FD2872,461t66

BIOS REPORT No. SC4
FKFS Report No. 392
Ernst/Dörr
29.3.41.

Investigations into the development of the self-ignition operation of mixture compression engines

Synopsis:
With a given mean working pressure an increase in the output per unit of displacement is possible by increasing the engine speed; for a constant mean piston velocity this would entail reducing the size of the individual cylinders and raising the number of cylinders. The reduction of the cylinder capacity meets with difficulties especially in connection with the ignition mechanism which in weight and dimensions occupies an increasingly larger part of the whole engine. Application of the self-ignition method would have the particular advantage of doing away with the ignition system.

Only easily ignitable fuels of correspondingly low anti-knock value may be considered for self-ignition. It is well known that the fuel yield obtained in synthesis increases with decreasing anti-knock value. It was therefore feasible to test synthetic fuels in self-ignition operation.

Consequently the following may be expected from the self-ignition process; a more economical application of fuels of low octane number, a simplified construction of the engine and an increase in engine speed.

The investigation is based on preliminary experiments commissioned by the Ministry of Transport. Their purpose was to determine the necessary conditions of operation from the point of view of the fuel and engine and to establish the mechanism of combustion with self-ignition and thus to lay the foundations of operation of the enigne by self-ignition.

Research Institute for Automotive Engineering and Vehicle Engines
at the Technische Hochschule Stuttgart.
Director: W.Kamm.

The investigations were carried out on behalf of the Scretariat for Economic Development. The preliminary work commissioned by the Ministry of Transport will be published as an intermediate report in the Deutsche Kraftfahrtforschung.

Index:

The report contains 27 pages of text and 13 figures.

1. State of Knowledge

The process of spontaneous ignition does not only occur in combustion in the Diesel engine but may also be found in the reactions in the gasoline engine. While on the one hand spontaneous ignition in the Diesel engine is the condition for the course of combustion, in the gasoline engine it appears as an undesirable and troublesome occurrence, accompanied by knocking. The phenomena of the two processes are similar.

The reaction of the fuel may generally be divided into the processes leading up to ignition and the main reaction. The reaction starts at conditions of pressure and temperature below the ignition temperature (1). In this region reaction occurs with only a small velocity. The heat set free may at first be conducted to the surrounding layers and thus need not lead to ignition of the mixture. If the reaction proceeds under conditions in which the heat lost is equal to the heat produced, then according to van 't Hoff, the ignition temperature is reached. A progressive heating up of the mixture can then occur, leading to an accelerated reaction. Explosion will eventually occur at locally overheated points (Heat explosion). A combustion front of high temperature proceeds from the point of ignition with a large combustion velocity and with an accelerating effect on the reaction.

In the reaction of hydrocarbons, side by side with the heat explosion one can always observe a so-called chain reaction with chain branching. This consists of the liberation of atoms and radicals, which react further and thus accelerate the reaction. A very few initial active components can thus produce a considerable reaction. Pure chain reactions are as rare as pure heat explosions. Cold flames which can be found in bomb experiments and also in the engine may be considered as pure chain reactions.

During combustion in the engine the heat explosion is always accompanied by chain reactions.

Spontaneous ignition in the gasoline engine is caused differently from that in the Diesel engine. The fuel is practically all evaporated in the compressed air/fuel mixture before ignition is produced by an ignition spark. The flame front spreads with a relatively small velocity from the point of ignition. At this stage the temperature of the unburnt part of the charge rises in consequence of the pressure rise produced by the combustion; the residual mixture is then vigorously oxidised. If this oxidation changes into self-ignition before the flame front originating at the point of ignition has passed through the residual part of the charge, then this residual part burns practically instantaneously, reaching high local pressures and temperatures.

The consequence of these pressure discontinuities is a pressure wave which passes through the combustion chamber at a velocity higher than sound; the so-called knock-noise occurs at the same time. The essential condition under which knocking and self-ignition occur is thus a pre-reaction in the unburnt residual part of the charge.

In the Diesel process the fuel is injected into the compressed air. Atomization, evaporation and reaction of the fuel thus overlap, a complicated physico-chemical process of combustion resulting. Evaporation of the fuel starts in the outer particles of the fuel stream. These have the smallest velocity and the smallest droplet diameter. These evaporated particles are the first to become active and induce the chemical reaction by colliding with the oxygen molecules. The fuel injected up to this point then burns with a very short ignition time, and finally the fuel being injected burns according to its ignition velocity.

