot surfaces so placed that the air will sweep over and pick up heat from them during compression, but will avoid them during its entry to the cylinder; thus we can raise the compression temperature without any loss of weight during entry. Yet again, we can reduce the delay period by increasing the pressure without increasing the temperature—that is to say, by supercharging—and lastly we can reduce it by doping the fuel to lower its self-ignition temperature. Whatever we decide to do, our first preoccupation must be to reduce to the limit the delay period, for not only does a long delay involve very high maximum pressures, but it means also lack of adequate control over the pressure and, what in practice is worst of all, the rapid pressure rise following a long delay period, causes very rough running and what has come to be described as "Diesel knock," a hammer-like blow very similar to detonation in a petrol engine.

If the conditions as to temperature and motion of the air in an engine cylinder were constant at all speeds, then the delay period would be nearly constant in time and, therefore, relatively greater as the speed is increased. Fortunately, they are not constant ; as the engine speed increases, the temperature of compression increases, also the turbulence, with the result that the delay period decreases in terms of time ; and even in terms of crankangle it increases only very slightly with increase of speed. It is true that in a small and high-speed engine we can afford to let the maximum pressure rise to nearly double the compression pressure, and are glad to do so on the score of efficiency, but we want to do it in our own way and under our own control, that is, by appropriate timing and rate of injection. We most certainly do not want to be jockeyed into it as the result of a long delay period.

With regard to the second stage, namely, the burning of the fuel which has entered during the delay period, the rate at which this will proceed depends primarily upon the rate at which the droplets can find oxygen ; that is to say, it depends upon the relative motion between the fuel and the air. Here again, as the speed is increased, so is the velocity both of the fuel injection and of the air movement within the cylinder, with the result that this speeds up and keeps pace automatically with the speed of the engine.

The third stage, namely that of controlled burning from the nozzle, depends solely on the rate of fuel admission and is at all times proportional to the engine speed.

During this stage we have direct mechanical control over the pressure in the cylinder, and this is the stage we should like to prolong at the expense of the other two. Its extent is all too short

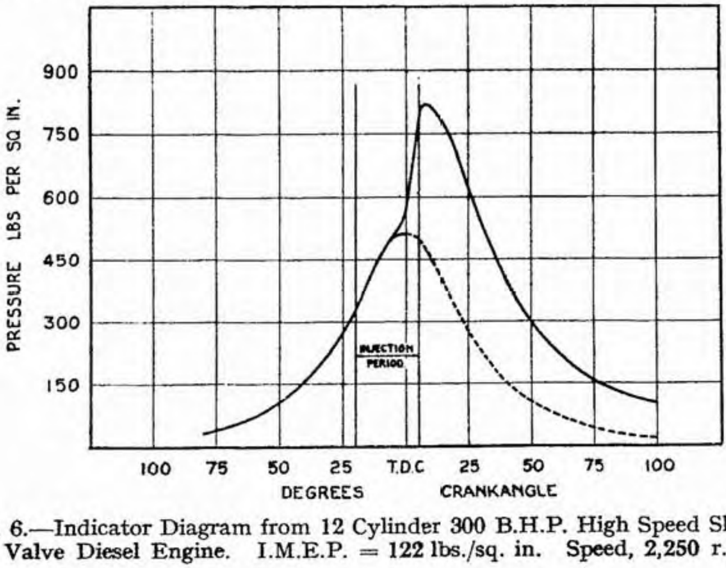


FIG. 6.—Indicator Diagram from 12 Cylinder 300 B.H.P. High Speed Sleeve Valve Diesel Engine. I.M.E.P. = 122 lbs./sq. in. Speed, 2,250 r.p.m.

as a rule, and in many cases it is shouldered out of existence by the first two stages.

Fig. 6 shows an actual indicator diagram taken from a high-speed Diesel engine running at 2,250 r.p.m. Fig. 7 shows actual diagrams taken from another high-speed Diesel engine when running normally and when supercharged. Fig. 8 shows the effect on the second stage of varying the air velocity within the cylinder.

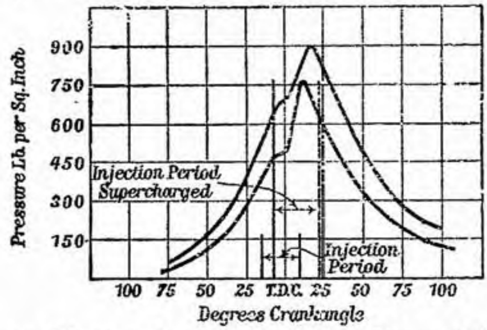


FIG. 7.—Indicator Diagram from 5½-in. × 7-in. Sleeve Valve High Speed Diesel at 1,300 r.p.m. I.M.E.P. Unsupercharged 141 lbs./sq. in. I.M.E.P. Supercharged 1·5 ATMS ABS 192 lbs./sq. in.

The advent of a really high-speed Diesel opens a new and vast field to the scope of the Diesel engine, for it now becomes available for road work. This is by far the largest territory of all, and is the only one over which the internal combustion engine already reigns supreme. Road service is exacting, cruel and terribly intolerant ;

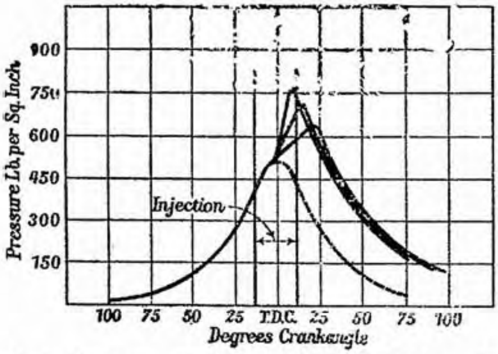


FIG. 8.—Indicator Diagram at three different Rates of Swirl. Speed, 1,300 r.p.m.

to qualify for it an engine must be capable of accomplishments undreamed of by any other prime mover. In most other services an engine is luxuriously housed and served by skilled engineers trained to anticipate all its needs and to minister to its ailments—it is allowed to run at its own chosen speed and is seldom, if ever, overloaded. Contrast this with the treatment meted out to, say, a modern bus engine. Here the engine is called upon to run about 16 hours per day in the hands, not of one driver who has grown accustomed to its whims, but of anyone who may be detailed to take charge of it from day to day. It is kicked off early in the morning and turned to work at once; it is run at any speed and any overload, at the whim of a driver who knows nothing of its anatomy and who considers that his daily obligations towards it are fulfilled so long as he sees that one compartment is kept reasonably full of fuel and another of lubricating oil. Of sympathetic attention it receives none whatever, nor is it ever seen, much less tended, while at work. At long intervals only is it even looked over by any skilled engineer, and in the ordinary course of events it is expected to carry on day after day and month after month with never a kind word or a sympathetic glance. To such use does the Diesel engine now aspire.

Such high-speed engines as have yet been developed may be divided into three general categories :—

(1) Those which depend upon high velocity and carefully aimed fuel injection, in an open combustion chamber—that is, those in which the fuel has to find the air.
(2) Pre-combustion chamber engines.
(3) Those which depend upon an orderly rotational air swirl across which the fuel is projected—that is to say, those in which the air has to find the fuel.

To these must be added the Acro Bosch system, a hybrid which does not fall into any of the above three categories.

Each of these systems has its advantages and its disadvantages, its champions and its opponents.

