FD28/2,431/20

B.I.O.S. No. U13

I.G. Farben, Ludwigshafen am Rhein Technical Test Station
Report No. 414

The Otto-Diesel Engine

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at the German Air Ministry.

Contents

Summary

A new working process is described for combustion engines which has the following characteristics:-

Mixture formation according to the Gasoline engine method by injecting the fuel in the induction or compression stroke.

Ignition according to the Diesel engine by injecting an easily ignitable oil into the gasoline mixture.

This is called the Otto-Diesel process. It is used with the low compression-ratios of the gasoline engine and therefore requires ignition-fuels which are much more ignitable than the usual Diesel fuels.

The new process has the following advantages:-

(1) Power is controlled not by throttling but by alteration of the excess air ratio. This gives a low fuel consumption at part load.

(2) The ignition system is not affected by the deposits from antiknock substances and there is also no interference with radio communications.

(3) The requirements for the antiknock performance of fuels are less than those of a gasoline engine with the same compression ratio of 1:8.

(4) The knock limit of fuels does not depend so much upon the mixture strength. This fact is particularly striking with aromatic fuels.

(5) This new process is not very sensitive to the quality of the mixture. Therefore high boiling safety fuels, as, e.g. TZ 900, can be used.

The method can be applied to existing engine types. A piston giving a compression ratio of 1:8 is necessary and a second pump for the small ignition oil quantities; also a second injection nozzle instead of the sparking plugs. Controls must be developed for the two pumps.

The chemical development of ignition oils is making good progress. Since the principle of the Otto-Diesel process appears to have been worked out so far satisfactorily, it is time that the aero-engine firms were called upon to join the efforts for its further development.

Introduction

The aero-engines of today are gasoline engines and Diesel engines. The compression-ratio is not an essential distinguishing feature, for there are gasoline engines with very high compression ratios, and Diesel engine development is in the direction of lower values. The mixture formation is obtained in both engines by injecting fuel, and even the timing of injection is not characteristic, for, e.g. in the "Hesselmann" engine - a special type of the gasoline engine - the fuel is injected almost as late as in the Diesel engine. The combustion of a Diesel engine is nowadays a constant volume combustion as in the gasoline engine. So the decisive distinguishing factor is only the ignition system.

Though the two engine systems are so nearly related to each other the ignition-system is just that factor which presents an opportunity of developing a new method which combines the characteristics of both engine types. This leads to new points of view as regards the relation:- "Fuel - Engine" which will be described in this paper.

In order to see how this new method differs from the usual way, I should like to explain briefly the Otto and Diesel engine processes and describe their properties.

A. Comparison of the Otto and the Diesel process.

(1) The Otto process

The main characteristics of the Otto process since the time of its invention are the effects of the ignition limits on the fuel-air mixture and the source of ignition - an electric spark. As every one knows the effect of the ignition limits is such that the engine output can be controlled by fuel regulation only to a limited extent (fig. 906). The usual means permit ignition of mixtures only up to an excess air ratio of approximately 30% which reduces the power output also by about 30%. In a main engine, however, the mixture regulation cannot be used to that extent.

The control of quality must consequently be supplemented by a control of quantity, i.e. by throttling (fig. 907). The disadvantage of this process is first, that the diagram shows an area of negative work; furthermore the relation of the residual gases to the fresh gases becomes more and more unfavourable, and finally there is incomplete combustion as proved by the CO-content of the exhaust gases at low loads. Thus at part load the Otto engine works with poor efficiency. At full load, however, the efficiency is good and there is also a high power output, since the cylinder capacity can be completely utilised. The fuel remains in the cylinder during the intake and compression strokes and therefore the mixture-formation is so good that mixtures without excess air burn completely.

With regard to the ignition, a point source is disadvantageous because it depends in its effect upon the accidental composition of the mixture near the spark gap. This is shown by the fact that with increasing excess air ratio the engine does not fail suddenly but that there are every now and then a few firing strokes when a somewhat richer mixture happens to be near the ignition spark. The typically irregular gasoline diagram (fig.908) indicates the irregularity of the mixture formation in the gasoline engine (fig.908).