Knocking may also occur in the Diesel engine. Here it is caused by too large an ignition delay of the fuel. Then so much fuel has been injected before ignition takes place, that a very sudden rise in pressure amounting to knock, is caused by the sudden combustion of these comparatively large amounts of fuel.

The cause of spontaneous ignition (knock) in the gasoline engine is thus too large an ignitability (too rapid combustion of the residual charge); in the Diesel engine, on the other hand, too low an ignitability is the cause. For this reason additions lowering the ignitability of the fuel by virtue of their chain-breaking effect are used for lessening the knock tendency of a gasoline engine fuel.

2. Conditions for spontaneous ignition in mixture compression methods

The mechanism of reaction which one may expect for self-ignition with mixture-compression cannot entirely be compared with either the Otto or the Diesel engine. One point in common with the Otto process is the distribution of the mixture. Combustion in the Otto engine is however, started by an ignition spark. The spreading of the flame from the point of ignition is not due to a spontaneous reaction of the mixture; it is rather due to a chemical reaction cause by the progress of a thin flame front. Only when self-ignition of the unburnt residual mixture (knocking) occurs conditions may be obtained similar to those which might be met with in the self-ignition process.

In the spark-ignition engine the residual mixture burns practically instantaneously on self-ignition. For mixture compression self-ignition conditions for sudden combustion must apply to the whole of the mixture. A rapid reaction of the mixture and knocking are therefore to be expected.

A comparison with Diesel engine combustion leads to similar conclusions. One may assume that the ignition delay of the fuel injected into the Diesel engine is greater than the time taken for the injection and evaporation of the whole jet; under these conditions the whole of the fuel will have diffused and evaporated before ignition takes place, similar to the conditions of mixture compression self-ignition. For so large an ignition lag the general experience in Diesel engine is very rough running, steep pressure rise and violent knocking caused by the sudden combustion of the large amount of fuel.

Combustion with knocking with mixture compression self-ignition may thus be expected from comparison with both the gasoline and the Diesel engines.

Though a complete elimination of knock with self-ignition does not at first seem possible, it is known that the pre-requisites for the occurrence of knock are high combustion and reaction velocities. A diminution of these velocities should therefore lead to a decrease of knocking.

3. Test Procedure

The conditions of self-ignition were elucidated by means of experiments on two engines of 200 and 700 cc. capacity.

The 200 cc engine was a single cylinder air-cooled engine normally operated as a spark-ignition four stroke. The combustion chamber was hemispherical with overhead valves.

The 700 cc engine was a water -cooled single cylinder engine, which had a variable compression ratio and was normally used as a 4-stroke Diesel engine, with side valves.

With these two engines the effects of cylinder head design, engine speed, the size of the cylinder and the method of cooling could be investigated and compared. Measurements taken related to the operational behaviour, the power and consumption, the course of the pressure rise, and the influence of the composition of the mixture when operating with self-ignition. The usual method of carrying out such experiments and the usual apparatus were used.

The main fuels used in the later investigations have the following characteristics (table 1)

Table 1

Characteristics of Fuels used

Fuel	Boiling Constant. (Siedekennzahl)	Cetane No.	Octane No.	Specific Gravity
Primary Gasoline	73	34	50.5	0.666
RCH-Diesel Fuel	240.5	78	(-80)	0.766
Mixture of 60 RT Primary Gasoline & 40 RT RCH-Diesel Fuel	129	49	- 5	0.708

4. Results of the experiments

a) Setting up of self-ignition operation

The 200 cc engine was warmed up with spark ignition at its usual compression ratio of 6:3. Using Leunabenzin plus 3% ethyl nitrate as fuel, spark ignition could be discontinued when the temperature of the plug seating had reached about 230°C; the engine then continued to give 4.5 H.P. at a consumption of 400 g/H.P./hour. Operation was knock-free but the engine could be run only over a very small range of load and speed. The temperature of the engine sometimes rose so much that the plug seat was at a red heat which would make pre-ignition very probable.

Even at higher compression ratios (7.7 and 10.2) self-ignition could only be obtained by the addition of ethyl nitrate. The temperature at which sparking could be discontinued was in this case reached after a shorter running period. The engine knocked before and after switching off the sparking plug. High temperatures were also reached here and the engine had to be cooled by a fan. The mean fuel consumption reached the comparatively high figure of 400 to 500 gm/HP/hour whereas the power output was little less than that of the spark ignition engine with the same fuel. The engine could always be controlled and operated in the range of 2500 to 5000 revs./min. Very heavy knocking occurred if the throttle was opened still further and this heated up the engine within a few seconds to beyond the highest permissable temperature. The engine could not be run in this range in spite of considerable cooling.