The first category, namely, the directed spray system, is that which was used at Farnborough in the classic experiments to which I have referred already. It is in no way novel, for it has been used in slow-speed engines for many years; it was developed by Messrs. Vickers and the Navy for submarine engines more than 20 years ago. That it has recently been adapted to very high speed engines is due to the fact that it has been overhauled and perfected by highly-skilled petrol engine designers rather than to any change in the system. In other words, the high-speed engine has been adapted to the principle, rather than the principle to the engine.

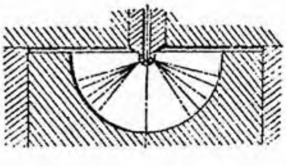


FIG. 9.

In this system shown in Fig. 9 the fuel is injected into an open combustion chamber of compact form, through a number of very fine jets aimed in various directions in order to spread the droplets as uniformly as possible throughout the air. There is, of course, a certain amount of turbulence due to the entering velocity of the air, but no attempt is made to stimulate this or to give it any organised directional flow. We rely upon the aiming of the fuel, coupled with a general rough and tumble turbulence of the air, to bring the two together. The great advantages of this system are that, owing to the lack of intensive turbulence and to the compact form of the combustion chamber, the loss of heat during compression is at a minimum, hence the delay period is short, the running is fairly smooth, the engine starts easily from cold, and will run on a wide variety of fuels. Again, owing to the compact chamber, the loss of heat during combustion is small and the efficiency is very high. Thus, with this system, we arrive at an engine of high efficiency, high power output, fairly smooth running and very easy starting—all very solid advantages.

The disadvantages are :—

(1) Our speed is limited by the speed at which the liquid fuel can travel throughout the combustion chamber. This involves the use of excessively high oil pressures, and even so, we eventually reach a critical speed of liquid flow which imposes a limit on our speed of rotation. Since the speed of projection of the liquid is determined by the pressure, or in the limit, by the critical speed of flow, it follows that as the engine speed is increased the time of injection must be advanced accordingly, just as the time of electric ignition must be advanced in a petrol engine, when the turbulence is inadequate. This means that we must place the control of the maximum pressure in the hands of the driver—a dangerous concession.

(2) The very high fuel oil pressure necessary with this system adds greatly to the difficulty of making suitable fuel pumps and fuel valves ; moreover, with these very high pressures, the leakage loss becomes the more serious as the size of the engine is reduced.

(3) It is necessary to employ a number of exceedingly small fuel jets and to maintain at all times precisely the same direction of flow from each of these jets. Not only is it extremely difficult to produce and subsequently to maintain the correct angle between all the various minute jets, but this angle is liable to be deflected by partial choking of the jet orifices.

(4) The susceptibility of these extremely small orifices to erosion on the one hand, and to partial or complete stoppage on the other hand, is at all times serious and increases

rapidly as the size of the engine is reduced. Even in a 5-in. cylinder the actual size of the holes is only about 0·008-in. The material of the flame-plate containing these minute orifices must necessarily be hard, to resist erosion, and the difficulty of drilling such holes of the correct diameter, length and angle, is no trifling one; moreover, in the event of a single hole becoming blocked under an oil pressure of some 8,000 to 10,000 lbs./sq. in. it is almost impossible to clear it and it generally becomes necessary to scrap the whole flame-plate.

Generally speaking, while the principle of directed spray is eminently suitable to large slow-running engines where the size of the jets is generous and where, on account of the low speed, a comparatively low oil pressure will suffice, this principle becomes extremely tricky and delicate when applied to small high-speed engines.

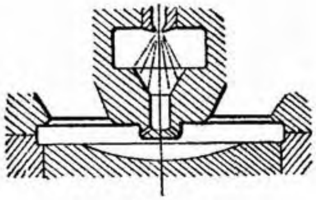


FIG. 10.

The second category employs what is termed a pre-combustion chamber, shown diagrammatically in Fig. 10. This consists of a small auxiliary chamber communicating with the main combustion chamber through a series of small holes. Fuel is sprayed into this auxiliary chamber and proceeds to burn therein; as the pressure rises, the partially burnt fuel is shot out through the small communicating holes at a very high velocity into the main body of the combustion chamber, where it quickly finds the oxygen necessary for its complete combustion. In this system, therefore, stages one and two are enacted inside the auxiliary chamber, while the projecting of the already blazing droplets into the main combustion chamber corresponds with the burning direct from the nozzle and forms the third stage. In so far as the third stage is concerned, the conditions are similar to those which obtain in any air injection engine, for the rapid rise of pressure inside the pre-chamber is made use of both to pulverise and to distribute the fuel. This system has certain important advantages; the actual fuel orifice can be fairly large, the precise direction of flow is of very little importance, and a relatively low oil pressure can be used. The duty of the fuel pump becomes, therefore, comparatively simple; it must meter accurately and it must time correctly, but owing to the low pressure, leakage troubles are not serious and, what is more important, thanks to the much lower oil pressure, the timing and metering are not affected seriously by the spring of the piping, etc., nor by the elasticity of the liquid fuel itself.

The disadvantages of the system are that—

A large proportion of the air during compression and nearly the whole of the burning fuel during combustion must be passed at an excessively high velocity through a number of small holes, with, in consequence, a very heavy loss of heat. This means—

(1) That, in order to attain a sufficiently high temperature for combustion, a very high ratio of compression must be employed, thus increasing the pressure scale generally and necessitating the use of very heavy working parts.

(2) Owing to the very large heat loss during the passage of the burning gases through the small holes between the pre-combustion chamber and the main combustion space, both the power output and efficiency are greatly reduced, the loss being of the order of 15 per cent. to 20 per cent.

(3) Owing to the loss of heat during compression the engine is a non-starter from cold and it becomes necessary to resort to artificial means of restoring the lost heat, such as the use of electric glow lamps, or fuses. Generally speaking, this principle has the merit of ease and simplicity, but these advantages are bought only at the expense of a heavy handicap in the way of power output and efficiency, and we are left with the combination of a very high compression ratio necessitating heavy parts, and a poor performance to boot.

The pre-combustion chamber would appear to be an easy but an inefficient, and therefore a temporary, way of getting round a difficult problem.

The third principle, that of causing the air within the combustion chamber to rotate at a high velocity past the fuel jet as in a petrol carburettor is, I am inclined to think, by far the most satisfactory. This principle, which is illustrated in Fig. 11, appears to combine the simplicity of the pre-combustion chamber with the power output and efficiency of the directed spray type.

Following this principle, the air is admitted to the cylinder tangentially during the suction stroke in order to produce a rapid and ordered rotary motion within the cylinder, as distinct from general turbulence. The combustion chamber itself may consist of a plain cylindrical pot of about half the diameter of the cylinder into which the whole of the air is compressed. In this chamber the air rotates at an extremely high speed. Into this rapidly rotating mass of air a stream of fuel is projected vertically downwards, that is, at right angles to the air flow. The stream of fuel is not admitted to the centre but right out towards one side of the combustion chamber, so that, during its rotation, the main body of the dense and highly heated air sweeps past the jet of fuel. In this manner the whole of the fuel is burnt in a current of rapidly moving air while fresh oxygen is being brought constantly across the fuel stream to replenish that which is being consumed.

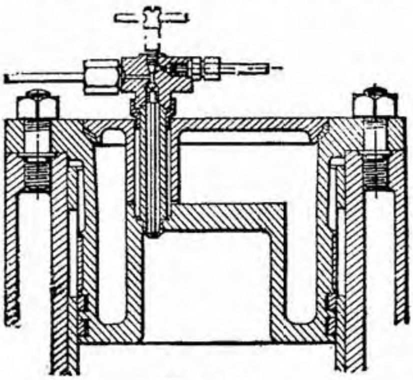


FIG. 11.