The non-uniformity of the mixture is particularly great when using fuels with a high boiling point which can only be admitted into the cylinder during the compression stroke, in order to avoid deposition during the induction stroke. (Hesselmann). The mixture formation - incomplete because of the short time - necessitates protruding electrodes, since experience shows that the mixture formation is particularly poor at the walls of the combustion chamber. It is self-evident that such sparking plugs are unsuitable for high loads.

As regards the reliability of electrical ignition, the electrodes suffer considerably from the deposits from the antiknock substances. Therefore sparking-plugs must be considered as consumable accessories and not as structural parts as they really should be, and as injection nozzles may now be considered. In addition, the whole ignition system must be very carefully screened in order to avoid interference with radio communications; the desire to produce the ignition in another manner is understandable.

(2) The Diesel process

Turning now to the Diesel engine, its most important advantage is independence of excess air, for even the smallest fuel quantity injected will burn completely if the temperature is sufficiently high. This, however, presupposes the stepping up of the compression ratio to about 1:14 or 1:18, merely to produce this temperature. From the point of view of thermal efficiency this appears worth while since it is still rising in this region (fig. 895). In practice, however, the mechanical efficiency decreases with the high pressures occurring, and the advantage is lost. It may be shown (fig.922) that with decreasing compression ratio, the power/of a Diesel engine does not decrease, but increases. The figure shows that a Diesel engine working with direct injection shows a considerable power increase with gas-oil when the compression-ratio is lowered from 1:17 to 1:11. The practical application of this advantage is not possible, because the ignition lag with low compression-ratio becomes so great that the engine cannot be started. Engine running is also very rough. This disadvantage of a high compression-ratio is the reason for trying to develop Diesel engines with a low compression ratio.

Considering now the ignition process itself: after the injection of the fuel into the air, heated to approximately 500-600°, atomisation and vapourisation of the fuel - at first with absorption of heat - takes place. During this process, to which the oxygen of the air is only partly contributing, cracking and oxidation on the surface of the fuel stream occurs. This oxidation increases during the reaction, and finally a visible combustion takes place which is followed by a pressure increase (fig.909). The ignition lag depends upon the quality of the fuel. The paraffins are very highly ignitable, the aromatic fuels, however, have a low ignitability.

The ignition is independent of the fuel-air ratio, since always somewhere on the surface of the fuel stream there is a mixture favourable to ignition. Therefore the power can be controlled from idling to maximum output by regulation of the fuel. But the Diesel engine cannot be operated at the stoichiometric fuel/air ratio though this would mean the complete utilisation of the cylinder capacity. The power available for practical purposes is limited by the necessity of having at least 20% excess air since the short time of the ignition lag would not be sufficient to provide every fuel particle with the necessary oxygen. (fig. 910) This means that the maximum power of the Diesel engine is smaller by 20% than that of the gasoline engine. On the other hand the Diesel engine is much more economical at lower loads. For at low load the Diesel engine works with a high excess air ratio whilst the gasoline engine is controlled by throttling.

B. The Otto-Diesel process

The two engine systems can obviously be combined in the following way: the engine forms and compresses its mixture according to the Otto engine method. This mixture is then ignited by a combustion according to the Diesel method. We have, so to speak, two engines in one. Up to the end of the compression the engine works as a gasoline engine and subsequently as a Diesel engine. The gasoline engine needs no sparking plug because the self-igniting Diesel fuel also ignites the gasoline mixture. Therefore we may call the whole method the Otto-Diesel process. We can easily appreciate the advantage of this method. As with the Diesel engine mixture-control is permissible since the Diesel combustion develops enough heat to ignite even very lean gasoline mixtures. At very small loads, as e.g. when idling, the engine operates exclusively on the Diesel process. Furthermore the mixture formation according to the gasoline method allows an even fuel distribution in the air so that no excess oxygen is required as in the Diesel engine. Thus the same power is obtained as in the gasoline engine. Instead of one or two ignition sparks there are innumerable ignition centres of the Diesel fuel, and instead of magneto and sparking plug an injection pump and nozzle are used.