The run showed the essential characteristics of a sparkignition engine with considerably enhanced knocking. Removal of the piston after a run of several hours showed the well-known pits in the piston due to detonation, some of them being finger-deep pits in the piston crown (Fig.I) Ring breakages and damage to the bearing were also observed frequently. It was at first attempted to counter-act this damage by a suitable treatment of the surface of the piston and the fitting of special piston rings. These attempts did not result in any appreciable improvement.

b) Experiments on the adaptation of fuels to self-ignition

The fuels of relatively low octane number, of higher ignitability than normal gasoline fuel, and of lower boiling-point, which accumulate during synthesis, are not suitable for either the gasoline or the Diesel engine. These fuels do seem to be suitable for use in the self-ignition engine on account of the very properties mentioned above. The low boiling-point ensures easy atomization and evaporation, and good ignitability is desirable for self-ignition.

The relavant fuels were examined as to their suitability in self-ignition operation by making engine tests.

The behaviour of the primary gasoline without additions was investigated first. Self-ignition operation could not be obtained at a compression ratio of 7.7 even when the temperatures were very high.

When ethyl nitrate was added the engine did work on auto-ignition; but relatively high percentage additions were necessary; medium temperatures could be employed when about 5% ethyl nitrate was added. This was practically impossible if the amounts added were less.

A compression ratio of 7.7 was evidently too low. The engine worked without any additions at a compression ratio of 10.2 but high temperatures of operation had to be employed. Addition of ethyl nitrate was thus again indicated, though not in such large amounts. Self-ignition operation was quite satisfactory with additions of 0.5 to 2%.

Small additions of Diesel oil effected no improvement. Other investigations on various mixtures may be left out here since no improvement could be attained. The results obtained so far led to the hypothesis that the cause of the unsatisfactory operation was to be sought in the low ignitability of the primary gasoline.

Various mixtures of primary gasoline and RCH Diesel fuel were tried out with an addition of 2% ethyl nitrate. With small percentages of RCH fuel no observable improvement resulted. One could, however, observe that the self-ignition was facilitated by increasing the fraction of RCH fuel. Good operation resulted with a 40% addition of RCH fuel; for this mixture the content of ethyl nitrate could thus be reduced to 0.5% . Further increase of the content of RCH Diesel Fuel (50-80%) gave less favorable conditions for self-ignition operation because of the low volatility of this Diesel fuel.

It was concluded that the engine could be run without ethyl nitrate if the compression ratio was increased. At $\varepsilon = 10.2$, mixtures with low content of RCH Diesel fuel were tried again. Satisfactory working in the absence of ethyl nitrate began with about 30% RCH Diesel fuel. 40% RCH Diesel fuel gave favorable results whioh could not be improved even by the addition of ethyl nitrate.

Further increase of the content of RCH Diesel fuel resulted again in less favourable operation. It is worth mentioning that in this engine a further increase of the compression to 11.9 gave favourable operation conditions but that the output was no longer sufficient.

The most favourable conditions were thus found with a composition of 60% primary gasoline and 40% RCH fuel. The following experiments were carried out with this mixture.

With all the mixtures examined so far knock-free operation was never attained.

Further investigations could therefore be pursued in two directions:

1) Experiments to weaken the effects of knocking while allowing knocking to continue
2) Experiments on all possible means of inducing knock-free spontaneous ignition operation

The values of output and consumption measured with the most favourable composition of the mixture are shown in Fig.II; the values of the gasoline engine at a compression of 6.3 working with spark ignition are given as comparison. The powers obtained with the self-ignition operation lie below the spark ignition engine values.

The conumption amounting to 370 g/HP hour at 5000 revs./min. is also less satisfactory than with spark ignition.

c) Diminution of Knock Tendency

According to knowledge hitherto gained one could not count on finding a fuel mixture which would give knock-free self-ignition operation. All the same, experiments were repeatedly performed with the object of obtaining a knock-free run or reduced knocking, by choosing the most varied mixtures by alterations in the combustion chamber and by studying the influence of temperature and compression ratio.

Additions of iron carbonyl were added as an anti-knock to the particularly suitable mixture of 60% primary gasoline and 40% RCH-Diesel Fuel. It was shown that additions of up to 0.25% iron carbonyl still permitted self-ignition operation with heavy knocking still occurring. The knock at 0.5% iron carbonyl was decreased, but with this percentage the limit of ignition was already reached, and self-ignition was no longer possible with larger additions of iron carbonyl.