The advantages of this system are—

(1) That the combustion air itself is utilised both to pulverise and to distribute the fuel; hence, as in the case of a pre-combustion chamber engine, a low oil pressure may be used, together with a single orifice of relatively large diameter.

(2) Neither the velocity nor the direction of the fuel jet are of vital consequence, since we depend upon the air to find the fuel rather than upon the fuel to find the air.

(3) Our speed is unlimited by any conditions of injection, since the speed of rotation of the air increases proportionally with that of the engine and we are very little dependent upon the velocity of the fuel stream. Hence we can work with a fixed injection timing throughout the whole speed range of the engine.

(4) No fuel valve in the ordinary sense of the word is required; we need only a plain jet, as in a carburettor, and some very simple form of check valve merely to prevent air being forced back into the fuel system.

The disadvantages of this system are—

(1) It can be used to the best advantage only when the air is admitted to the cylinder through ports round the circumference, that is to say, in two-cycle engines or in sleeve valve four-cycle engines.

(2) The outer layer of air into which the fuel is projected is cooled somewhat by its rapid flow over the cold walls of the combustion chamber, hence the engine does not

start so readily from cold and the delay period is increased. This latter can, however, be obviated by fitting a loose liner inside the combustion chamber which will reach a temperature well above the mean temperature of compression, while the starting can be facilitated, if necessary, by checking the air swirl by means of guide vanes placed outside the air intake ports, which can be set normal when starting and tangential when running.

The system of rotational air swirl, when applied to a two-cycle or sleeve valve four-cycle engine, allows of a larger proportion of the oxygen being utilised and therefore a higher power output per unit of cylinder capacity than any of the others. Also the highest efficiency yet recorded in either large slow-speed or small high-speed engines has been obtained with this system.

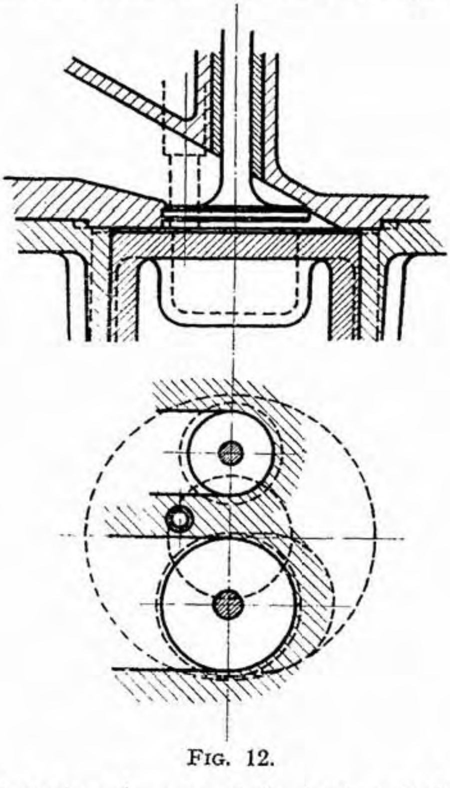


FIG. 12.

Although this system is seen at its best only in two-cycle or sleeve valve engines, yet very good results have been obtained when it is applied to poppet valve engines. In this case the necessary air swirl can be produced :—

(1) By masking part of the circumference of the inlet valve—the system adopted by Hesselman and others. This is

open to the objection that, in order to give a sufficiently rapid swirl, nearly one-half of the circumference of the valve must be blanked off and nearly one-half the breathing capacity of the engine must be sacrificed, as shown in Fig. 12. This is all very well for low or moderate speed engines, but is a very serious handicap when really high speeds are attempted. Again, the same result can be achieved by separating the combustion chamber from the main body of the cylinder and forcing the air into it through a tangential passage during the compression, as shown in Fig. 13. In this manner, ample rotational swirl can be obtained, but at the cost of some heat loss, for the burning gases have also to pass out through this passage at a high velocity and in so doing lose heat to the surrounding walls.

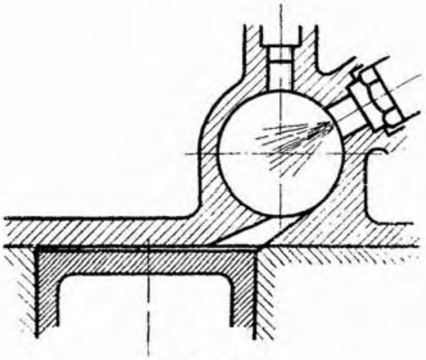


Fig. 13.

In the Acro Bosch system, shown in Fig. 14, the combustion chamber is divided into two compartments of nearly equal capacity separated by a narrow neck. The air in the first compartment, which is open directly to the cylinder, is relatively quiescent, but that in the second compartment has been forced to enter through a narrow passage and is in a state of violent turbulence. Fuel is injected across the first compartment and aimed at the opening into the second, which is generally termed the air cell. The process of combustion in this case is somewhat speculative ; ignition probably takes place at or about the mouth of the air cell and combustion probably oscillates very rapidly on either side of the restricted neck and is completed during the expansion stroke by the outflow of the remaining air from the air vessel. The whole system is extremely sensitive, and depends for its proper functioning on a nice balance both of penetration of the fuel jet and of the delay period. Over penetration or too long a delay period will allow fuel to penetrate into the air cell, where it will burn far too rapidly owing to the excessive turbulence, and so give rise to excessive knocking and very high maximum pressures. The scheme is ingenious but depends for its proper functioning on a nicety of adjustment which is hard to maintain in practice.

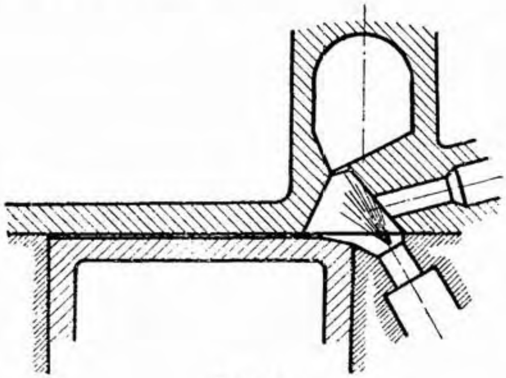


FIG. 14.