Tests have already been made to operate Diesel engines with a gas-air mixture. In Germany this method was several times used under pressure of Diesel oil shortage, and we have also carried out such tests. We have converted several Diesel vehicles to a mixed system where the engine operates with gas-oil as usual when idling or at low loads. With higher loads we added fuel-gas to the air. This method is only an emergency measure since there is still a considerable consumption of gas-oil and the process is not economical. Experience shows that the use of this method under normal circumstances is out of the question. But it must be emphasised that in this case the engine still remains a highly compressed Diesel engine.

But the Otto-Diesel method which is the subject of this paper, is based on the gasoline engine in which, in spite of low compression, a Diesel process is involved. The low compression and consequently the necessity of using particularly highly ignitable Diesel fuels together with the special requirements of aero-engines give us so many new points of view that it may be considered as a new process.

In connection with the Diesel process it was shown that it is best to work with as low a compression ratio as possible. Diesel engine tests show (fig. 880) that the ignition lag depends very much upon the compression ratio. This is particularly the case in the range of low compression where, with normal gas-oils, the ignition lag increases so much that it cannot be used in practice. But the Otto-Diesel engine must be operated with compression ratios as low as possible, firstly because high pressure peaks are undesirable and secondly to restrict the antiknock requirements of the gasoline fuel.

This necessity of using low compression ratios necessitates the development of Diesel fuels of particularly high ignitability. The necessary conditions for the Otto-Diesel process were established first by the Research Laboratories at Oppau and later in collaboration with other department of our works, so that now the Otto-Diesel engine can be operated with a compression ratio of 1:8 as occasionally used also in gasoline engines. The following chapter will deal with the salient features and properties of the Otto-Diesel engine.

(2) The details of the Otto-Diesel method

(a) Ignition lag

Although the Otto-Diesel engine derives from the gasoline engine it behaves in many ways, e.g. as regards the ignition, like a Diesel engine: (fig.911) shows e.g. that in the Otto-Diesel engine as in the Diesel engine the ignition lag increases with decreasing compression ratio. The same phenomenon is apparent when the temperature of the inlet-air is lowered. When the ignition lag becomes greater the injection takes place in a cooler gas mixture, so that the ignition lag below 50° air-temperature rises very steeply. High ignition lags cannot be made because during the long time required for the mixture formation, fuel spreads through the whole cylinder and so leads to a bulk explosion. Further, in the Otto-Diesel engine, the compression-temperature is lower than with the compression of pure air, for the gasoline fuel consumes heat when vapourising and so lowers the temperature. We find therefore (fig.912) that the ignition lag increases with rising fuel quantity, i.e. with increasing load.

The ignition lag does not depend only on the temperature at the end of compression (fig.914). This graph shows the ignition lag in terms of the compression temperature. Different temperatures were obtained, first by altering the inlet-air temperature at a constant compression ratio of 1:8, secondly the compression ratio was altered at a constant inlet-air temperature of 80°. Starting from the point of intersection of the two curves, i.e. at 80° air temperature and compression ratio of 1:8, and consequently a final temperature of 380°, a decrease of the final temperature by a decrease of compression ratio, E, affects the ignition lag much more than a decrease of the inlet-air temperature. This means that the pressure plays a very important part.

The test shows too (fig.915) that the ignition lag decreases considerably with increasing boost pressure. ~~In this test, however, the ignition was not~~ set, as before, at T.D.C., but at the optimum value. This injection advance angle does not correspond exactly with the ignition lag. The influence of the pressure, however, is unmistakable.

When injecting the ignition fuel into the gasoline mixture partial mixing of gasoline and ignition fuel is unavoidable and the ignitability is reduced. In fact the ignition lag is increased as soon as lead tetraethyl is added to the gasoline fuel. The results shown in fig.916 are rather surprising, for the ignition lag is greater with iso-octane than with benzene, although the reverse would be expected because of the higher antiknock value of the benzene. As mentioned before, the effect of lead tetraethyl is evident. It is, however, very small and cannot be compared with the increase of the antiknock value caused by these additives to the gasoline fuel.

(b) The ignition fuel

For ignition fuel a substance is required which is much more ignitable than the usual Diesel fuels. The development of ignition fuel is undertaken in two ways:-

(1) The development of additives which are in contrast to antiknock substances such as lead tetraethyl. When added in small quantities to an already quite easily ignitable Diesel fuel they will increase its ignitability considerably.