The power output of any internal combustion engine depends primarily upon the weight of air which can be passed through the cylinder in unit time. We can increase this either by increasing the speed or by supercharging or both. In the most recent developments of high-speed engines we have nearly reached the limit of speed as set by the dynamic loading on the bearings and by the valve mechanism, and to gain any substantial further increase we must turn our attention to supercharging for this, though it increases somewhat the gas pressures, does not increase the dynamic loading. If we seek to double the power output of a given engine, we may do so either by supercharging to double the initial atmospheric pressure, in which case we shall double the gas loading on the bearings, but leave the dynamic loading unaltered; or we may double the speed, in which case the gas loading remains unaltered, but the dynamic loading is increased to four times. This, in the present state of the art, would be quite prohibitive. The supercharging of petrol engines for aircraft and for racing purposes is, of course, common practice, and it is customary also in the case of large slow-running Diesel engines. Though a great deal of experimental work has been carried out on the supercharging of high-speed Diesel engines, very little has, as yet, been put into practice. When we apply supercharging to a petrol engine, we raise the whole pressure scale throughout, and the gain in power is in direct proportion to the absolute pressure; actually it is rather more than in proportion, for the clearance space in the combustion chamber is supercharged also. In the case of the Diesel engine, we cannot afford to allow the maximum pressure to rise in proportion, for it is presumably already almost as high as is good for the bearings. This means that when supercharged we must work much more nearly on a constant pressure cycle and so lose in efficiency through the reduced expansion ratio. Again, when supercharged, but with the maximum pressure limited to the normal figure, the fuel admission becomes so late that we are injecting into retreating air and so have more difficulty in finding the oxygen. Lastly, the clearance volume in a high compression Diesel engine is so small that we gain very little on this score. Taking all these factors into consideration, we find that whereas supercharging the petrol engine to double the initial atmospheric pressure considerably more than doubles its power output, the same degree of supercharge increases the power output of the Diesel engine by about 75 per cent. only. On the other hand, the increased density of the air when supercharged tends greatly to reduce the delay period, and therefore to give us better control over the pressure and in consequence sweeter and smoother running. Personally, I doubt very much whether, apart from certain specialised uses, it will pay individually to supercharge small high-speed Diesel engines as a regular habit, for the supercharger itself adds considerably to the cost and complication of the engine, but I think there can be no doubt that, wherever groups of engines are installed, it will pay handsomely to provide a single large blower and to supercharge the whole group during periods of overload. In many large Diesel engines, particularly large marine engines, the Buchi exhaust turbine supercharger is employed. During the War, both we, in this country, and the French also, developed exhaust turbine superchargers for aircraft engines for high altitude work, but they did not prove very successful and have now been superseded by gear-driven superchargers. The Buchi supercharger, as now fitted to large engines, differs very little from that used for aircraft, and its success is due probably to the higher efficiency which improved technique and, above all, larger size confer.

In the case of large slow-running Diesel engines, the two-cycle system holds nearly equal sway with the four-cycle, but with one or two striking and interesting exceptions, notably the Junkers engine and the new high-speed Petter engine, the four-cycle system at present reigns supreme among the smaller fast-running engines. At first sight, the obvious simplicity of the two-cycle engine looks most convincing, but simplicity is a fickle jade—too often it spells merely excess of compromise. To abolish all valve gear with its cost, its noise and its various ailments, to make the existing piston do substitute for all this mass of intricate mechanism and to use it and the crankcase as a scavenging and charging pump, sounds ideal, for it reduces an engine to the very acme of simplicity. Unfortunately, the piston is not an efficient valve, while the crankcase is far from being an efficient air pump. When a single piston is used in this manner, all the functions of respiration must be symmetrical about the bottom dead centre, and in postulating this we outrage every one of them. We require first to open the exhaust ports alone and to allow the exhaust to escape until its pressure has fallen to nearly atmospheric ; next, we require to open the inlet ports also and to allow air at a low pressure to sweep through the cylinder and to expel as much as possible of the remaining exhaust products ; lastly, we require to close the exhaust ports, still leaving the inlets open and to allow air at a higher pressure to enter and partially to supercharge the cylinder. To carry out these functions effectively the piston valve should be out of phase with the crank, and the scavenge piston out of phase with the main piston. Clearly, this cannot be accomplished so long as the main piston assumes the functions either of valve or of displacer or both. Yet again, in order effectively to scavenge the cylinder it is desirable to separate the inlet and exhaust ports by the full length of the cylinder barrel, while, to give adequate port area to enable the two-cycle engine to compete in power output with the four-cycle, it is necessary to use nearly the whole circumference of the cylinder for each set of ports. Clearly, a single piston cannot alone control two completely independent belts of ports separated one from another by the whole length of the cylinder. We can achieve the desired end by using two pistons moving in opposite directions with their respective cranks set out of phase with one another or by using one piston controlling one belt of ports alone and either poppet valves or a sleeve valve to control the other. In the former case we are faced with the difficulty of utilising the power from the second piston, while in the latter we have introduced in the two-cycle the valve mechanism of the four-cycle. In either case, gone is the charm of simplicity.

In dealing with two-cycle engines, I have started by stating the case against them, but I do not for a moment wish to imply that either in the simple or the complex form there is not an equally strong or even stronger case in their favour. In the simple crankcase scavenging form none of the functions are performed adequately ; the piston is out of phase with the ports it has to control, the scavenge pump is both out of phase and of inadequate capacity, and, in fact, compromise has run riot. On the other side of the picture such engines have given, and will continue to give, admirable service in applications where neither bulk nor weight nor efficiency are of first importance. The handyman who does everything a little, but nothing well, is often more valuable than the specialist, and of the simple two-cycle engine we can justly say that it is a handyman par excellence.

In its complex form and with an independent air pump or blower, the two-cycle engine has no advantage on the score of simplicity over its four-cycle competitor, but in this form it can compete with the latter on its own ground, and in many applications will probably defeat it. With double rows of ports we can pass more air through the cylinder in unit time than in a four-cycle engine, and so can develop a greater power from the same size and weight of engine even than the supercharged four-cycle. Moreover, owing to the fact that the dynamic loadings are largely balanced by and, therefore, cancelled by the gas pressure, the bearing loads are reduced enormously, while the greater uniformity of turning moment is yet another important advantage in favour of the two-stroke cycle. In places where weight and bulk are primary considerations—as, for example, in aircraft—it would appear to have every advantage. As to other applications, I am not so sure. The efficient two-cycle engine, like the supercharged four-cycle, needs an efficient and, in most applications, an inexpensive and silent blower; for this we are still waiting. No one yet has solved satisfactorily the problem of dealing with large quantities of air at a pressure of about 4 to 6 lbs. (the pressure needed either to scavenge a two-cycle or to supercharge a four-cycle engine). Such a pressure is an out-size, it is too high for a simple fan, too low for a piston pump; a rotary displacement blower is indicated, but something cheaper, lighter and more compact, than is available at present. When this problem is solved the two-cycle engine will, I think, come into its own as an active competitor of the light high-speed four-cycle engine.

LECTURE III.

In my last lecture I dealt with the application of the Diesel cycle to high-speed engines. This is quite a recent development, and bids fair to be by far the most important one in the life history of the heavy oil engine.

Because of its economy in space and in material, the slow-speed engine must always, it seems to me, give place to its higher speed offspring. This, I believe, is almost a law of evolution. We have already seen this progress through several phases in the case of the steam engine. The staid slow-running type gave place to the Willan's quick-running single-acting engine; this was ousted by the even quicker running double-acting engines of the Belliss type; these, in turn, were displaced by the still faster running turbine. The same process of evolution is, I think, bound to proceed in the case of the internal combustion engine, though, as yet, I see but little prospect of the turbine as an ultimate stage of its development.

I do not suggest that such development will proceed smoothly, there will be periodic setbacks due to designers and makers overreaching themselves, and still more, perhaps, to inappropriate treatment; further, there will inevitably be much opposition and heartburning due to shattered traditions. No new development in engine design within my experience has been made without much bitterness of heart. There is always a large body of conservative opinion to regret or even resist any change, and he would be unimaginative indeed who did not appreciate and sympathise with this regret. Gone for ever is the impressive magnificence of the large and stately steam engine with all its romance and unhurried dignity ; in its place we have to-day a machine which looks no more imposing than a beer barrel ; no more romantic than a piece of drainpipe ; but such, alas ! is progress.

I have seldom met an operating engineer who did not groan in spirit when first inflicted with a quicker-running or more self-supporting engine than he had been accustomed to previously ; but, on the other hand, I have never met one who, after prolonged experience, would conscientiously recommend his Board to revert to the older type. The truth is that we all sigh for the good old days, but I doubt if one of us would accept the offer of a lift on a magic carpet.

High speed and small size are, of course, relative terms, and before proceeding further I had better define a little more closely what such terms, imply to me. By high speed I mean a piston speed of 1,500 or more feet per minute, and by small size I mean something less than 8 in. diameter of piston, and I am going to suggest that the internal combustion engine of the not far distant future will invariably run at a piston speed of over 1,500 ft. per minute, and that, for all powers and for all purposes, cylinders of less than 8 in. and probably of less than 6 in. diameter will suffice eventually—save possibly for a few exceptional applications, where the mechanical gearing of a large number of small quick-running units to, say, a single low-speed shaft may introduce intolerable mechanical difficulty. By keeping down to such sizes we lose nothing in efficiency, we gain considerably both in first cost and in weight per horse-power, and above all, we keep clear of trouble due to heat stresses.

The most striking feature of recent times is the extraordinarily rapid development of the light mobile high-speed petrol engine. To-day the output of such engines is of the order of 300,000,000 h.p. annually, and probably about ten times that of all other prime movers—steam, water or oil—put together. At present 99 per cent. of this huge output is catered for by engines using petrol as their fuel, and while I am well aware that if we suddenly changed from the use of petrol to that of Diesel oil the price of the latter would rise to very nearly the same level, yet so vast is the demand that we could bring into use many millions of horse-power of heavy oil engines without disturbing appreciably the present economic balance.

The essential advantage of the light engine is its ease of transport, whether under its own power or as a passenger ; the next advantage is its low cost of manufacture when made in bulk. The petrol engine of to-day, comprising the most superb workmanship, costs from 20*s*. to 40*s*. per horse-power, according to the output of the manufacturer, and there is no earthly reason why the high-speed Diesel should not ultimately come down to very near these figures when it is manufactured in quantity by firms who are already accustomed to build petrol engines in bulk. Certainly, it requires no better workmanship nor material than is at present put into the petrol engine as built to-day by any reputable firm.

One of the arguments used against the high-speed engine of any type is that wear will be excessive, and the cost of maintenance and renewals prohibitive. With this I cannot agree, nor is it borne out by experience with such engines as, say, bus engines, which run regularly 16 hours per day, and under about the most severe conditions imaginable.

Before proceeding further, I would like to enlarge a little on the question of wear. Broadly speaking, it may be stated that the cost of renewal of worn parts is directly proportional to the weight of material worn away, irrespective of the size or speed of the engine. Given equal lubrication and equal surface hardness, the rate of wear in terms of lbs. per hour will be much about the same for either slow or high-speed engines, but the high-speed engine cannot, on account of its small size, sustain so large a loss by wear as the larger slow-running type. The high-speed engine, however, can and does employ harder wearing surfaces and is better lubricated; consequently, although renewals must be more frequent, they are not proportionately so, and, when necessary, are much less expensive. Moreover, owing to the small size and ease of handling of the parts, renewals occupy far less time.

On the general grounds, therefore, of wear and cost of renewal, it may be concluded that, although more frequent renewals will be required, the aggregate cost of these renewals and the aggregate loss of working hours will, on the whole, be substantially less in the case of the high-speed engine. It is not suggested, and, indeed, it is misleading even to suppose, that the high-speed engine will run for such long periods without overhaul and renewals as the slow-speed type, but it is argued that these overhauls and renewals, though more frequent, are far less expensive and occupy far less time.

We are now, I believe, on the eve of seeing the light high-speed Diesel turned out in bulk production like the petrol engine, and it behoves us, I think, to review and revise our ideas as to how it is to be treated. In the first place, we must keep it always before our minds that the efficiency of the Diesel engine is absolutely independent of size. In the past the Diesel engine's chief competitor was the steam engine, and the steam engine is efficient only in very large units. From long acquaintance with the steam engine, we have grown accustomed, therefore, to think in terms of few and large units; we have struggled hard and, to my mind, quite unnecessarily, to produce very large Diesel engines, and in doing so we have run into all manner of troubles which might easily have been avoided. For a given aggregate horse-power we are bound, on the score of efficiency, to employ the largest possible units when steam is the motive power, but where Diesel engines are used we should, I contend, employ the largest possible *number* of units each of the smallest possible size. By so doing we shall, in fact, gain in efficiency, since the units in operation can be run always at their most economical load factor. We shall gain enormously in first cost; we shall gain enormously both in weight and in space occupied; and, above all, we shall gain, hands down, in reliability. I have never been able to discover whether the aversion to a large multiplicity of units is due to steam tradition or to mere fear of the unusual. As a rule, the arguments advanced against it appear to me to lack weight. One is asked to view with horror the vision of a power plant containing, say, 1,000 pistons and 2,000 valves, all of which have to be maintained in working order, and to turn with comfort and assurance to, say, a single turbine doing the same work. At first glance the comparison may seem appalling, but let us consider it a little more closely. Of the 1,000 pistons we can afford to allow anything up to, say, 100 or 150 to go wrong even simultaneously and still be able to carry the full load, for the remaining units will have at least a 10 to 15 per cent. temporary overload capacity. We could afford to crash even 200 or 300 units at the same instant without any serious inconvenience. Now let us consider the single turbine. Inside its simple casing, unseen but not forgotten, are several thousand blades, the failure of any single one of which will bring the entire plant to a complete standstill. The chance of a turbine blade coming adrift is, happily, fairly remote, but the chance of a thousand Diesel engines all breaking down at the same moment is almost beyond the bounds of possibility. One is told, again, that the engineer in charge of such a Diesel plant would be so worn out with anxiety that he would never sleep a wink. One of the largest and probably quite the most important power plant in the world is the four hundred thousand horse plant, which is responsible for the above-ground passenger traffic of London. A failure of this plant would certainly cause annoyance and dislocation to more people and to more business interests than of any other I can conceive. This plant consists of over 5,000 engines with 30,000 pistons and 60,000 valves, yet the engineer in charge of the London General Omnibus Company is anything but a nervous wreck and, I am told, sleeps like a child.

It is my confirmed belief that the Diesel engine of the future will be a small high-speed unit of a size which can be turned out very cheaply by bulk production methods, and that where large power concentrations are required, we shall employ large batteries of such units. We must, however, revise also our ideas as to how such engines are to be handled. The large slow-running engine is far from self-supporting—it requires sympathetic care and constant attendance; the high-speed engine requires none of these things; in fact, there is nothing whatever that the most conscientious or sympathetic attendant can do to minister to its needs. So long as it has oil and fuel it will run, for its lubrication is entirely automatic, and whether tended with skill or neglected, it will continue to run for a similar period until wear or carbonisation bring that period to a close. Experience will soon show just how long it is economical to allow any particular make of engine to run between overhauls.