(2) The development of substances which by themselves are much more

ignitable than the usual Diesel fuels.

If the ignition fuels of the first kind can be compared to leaded gasolines we may compare the second kind to high grade substances such as iso-octane or cetane.

Both kinds of material are available. To a large extent an additive was used with "RCH" Diesel oil which has a very high cetane number. From the results of recent researches it may be assumed that the effect of such additives is as follows:- (fig.894). Substances with a low ignitability reach a reaction velocity with which ignition takes place after a longer period than with easily ignitable substances, which react more rapidly. In any case the longest time is spent at the beginning of the reaction, and so we can imagine that here the small quantity of additive by its rapid disintegration gives a vigorous impulse which is sufficient to shorten the ignition lag.

Such substances are, e.g. nitrates and peroxides but they could not be used successfully to increase the ignitability. They were unstable, not sufficiently soluble, produced poisonous vapours, supplied noxious combustion products or had other disadvantages.

A peroxide was found, however, which had none of these disadvantages. An essential condition is that the oil with which it is mixed shall have no unsaturated components. The most important properties of this new peroxide are the following:-

Colour	Colourless
Solubility	Miscible in any proportion with hydrocarbons
Viscosity	3 cs. at 20°C.
Specific gravity	1.07
Vapour pressure	Lower then that of Diesel fuel
Calorific value	Approximately 6000 kcal/kg.
Air requirement	8 kg/kg.

This peroxide must be handled with particular caution when pure, but when mixed in equal parts with Diesel fuel it is not dangerous. An addition of 10% was usually found sufficient. We are at present engaged in finding out the effects of greater additions. Fig.917 shows that in the Otto-Diesel engine the ignition lag is considerably reduced by doubling the additive. The power, however, is hardly affected. The additive alters the properties of the Diesel fuel only as regards the octane-number which rises from 90 to approximately 200. Fig.923 shows that the additive "D" is much more effective than, e.g. amyl nitrite.

There is still a disadvantage at present and this is the small low temperature stability of the "RCH" Diesel oil which we use as the basic oil, and which starts to crystallise below -10°C. We are endeavouring to use other oils for this purpose.

We expect to find a final solution of the ignition oil problem by using the second method.

Instead of a mixture we have a homogeneous substance which is highly ignitable. Already quite a number of suitable substances have been found. As soon as the numerous possibilities are reviewed a choice will be made bearing in mind the possibility of large scale production.

(c) <u>The ignition oil nozzle.</u>

The quantity of the ignition oil, necessary to ignite the gasoline mixture, and the ignition lag which then occurs, depend on the type of injection nozzle. It is not advantageous to use fine atomisation. Good results have been obtained with a single hole nozzle which gave a nearly solid stream. Two points will explain this phenomenon. First, as mentioned before, a certain mixing of the gasoline and the ignition fuel is unavoidable and this will occur more with finer distribution of the ignition fuel. With a solid jet, however, the proportion of gasoline will be relatively small. Secondly, atomised ignition oil droplets will transmit the heat generated during the reaction immediately to the gasoline mixture whilst a solid jet retains the heat. Only a small quantity of oxygen is introduced by the ignition accelerator, covering only 1.5% of the air requirement. In any case, it will favour the start of exothermic reaction.

Evidence of this is provided by the test shown in the next diagram (fig.921). Here the quality of the atomisation was varied by altering the injection pressure, and it was found that the best value for the nozzle used was approximately 110 atmospheres. The injection pressure was increased and the atomisation was improved, and the ignition lag then increased. When it was reduced, the depth of penetration was less and the atomisation became so bad that the ignition lag again increased.

(e) The ignition fuel quantity

Fig.917 showed that the quantity of the ignition fuel has almost no influence on the performance of the engine, even if it is operated with excess air as in these tests. As we shall see later, this means that the ignition fuel burns almost without any pressure increase. If the ignition fuel quantity is reduced below a certain level, the ignition lag increases and the engine eventually cuts out. The reason is not so much that a minimum quantity of energy must be supplied but rather that the regulation and jet formation of such small quantities - 8 to 10 mm^3 - becomes imperfect. This is proved by experience with supercharging where small quantities are sufficient for ignition, though they are only 2% of the fuel or less, whilst approximately 4% is necessary with normal aspiration.