When the time is ripe for overhaul the engine will be removed bodily and replaced by a reconditioned unit. There should be no question of repairs *in situ:* if an engine is out of order or has run its allotted span, it should be removed and replaced by another. In the case of light high-speed units this can be done by a couple of fitters in an hour or so, and the decarbonising or reconditioning of the weary engine can be carried out in comfort and at leisure in a properly appointed hospital. In hospital the engine will be subjected to one or other of two treatments, either what, in aircraft parlance, is termed a top overhaul—that is, decarbonising, cleaning the piston ring grooves and possibly replacing any faulty rings and grinding or adjusting the valves and injectors—or to a general overhaul involving probably the fitting of new liners, bearings and other wearing parts. The former, in the case of a 100 to 150 h.p. engine, can be accomplished by two mechanics in one day; the latter may involve a week's work while the cost of replace parts may amount to 10 per cent. of the first cost of the engine. It is early days yet to say how frequently such overhauls will be required, but, speaking from my own experience to-day, with two high-speed sleeve valve Diesel engines, one of 100 h.p. and the other of 300 h.p., during three years of strenuous service I find that in the present state of the art it pays to give a top overhaul—that is, one day off—every 1,200 hours, and the indications are that a general overhaul will probably be desirable after 9,000 hours. Taking the average service of an engine as eight hours per day, this means a top overhaul—that is, one day off—once every six months, and a general overhaul—say, 10 days off—every three or four years. As technique and experience develop these periods will gradually be extended. In the case of aircraft engines, for example, the untouched running period is now just three times as long as it was ten years ago, despite reduction in weight and improved performance gained during this period.

So rapid has been the development of the light high-speed Diesel engine during the last few years that it is now competing in that most exacting and difficult of all services, the public service road vehicle. Here it is attacking the petrol engine in its securest stronghold. In this vast field it has to compete with probably the most highly developed and mechanically perfect prime mover in existence. In its competition with petrol, the Diesel engine has one trump card, its much lower fuel consumption and, at the moment, this card has an exaggerated value because of the tax on its rival's fuel. This latter is a temporary advantage only, for it is not to be hoped that the Chancellor of the Exchequer will for long allow himself to be cheated of his revenue. Apart from the tax, the Diesel engine uses a cheaper fuel, an advantage it will probably retain for several years to come. In the long run, however, the difference in the cost of fuel will diminish almost to the vanishing point, and the Diesel engine will have to compete ultimately on its lower fuel consumption alone.

On full load the Diesel engine can show a gain in thermal efficiency of about 25 to 30 per cent. over that of a good modern petrol engine. As the load is reduced, however, the Diesel engine gains in efficiency, while the petrol engine loses. In road service the average load factor is approximately 33 per cent. only, and, at this load, the fuel consumption of the Diesel engine is approximately half that of a good modern petrol engine. On the other side of the picture, the Diesel engine has certain inherent disadvantages which development may mitigate but cannot wholly eliminate. Owing to its high ratio of maximum to mean pressure, the Diesel engine must always be somewhat heavier. Owing to its higher pressure, the wear of the cylinder liners and the punishment of the connecting rod and crankshaft bearings will be more severe. Owing to its much higher compression pressure the torque reversals and, therefore, the torque recoil is much more serious and, owing to the rapid rate of pressure rise, it is bound to be rougher running and somewhat noisier than the petrol engine. Again, it is more difficult to start from cold and, unfortunately, it is too often true that the more efficient or the more flexible the Diesel engine the more difficult becomes the starting problem. Lastly, the fuel itself is messy and smelly and unless great care is taken in the design of the combustion chamber to avoid as far as possible the formation of aldehydes, the exhaust, even though invisible, is liable to have a very pungent smell. In the light of present knowledge, this latter difficulty can be surmounted almost completely, but it is unfortunate that many of the high-speed Diesel engines now on trial on the road are arch offenders in this respect.

On the other side of the picture, the Diesel engine has the advantage over petrol of a cooler cycle and, therefore, less trouble with exhaust valves ; it is very free from the constant irritation of electrical ignition apparatus, and it is free from carburettor and distribution troubles.

In its competition with the petrol engine on the road, the Diesel engine is face to face with a tremendous task. Let us consider for a moment what the petrol engine does and the Diesel will have to do if it is to compete on level terms. The modern petrol bus engine develops anything from 100 to 130 h.p. on a total weight of about 10 lbs. per h.p. ; it will run impartially at any speed between 200 and 3,000 r.p.m. and will exert its maximum torque over a very wide speed range. It has got to withstand overloading till it is brought almost to a standstill. It is expected to be free from vibration and reasonably silent at all speeds ; in particular, it must be almost perfectly silent and vibrationless when idling, and, most important of all, it is expected to run day after day and month after month without any attention whatsoever. To the

Diesel engine most of these are novel conditions, quite foreign to any which have been asked of it hitherto.

The most recent examples of high-speed Diesel engines developed in this country for road work run the performance of the petrol engine very close, and are, I think I can safely say, far and away ahead of any of their Continental rivals. Their weight ranges from 11 to 15 lbs. per horse-power, their useful speed range is nearly and, in one stance, quite equal to that of a petrol engine. On the road they show almost exactly double the mileage per gallon of fuel. It yet remains to be seen how long they will withstand the rough treatment to which they will be subjected in regular commercial service. During the past four or five years a few Diesel engines, mostly of Continental design, have been fitted to commercial vehicles in this country, but they have, for the most part, been in the hands of enthusiasts who have extolled their virtues and glossed over their faults. At the beginning of this year the total number of Diesel engined commercial vehicles on the roads in this country was, I believe, under a hundred. During the last nine months the number has increased to over four hundred, while the next few months will see another two or three hundred more, and they are passing now into the hands of severely critical users. This rapid increase during the last few months is due entirely to the great progress made by English designers and engine builders. When a thousand or more such engines have had some 20,000 miles each of satisfactory road service to their credit, we shall be able to say that the Diesel engine has graduated in the most difficult service to which any engine can aspire.