It is therefore necessary to develop pumps and nozzles which supply and regulate the small quantities reliably. At the same time good cooling is necessary for the small oil quantities can only dispose of a small quantity of heat. We have recently worked with Bosch nozzles which are externally similar to the nozzle DE 40N60M6 but have a bore of 0.25 mm. only. We use a 5mm. pump plunger. The tests show that this arrangement is satisfactory, though the effective stroke is hardly 1 mm.

(f) The control of the Otto-Diesel engine

After thus having described the details of the Otto-Diesel engine we can now discuss the engine as a whole and briefly deal with the problems of its control.

Fig.912 showed that the ignition lag increased with increasing load. But this is only the case if the pressure increase takes place exactly at the dead centre. However, it is better, particularly with lean mixtures, to initiate the ignition before T.D.C. as in the gasoline engine. Fig.926 shows that the injection advance angle which now is no longer identical with the ignition lag, is approximately 45° for all loads. This fact is advantageous for control, since a constant injection advance angle can be used. The injection advance angle showed the peculiarity in all tests of increasing a little in the region of $\lambda = 0.8$ to 1.2 and then returning to its original value at $\lambda = 1.6$. It is possible that the reason for this is the design of the cylinder and its gasoline injection system. It is interesting that the injection advance angle increases above $\lambda = 2.0$, and that it becomes necessary at the same time to supply a little more ignition oil. The reason is that the gasoline mixture becomes so lean in this region that the ignition energy must be increased, so that eventually the engine, when idling, runs as a simple Diesel engine on the ignition fuel only.

Please note also the course of the specific consumption which shows a clear minimum at a certain excess air ratio. I should like to show you a second test which was carried out in a very similar manner, only with the difference that we used another nozzle for the ignition fuel (fig.930). You see that now the consumption curve remains constant at a low value for a considerable range of the excess air and independent of the power. This consumption-curve reminds us of the Diesel engine and is exactly what we must try to achieve. It shows the importance of the development of an ignition fuel nozzle.

Thus we see that the output is controlled by the delivery adjustment on the fuel pump, the upper limit of which must be influenced by the air-density in the induction pipe in order to avoid an excessively rich mixture. Apart from that the regulation of the fuel is, contrary to the gasoline engine, independent of the air density. The ignition fuel quantity is either set to a constant value or regulated by the delivery setting of the fuel pump. The same applies to the injection advance angle. The tests on ignition lag, already discussed, showed that it can be also reduced with increasing boost pressure, i.e. air density.

I should like to point out that it is also possible to operate the engine as a gasoline engine and only to replace the sparking plug by an ignition fuel nozzle. The engine is then controlled by throttling as usual. Fig.931 shows the control of such an engine. At first the power is reduced by weakening of the mixture. Then at an excess air ratio of 1.15 throttling begins. The excess air ratio did not remain constant as should have been the case with a gasoline engine proper but rose to approximately 2.0 when idling, since the throttle was operated by hand. This method of control has no particular advantage since the consumption is not so good as in the Otto-Diesel engine, and it is mentioned only to show that engines with a given control system can be converted without difficulty to operate with ignition fuel.

With reference to the operation of the engine on ignition fuel only it could be asked why the engine is not exclusively operated as a Diesel engine on the highly ignitable ignition fuel. Referring again to fig.922 which shows the output of the Diesel engine at various compression ratios, we see that with the most ignitable fuel we can work with the lowest compression ratios, but at the same time the power drops with increasing ignitability. We also know that Diesel engines require special adjustment if they are operated on pure "RCH" oil. The reason for this is shown by the pressure curves in fig.924, in which the pressure rise flattens out when using highly ignitable fuels.

We must first reckon with an uneconomical combustion of the ignition fuel. But since we are only at the very beginning of the development it seems possible that we can achieve an improvement, e.g. by a suitable modification to the injection or the nozzle design. We expect that best progress will be made by the chemical development of other ignition fuels. Fig.928 shows that this is justified. This diagram compares the pressure diagram of the ignition fuel mixed with an additive hitherto used in the I.G. test diesel engine, with that of a new fuel of a totally different composition. This is one of the homogeneous fuels already mentioned. The ignition lag is exactly the same but the combustion is considerably better, for the pressure rises more steeply and the effective area of the diagram is larger. This means that the homogeneous fuels will improve the working of the Otto-Diesel engine considerably.