On the sea the Diesel engine has to compete, in the smaller sizes of craft, with petrol or kerosene engines; in the intermediate and larger sizes, with steam. Compared with petrol or kerosene, the high-speed Diesel engine would appear to have overwhelming advantages. It is almost immune from fire risk—a very real and serious factor at sea. It is free from electrical ignition gear which, in the presence of salt water, becomes an everlasting source of trouble. It is not called upon to do any trick-riding as on the road—for the marine engine runs for the most part at a steady gait and at a comfortable load factor. So long as it will start at once, will idle steadily and will respond at once to its simple orders, little else is asked of it. All these conditions the high-speed Diesel can fulfil easily, in fact, even more easily that the petrol engine; so easy, in fact, is the duty that the simple two-cycle surface ignition engine, the leat versatile of all engines, has in the past been able to fulfil it admirably. In this field, therefore, the light high-speed Diesel engine should soon reign supreme. In the intermediate sizes of vessel, of horse-powers ranging from, say, 200 to 6,000, the Diesel engine finds itself face to face with its old rival, the reciprocating steam engine. It has already defeated and almost completely eliminated this competitor on land and is rapidly displacing it at sea. Lastly, we come to the largest class of ships with shaft horse-power ranging from 6,000 upwards. Here, the Diesel engine finds itself in direct competition with the steam turbine, and the state of affairs which exists to-day is, to me, somewhat puzzling and illogical. On land, the large steam turbine has eliminated the Diesel, as completely as the latter has eliminated the reciprocating steam engine. At sea, the steam turbine is working under even more favourable conditions, in that it has unlimited cold water for condensing and every advantage would appear to be in its favour. With high pressure and high superheat, its thermodynamic efficiency in large units approaches that of the Diesel and, since it can use a cheaper fuel, its economic efficiency is nearly equal. In large powers the steam plant is lighter; its first cost is less and its maintenance cost apparently considerably less. One cannot escape the suspicion that the extensive use of very large Diesel engines at sea is due, as Sir Alfred Ewing suggested recently, " rather to the taste and fancy of some dominating personality than to a careful weighing of arguments such as appeal to engineers." I fancy the next few years will show a reversion to steam in the larger and faster classes of shipping. So far, the intermediate and larger classes of shipping have been equipped with large slow-running Diesel engines, usually direct coupled to the propeller shaft. As yet, with but one interesting exception, no serious attempt has been made to employ a large number of small and really high-speed engines, though it is obvious that the saving in weight and space and, above all, the gain in reliability would be enormous. The case of the large ship introduces the problem of connecting up a large number of small units to a single shaft. The number which can be connected by direct gearing is limited. Moreover, mechanical gearing necessitates the engines being spread along the propeller shaft, which is inconvenient on the grounds of space. It would seem that electric transmission will be necessary, but even so, the weight and space occupied will be insignificant compared with that of a direct coupled slow-running engine. High-speed Diesel engines running at, say, 1,500 r.p.m. need weigh no more than 20 lbs. per horse-power even when neither aluminium nor welded steel are used in their construction; high-speed electric generators to suit weigh about 12 lb. per horse-power, so that the entire weight of the power generating plant should not exceed, say, 32 lbs. per horse-power. I do not pretend to know what will be the weight of the propelling motors and switchgear, but at least I feel sure that, with gear reductions, it would not exceed 30 lbs. per horse-power, making a total of, say, 70 lbs. per horse-power at the propeller shaft after allowing for the loss in conversion. This figure compares with about 200 lbs. per horse-power as an average figure for a direct coupled plant. In the case of a 4,000 h.p. ship, I suggest we should use, say, 30 self-contained direct coupled generating sets each of, say, 150 h.p. and weighing, complete with dynamos, a little over two tons each—these could be handled easily by any ordinary deck hoist. We shall need another five or six identical sets for lighting and auxiliary services, and we might, for a very prolonged cruise, carry perhaps half a dozen spare sets. Normally, we should cruise with about 30 per cent. of our generating sets in reserve and could, therefore, afford to face the possibility of as many as ten engines being put out of action without loss to our schedule speed, and without calling upon our reserves. With such an equipment I would suggest that no repairs or maintenance of any kind should be carried out at sea, but that, on return to the home port, those engines which had run their allotted span or had shown any signs of distress should be lifted out and replaced by reconditioned ones. In such a vessel the engineering crew would remain ashore and would consist of perhaps a couple of fitters engaged in reconditioning the exhausted engines left behind after the last voyage. At sea, a competent clerk to keep records and a couple of charwomen would, I suggest, be all that is required, so far as the Diesel engines are concerned.

I referred to one interesting exception to the use of comparatively slow-speed engines; I had in mind the power plant used in the latest German warship. This consists of 36 small high-speed double-acting two-cycle cylinders, coupled by mechanical gearing to each propeller shaft. In addition to the 72 cylinders driving the main propeller shaft, a further 20 cylinders of identically the same size are used to provide the scavenging air and generally to feed the propelling engines, making a total of 92 cylinders in all for propulsion alone. Added to this, there are 48 cylinders of high-speed auxiliary engines for electric generating, etc., making a total of 140 cylinders in all. This is going some way towards the multiple engined ship, but I would like to see some enterprising shipowner go even further on the lines I have just suggested.

The application of high-speed Diesel engines to railway work has been the subject of much talk for many years. I have never been able to understand why, in spite of so much talk, so little actual progress can yet be recorded. In this country of ours where coal and water are plentiful and the incentive to use native products bulks very large, it is easy to understand why steam still reigns supreme, but in countries where coal and water are scarce the arguments in favour of the Diesel engine would seem to be overwhelming. In the locomotive we see steam used under about the most unfavourable conditions imaginable, for it has to work non-condensing and, therefore, at a very low efficiency, in addition to which it has to carry with it not only a bulky and heavy fuel of which it consumes an inordinate quantity, but also the whole of its water supply, which, for so thirsty a creature, forms no small proportion of its available paying load. That the Diesel engine should have been able to rival the steam engine at sea where the latter has every possible advantage is surprising; that it should, so far, have failed to do so on the railways where steam is at every disadvantage is, to me, even more surprising. I am inclined to think that the comparative lack of progress is due to unsuitable application. We have grown accustomed to the single large locomotive hauling a long and heavy train and have been inclined to take it for granted that the Diesel engine should be used in the same way; I doubt if this is a correct assumption. The single large locomotive is a natural development of a system whose inherent efficiency increases and whose relative cost diminishes with the size of the unit, conditions which do not apply to the Diesel engine. In the case of the Diesel engine, the small unit is just as efficient as the large and is both cheaper per horse-power and very much lighter.

So far as passenger traffic is concerned, we should, I think, consider two alternatives: (1) the self-propulsion of each individual coach as in the case of many electric trains, and (2) the use of what would be, in effect, mobile power stations which need not themselves be self-propelled, but which would be hitched on to electric trains—the former would be preferable in sparsely inhabited countries and the latter might be used to extend the range of existing electrically propelled rolling stock from one congested area to another. In many countries there are, scattered about at wide intervals, large centres around which it pays to employ electric propulsion, but it will never pay to extend electrification from one such centre to another. The travelling power station consisting of a battery of small high-speed Diesel engines driving generators, would enable the electrically propelled trains to travel vast distances over any part of the system or from one electrified centre to another. Such a mobile power station would have no standby losses, and being composed of several independent units, would, therefore, be very reliable and could be operated always at the highest efficiency. The capital cost involved in providing a supply of these mobile power stations would be insignificant compared with that of electrification of long stretches of line. The other alternative, the self-propulsion of each individual coach, has made some progress, but to my mind such railcars as have been produced are far too large, too complex and too costly. To propel a single existing passenger coach requires, I understand, about 120 to 150 h.p., no more than is required by a modern motor bus, and a power which can easily be transmitted by simple mechanical gearing, provided a good clutch, preferably of the fluid type, is used. Such few railcars as have been built as yet have been equipped in nearly all cases with electric transmission, which renders them far too costly and cumbersome for practical politics. I believe that it would be found practicable to convert existing rolling stock with comparatively little alteration, and to make it self-propelled by the installation of just such an engine as is now used for the larger types of road vehicles, with perhaps an epicyclic in place of a sliding gear box.

In the case of freight there exists in every country so much rolling stock which could not possibly be converted to self-propulsion, that the separate locomotive must be employed for many years to come, both for main line traffic and for shunting. For this purpose let the steam engine carry on where water and coal are plentiful; where they are scarce, I suggest that the Diesel engine with compressed air transmission in likely to prove the most promising development, for it has some very decided advantages, not the least of which is that for the final transmission to the wheels the existing and well-tried steam locomotive mechanism can be used again. As a general rule, compressed air transmission shows a very low efficiency, but when used in conjunction with an internal combustion engine, the efficiency can be improved greatly by utilising the waste heat in the engine's exhaust to re-heat the air between the receiver and the air cylinders. Again, air transmission provides a considerable storage capacity to deal with starting and acceleration, while for climbing banks, etc., the power delivered to the road wheels can be increased by burning additional oil fuel in the compressed air and increased again to nearly double that of the Diesel engines by injecting water as well as fuel to produce steam and to keep the temperature within bounds. I think that such a scheme is worthy of more serious consideration by railway engineers than it has yet received. Such a locomotive might consist, for example, of a battery of combined high-speed Diesel engines and air compressors of an aggregate output of, say, 1,200 b.h.p. and a relatively small air receiver of sufficient capacity for starting and accelerating—the whole mounted on an existing steam loco frame. The rest of the mechanism, the cylinders, axles and motion work generally, would be identical with that of a steam locomotive. With a collective engine power of, say, 1,200 b.h.p., the normal power available at the track would be about 1,000 b.h.p. when re-heating from the exhaust alone, about 1,400 b.h.p. when burning additional fuel in the air, and about 2,000 b.h.p. when delivering both fuel and water into the air. For shunting purposes a somewhat similar, but smaller, locomotive might be used, but in this case with a very small compressing engine and a large air storage capacity. In such a case the power of the Diesel engine need be a small fraction only of that required at the road wheels, for it will be running continuously during the many standby periods, re-charging the air receiver, whose capacity can easily be made ample for all the work required in a shunting yard. I understand that the average load factor of a shunting engine in the busiest of yards is considerably less than 20 per cent. The maximum power required is, I believe, about 500 to 600 h.p. This could be maintained for as long as is required in service from the air storage receiver, while a single 150-h.p. Diesel engine running continuously will be ample to charge the receiver.