(g) Comparison between the gasoline engine and the Otto-Diesel engine

The diagrams show that the maximum power of the Otto-Diesel engine is somewhat lower than that of the gasoline engine. At the present stage of development we are not so much interested in the extent of this difference but rather in whether this difference can be avoided. This can be answered in the affirmative for the defficiency is essentially due to the imperfections of the ignition fuel injection.

At part load the consumption of the Otto-Diesel engine is better than that of the gasoline engine, which is to be expected (fig.932). The curves shown here differ less than those of our first tests. In an attempt to make a clear comparison possible, the consumption of the gasoline engine was reduced still further by suitable adjustment. But we are certain that we will be able to increase the present difference of approximately 10% in the course of further development of the Otto-Diesel engine.

In order to compare two engines we must notonly consider power and consumption but also peak pressure. Fig.929 shows the M.E.P. and the peak pressure. Whilst the M.E.P. was calculated as usual from the torque, the plotted peak pressures represent mean values from a larger number of indicator diagrams. The Otto-Diesel engine never shows higher peak pressures than the gasoline engine. In the present tests they were even considerably lower which is partly due, however, to the lower power.

Quite interesting is the steady running by which I mean the variations of the peak pressure from its mean value. We see that in the gasoline engine the variation increases both in the rich and the lean region when approaching the ignition limit. In the lean region the engine runs most unevenly at the moment when mixture control must be changed to throttling. The variation decreases again as the excess air ratio dedreases with throttling.

In the Otto-Diesel engine the powerful ignition by the igniting stream should be noticeable especially in the lean region by smoother running. The diagrams show a variation which was smaller than that of the gasoline engine diagrams in the excess air region. Thus the Otto-Diesel engine runs evenly up to very high excess air ratios. In rich regions at present a somewhat larger variation is observed which, however, can certainly be avoided.

(b) Boosting of the Otto-Diesel engine

We know from the gasoline engine that the M.E.P. obtainable at the knock limit, decreases at first with increasing excess air and rises again at about 1.1. This rise, however, is only short since at about 1.3 the mixture is no longer ignitable. In the Otto-Diesel engine, however, the limit curve continues to rise steadily and reaches higher values than in the rich region (fig.927, fuel C). In order to avoid too high boost pressures this test was performed with 100° air temperature. All the same a boost pressure of approximately 3 atmospheres was reached at an excess air ratio of 3.0 so that the test could not be continued. It is up to the engine experts to find out the limit of economical operation with a highly supercharged lean mixture. In these tests here the power of the blower was not taken into account and the specific consumption in the lean region remained almost at the same low value. The cylinder-head temperature and the exhaust gas temperature, which we have not discussed here, decreased corresponding to the fall of calorific value of the mixture. The ignition fuel quantity was adjusted to a fixed value, so that this quantity referred to the fuel, decreasing with increasing excess air ratio.

We can clearly supercharge the fuels to a larger extent in the Otto-Diesel engine than in the gasoline engine (fig.925). I should, however, like to point out that it is not simple to obtain comparable conditions, since the knock limit is strongly affected by the selection of the "ignition advance". The gasoline engine was operated with a constant setting of 32°. In the Otto-Diesel engine we used the injection angle which proved to be best for the knock limit at an excess air ratio of 1.

As shown in former tests, in the Otto-Diesel engine the limit curves of the aromatics fuels are considerably flatter in shape than those in the gasoline engine. This improvement with the aromatic fuels leads to a change in their order of evaluation. CV23 is always above C_3 in the Otto-Diesel engine. The particularly flat curve for ET 100 can be noticed in both engines.

A better knock behaviour of the Otto-Diesel engine may be anticipated because of the multi-point ignition which prevents the occurrence of large residual gas quantities. But it must not be forgotten than the Otto-Diesel engine works with a compression ratio of 1:8 and therefore requires more from a fuel than the gasoline engine with lower compression. No statement can yet be made on the influence of the development of the ignition oil on supercharging.