Great efforts are at present being made to develop Diesel engines for aircraft propulsion. The arguments in favour of the Diesel engine as compared with the present day petrol engine are :—

(1) Elimination, or at least great reduction, of the fire risk in the event of a crash.
(2) Elimination of the magneto—a very disturbing element from the point of view of wireless communication.
(3) Increased range of flight, due to the lower fuel consumption under all conditions, and more particularly at cruising speeds.
(4) Reduced cost of fuel.
(5) Greater reliability due to freedom from electric ignition apparatus and the employment of a cooler cycle generally.

These are all cogent arguments in favour of the use of Diesel engines for aircraft, but they are, I think, apt to be over-stressed in the enthusiasm of the moment.

Against the Diesel engine lies the solid fact that in the four-cycle form, at any rate, it is bound to be very much heavier—probably at least 50 per cent. heavier—than a contemporary petrol engine of similar design. It is true that the weight of fuel it carries is less, but it will require flights far longer than are usual to-day and longer than the average pilot or passenger will care to undertake, before the handicap of additional engine weight is offset by that of reduced fuel.

When discussing aircraft, we have to consider their use both in war and peace. In war none of the foregoing arguments will weigh with a pilot if his heavier engine allows his opponent to outmanœuvre him. For the long distance bombing machine the four-cycle Diesel engine will be able to show an advantage, but apart from this application, I am doubtful as to its military value.

In peace and for commercial aircraft paying load is the vital consideration. Paying load constitutes what is left over after the weight of the engine is taken into account, and it so happens that the present paying load and the present engine weight, even under the most favourable conditions, are in the ratio of about 2 to 1 only. If, therefore, we add 50 per cent. to the engine weight, we reduce the earning capacity of the machine by 25 per cent. Against this, we cannot make much capital out of the reduced weight of fuel carried, for, except for oversea flights, there is no reason why the commercial aeroplane should not land and replenish its tanks as often as it likes. We are left then with the one outstanding argument of the fire risk—a powerful argument, but one which cannot be assessed in any quantitative terms. Such arguments as lower fuel cost must fall on deaf ears if the earning capacity is to be so reduced.

There remains yet another class of aircraft to which I venture to think the Diesel engine is the most applicable of all, namely, the privately-owned light aeroplane. Here paying load, as such, does not come into the picture at all. The fire risk bulks very large, as is natural, in a machine used purely for pleasure, and the cost of fuel, even though it may be but a small proportion of the annual expenditure, is a daily recurring one, and, therefore, assumes an importance far greater than its due.

In all the foregoing remarks I have had in mind the four-cycle Diesel engine, and, apart from one striking example—the Junkers engine—the four-cycle is the only form of Diesel which as yet is receiving serious consideration for aircraft use. If the skill and attention which, in this country, is being devoted to the four-cycle Diesel aero engine, were turned to the two-cycle version, I believe that we should very soon succeed in producing a Diesel aero engine of about the same power weight ratio as a petrol engine, namely, about 1·5 lb. per horse-power. If this were achieved, then the case for the Diesel engine for aircraft would become almost an overwhelming one. There are difficulties to be overcome, but they are all mechanical difficulties of the kind which past experience shows can always be overcome if the incentive is great enough.

The fact that a two-cycle engine involves the addition of a blower for scavenging detracts rather from its charm for most purposes, because blowers, as a general rule, are very noisy and somewhat costly, but in the case of almost all service and many commercial aero engines, blowers are used in any case—for supercharging—so that this objection does not apply.

Until comparatively recently, the largest scope for the Diesel engine was in electric power stations, where it was in competition with steam. Compared with the latter, it could lay claim to the following advantages :—

(1) Its efficiency was so much greater that, even though it used a more expensive fuel, it could still show a considerably lower fuel bill.

(2) Since it could be started instantly and put on to full load within less than a minute, there were no standby losses.

(3) Since the bulk of fuel required was relatively small and that of water almost insignificant, it was independent of geographical position.

With these advantages in its favour, the Diesel engine, for many years, put up a very good fight against its old rival, a fight which, in fact, stimulated the steam engine to renewed efforts and to achieve fresh heights from which the Diesel engine cannot now hope to dislodge it. To-day, after nearly 30 years of competition from Diesel and gas engines, 98 per cent. of all public service electricity supply in this country is produced by steam. In foreign countries where coal or fuel oil are scarce, the Diesel engine still has opportunities, but in the large centralised power stations of the present day steam has again come into its own, and its supremacy is now, I think, absolute. To-day, I think we may rule out the Diesel engine so far as large central power stations are concerned, and consider it either for peak power stations or for isolated stations outside the range of bulk supply. For such purposes batteries of small units would seem to be ideal. Here, high-speed is not only a means to an end, but has the additional advantage that it permits of the use of lighter, smaller and cheaper generators. Moreover, with a battery of engines, it becomes possible to arrange for centralisation of their auxiliary services, which will reduce considerably the capital cost. For example, all can be lubricated from a common rail system which would allow of much more efficient cooling, filtering and settling of the lubricating oil. At periods of peak load all could be supercharged from a common rail supplied by large and, therefore, efficient turbo blowers, while the overhauling or reconditioning could be carried out as a regular routine (one engine a week or one engine a month, according to the total number) being removed and replaced. In such a plant not only will the cost of both engines and generators be very small as compared with one equipped with large units, but that of the buildings and foundations also will be reduced enormously, while there will be no necessity for overhead cranes or costly lifting tackle.

In these lectures I have stressed my belief that the future of the Diesel engine lies with the small high-speed version, and my conviction that wherever possible it should be used in large batteries of small interchangeable units which should be exchanged and reconditioned periodically, but never tinkered with. I will even go so far as to suggest that a six-cylinder engine of about 120 to 150 h.p., built by what we are accustomed to term bulk production methods and, therefore, produced at a very low cost, will ultimately be found to fulfil nearly all our needs on land or water.

Of such an engine we shall require, as we do of the petrol engine to-day, that it shall be entirely self-supporting and reliable during its working spells, and that its capital cost shall be so low that we shall not hesitate to scrap it as soon as it becomes obsolete. We are accustomed to tell ourselves that we live in an age of progress; if we really believe this, then what is the use of building engines to last more than, say, 10 or 15 years? Our forefathers were wont to boast that they built machinery to last a century, and this they accounted a virtue. In so doing they created impressive monuments to themselves but most embarrassing heirlooms for their descendants. To-day much of our trouble is due to the sturdy vitality of machinery which has long since grown obsolete but will not die.

Low first cost, light weight and ease of transport are the needs of the present day; let us be content to supply these, and to leave our descendants a free hand to make use of the better knowledge and altered conditions which will be their portion.

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