C. Use of safety fuels in the Otto-Diesel process

(1) Quality of the gasoline mixture

It may be expected that the Otto-Diesel engine is not so susceptible to deficiencies of the mixture formation as the gasoline engine, since the ignition depends no longer upon the accidental quality of the gasoline mixture near the sparking plug.

This fact can be proved by producing gasoline mixtures of different quality be altering the injection timing. If the start of injection in a gasoline engine is changed and thus the time for mixture formation, the mixture formation becomes worse with later injection and the engine fails. with injection at the end of the inlet stroke. The Otto-Diesel engine, however, works satisfactorily with mixtures which are formed only during the compression stroke. It even runs with still poorer mixtures but then there is a loss in power (fig.918). In this case it was found that at 260° T.D.C., i.e. 100° after T.D.C., the power was gain slightly improved which is apparently caused by turbulence.

Thus we find that the Otto-Diesel engine is less susceptible to deficiencies in mixture formation than the gasoline engine. The gasoline engine is operated on light fuels the boiling behaviour of which has been determined under consideration of the fact that this engine requires a high quality mixture formation The new process makes it possible to be more independent of the boiling point. This quality of the Otto-Diesel engine means a considerable advance in the use of fuels with higher boiling points, i.e. safety fuels.

(2) Safety fuels

It is obvious that a fuel is less likely to inflame the more it differs in viscosity, boiling behaviour and flash point from the highly inflammable gasoline. There are various safety stages which can be reached. A small degree of safety is shown by fuels which do not flash during accidents or do so only reluctantly. We call these "crash proof" fuels. A considerably greater measure of safety is required of fuels which are exposed to incendiary shells. Whilst the first kind is important for commercial aviation, the Air Force requires a fuel which is safe against firing. Between these two stages there are fuels which are not absolutely safe against firing, yet do not catch fire each time they are fired on.

The firing tests which were carried out by the experimental station "Rechlin" had very interesting results which are shown in the numerical table (fig.934). In the first group we find the light fuels. Here it is remarkable that the heavy gasoline in spite of a higher boiling point and a very high flash point gives no safety. Also its higher viscosity is apparently not sufficient to have any influence. With the exception of exposing this fuel to direct firing, there is a certain improvement; for if we light an asbestos fibre soaked in fuel the flame spreads with only one tenth of the velocity of light gasoline.

The second group contains fuels partially safe to firing, viz. ET 200 and gas-oil. The higher boiling point and viscosity have apparently a favourable effect. The boiling point alone is not the decisive factor, for in the third group we find the same gas-oil thickened by a little wax. This affects its fluidity only, but the result is complete safety against firing. It cannot be assumed, however, that the viscosity is the most important feature for this is contradicted by the fact that the TZ 900/1.38 fuel is not completely safe while the considerably thinner coal tar oil meets all requirements in spite of its lower flash point. This striking behaviour is apparently due to its aromatic character for comparative tests on flame velocity between gasoline and benzene show a similar advantage for the aromatic fuels. As soon as the engine development permits we must direct our attention particularly to aromatic safety fuels.

The very viscous fuel TZ 900/30 is completely safe against firing, but since the thin fuel is almost satisfactory, and engine oil is safe, we may assume that a fuel TZ 900/2 gives sufficient safety.

Thus not one but several properties together are decisive. Apparently high viscosity is not essential and this is the most important result of the firing test. This fact facilitates considerably the use of safety fuels in engines, for it is extremely difficult to deliver and atomise viscous fuels. Preheating is not only difficult but it excludes the use of antiknock additives.

When surveying the safety fuels in order to find one which can be used without difficulty in engines it is seen that TZ 900 has properties which make it particularly suitable.

TZ 900 is a substance which is formed through polymerisation of isobutylene and, according to the treatment, substances of quite different viscosity can be obtained, ranging from thin oil to gum-like materials. We can use the polymerisation product in its viscous form to improve lubricants and with lower viscosity it can itself be used directly as a lubricant. Another extremely important feature which makes it an interesting fuel is the fact that TZ 900 decomposes into its components when heated to 300° without leaving any residues. Thus TZ 900 is a very rare case in hydrocarbon chemistry. This decomposition produces thinner fuels, and finally the initial isobutylene.

The normal heavy oils, however, evaporate leaving residual deposits which spoil the lubricant. Since in present-day tests we must always expect deposits in the lubricant, the importance of a fuel giving no residue and not spoiling the lubricant is obvious.

Some time ago we made extensive tests to break TZ 900 down to a gaseous state and to feed the engine with this gas. We found that this could be done, but it is hardly applicable to aero engines.

Thus we had to give up the idea of using the decomposing property, and attempt to supply the cylinder with TZ 900 in atomised form. But even with special nozzles it was not possible to produce a mixture which could be ignited by means of a sparking plug.

In seeking a means to ignite the imperfect mixture the Otto-Diesel method was developed and operating with TZ 900 was then possible. This represents the most striking advance due to this new method. (pencil note: not only the operatio with safety fuel is thus considerably advanced, but also the problem of starting has a new solution. It is obvious that a gasoline engine cannot be started with a safety fuel alone, but the Otto-Diesel engine can be started and warmed up with ignition oil only).

The result of such a test is shown in the next diagram (fig.920). As expected in the present circumstances, the maximum power was not satisfactory, being 10% less than that obtained from light gasoline. But the engine shows remarkable behaviour with a lean mixture. At a high excess air ratio even a higher power than with light gasoline was obtained. This phenomenon can only be explained by the fac that the TZ 900 has the property of decomposing when heated. Apparently the TZ 900 decomposes when it is injected into the heated air, which process produces highly volatile substances and also gas, so that a very good mixture is produced.

This surprising fact can be seen from the consumption figures (fig.919) which at part load are better for TZ 900 than for gasoline. At high load, however, the consumption is still high. We may expect some progress through attention to atomisation, and we are all the more certain that progress will be made since we have not yet made any systematic tests on nozzles for viscous fuels. (Pencil note: Daimler Benz made tests on nozzles and have begun on nozzle development. Junkers, too, have taken up the problems of delivery and atomisation).

Even if we had an increase of fuel deposits in the cylinder, it would not matter in the case of TZ 900 for the fuel which entered the lubricant would have a lubricating effect. We have established by tests that TZ 900 is an excellent lubricant. An engine which ran under conditions causing ring-sticking after 10 hours at the most with commercial oils, could be made to run for 100 hours with TZ 900 without any ring-sticking. Thus there exists the possibility of operating an engine with TZ 900 working at the same time as a fuel and as a lubricant. We have already successfully carried out tests on feeding the fuel pump with TZ 900 heated in the crankcase. The residual fuel condensed and returned again to the crankcase, starting its circulation again.

Though much work remains still to be done, you will see that in connection with the Otto-Diesel method there are good prospects of using safety fuel for the operation of engines.

D. Conclusion

The tests in connection with the Otto-Diesel process show that its basis is secure, and more and more questions arise which are outside the sphere of fuel research, and mainly concern engine design. Therefore the time has come when at as many places as possible tests of this kind should be carried out using the wide experience given by aero engine developments. We, as fuel research workers, should first of all try to develop the ignition fuels and carry out fuel research according to the new operating method.

It will be best to start with single cylinder tests which need only an additional pump and nozzle and a piston for a compression ratio 1:8. There will probably be no difficulty with the necessary equipment, such as governors, pumps and nozzles since wide experience is available in this field. Extensive tests to investigate starting are most important, since it is desirable to avoid using a sparking plug, even for this purpose only.

As soon as we have enough experience as regards the operation of the injection ignition we shall have to increase the number of tests with safety fuels. Here, previous experience of delivery and injection will be very useful. It is quite probable that greater problems of construction and design will have to be solved than with the Otto-Diesel method using light fuels. As I said before the deposits of safety fuel are immaterial if we use TZ 900. But the development will have to be carried on beyond this one possibility. For all other safety fuels we have to employ principles such as that of Hesselmann.

I hope I have shown what has been done and what remains to be done. What was done was the result of collaboration between engine designers and chemists. I have no doubt that similar ideas were pursued in other quarters but they have only become practicable by the collaboration of these two branches of scientific workers. Our works are particularly well suited to the furtherance of such ideas. We are only too pleased to place our experience at the disposal of those engaged in such work and hope that the development continues to make good progress on a broader basis.

Graphs