The same result was obtained with other mixtures e.g. a mixture of ethyl nitrate and primary gasoline. Here again operation was no longer possible with 0.5% iron carbonyl. If the content of iron carbonyl was diminished knocking occurred simultaneously with self-ignition. Attempts to prevent knock by influencing the properties of the fuel were then abandoned.

Finally simple alterations of the combustion chamber were undertaken with the aim of diminishing the knock tendency by dividing up the combustion chamber.

A recess was milled out in the piston crown and a pin was screwed into the cylinder head inside the combustion chamber to serve as an ignition point and thus effect a slower combustion. No improvements worth mentioning were obtained.

d) Influence of Composition of Mixture

As was stated at the beginning it is the suddenness of the reaction of the air/fuel mixture that is the cause of the knocking. Attempts to slow down the reaction of the mixture by means of anti-knock agents lead to a diminution of ignitability without the elimination of knock. This shows that if operation by self-ignition is desired the ignitability as such must not be reduced. Further experiments were therefore carried out only with ignitable fuels.

The knock investigations led to the result that knocking occurs with a correspondingly increased velocity of reaction. Reducing the velocity of reaction must thus entail a reduction in knocking. Another possibility is thus presented, namely, to attempt to reduce the velocity of combustion while keeping to a fuel with favourable ignition properties. It is well known that the velocity of reaction is strongly influenced by the composition of the air/fuel mixture. The next step was therefore to ascertain the influence on the knock behaviour of the mixture composition with the above fuel blend used for mixture compression on self-ignition.

The composition of the mixture can only be varied within limits with the ordinary carburettor. A special carburettor was therefore developed for the investigation of the influence of the fuel/air mixture, which allowed regulation of the air/fuel mixture independent of the operation of the engine. The carburettor was first constructed for the water-cooled side valve 700 cc engine. The composition of the mixture was determined from separate measurements of the air by means of a rotating piston gas meter and of the fuel consumption by means of the usual instruments. The mixture of 60% primary gasoline and 40% RCH fuel which is particularly suitable for spontaneous ignition was used at a compression ratio of 10.

The influence of the composition of the mixture on knock was measured from 800 to 2400 revs/min. with the throttle fully open. Power and consumption were measured at the same time.

It may be seen from Fig. III that the engine could be run on self-ignition within a mixture range, expressed as the ratio of the weights of air and fuel, i, of from 6 to 28. The following remarkable phenomena were observed.

At 2200 revs/min. operation was not possible below an air/fuel ratio of 8. Practically knock-free self-ignition operation occurred at air/fuel ratios of 8 to 10 (rich). Between 10 and 25 self-ignition was accompanied by vigorous knocking. Operation for long periods was impossible since very high temperatures were produced by the knocking which made it imperative to switch off the engine. Between i = 25 and i = 28 operation was again knock-free (lean setting). The engine could not be run above i = 28. The results for lower engine speeds were similar, for instance at 1200 revs/min the knock free ranges lay between i = 6 and 7, and i = 24 and 27. In the transition stages from knock-free operation to knocking, small alterations of the mixture immediately produced heavy knock, the transition thus not being continuous. In the top of Fig.III are entered the measured values of consumption and power. With rich setting and at 2200 revs/min. the power output in the knock-free region is about 8 H.P., at lean setting about 7 H.P. This corresponds to a specific output of about 12 H.P./litre.

The values of consumption in knock-free rich region were very high at 400 to 900 gm/H.P. hour; for the lean region the values were from 190 to 240 gm/HP hour. These figures apply to the single cylinder engine which has a comparatively low mechanical efficiency. The values for knocking operation lay in between those forrich and lean knock free operation.

The cylinder head temperatures in the knock free region, measured at the seating of a bolt screwed into the sparking plug thread between inlet and outlet valves, were comparativley low at 150°C. The jacket temperature in the water-cooled test cylinder lay between 60 and 90°C.

Knock-free self-ignition with rich mixture is not to be considered because of its uneconomically high consumption. Neither can the knocking range be employed on account of its mechanical disadvantages (falling off of output after short run, knock, pitting). Knock-free lean operation seems the only method favourable for putting the self-ignition process into practice. The main difficulty is the high sensitivity to the mixture strength.

e) Experiments to extend the range of knock-free self-ignition

The reason for the absence of knock in the self-ignition operation is not a diminution of ignitability but a reduction of the velocity of combustion. For the practical application of the self-ignition engine an extension of the knock-free range is required. Furthermore, one needs an accurate control instrument for adjusting the mixture strength.

In conjunction with the previous work it was attempted to extend the knock-free range by alterations of the engine. An ante-chamber of heat resisting material was fitted to the side valve engine in order to modify the course of the combustion (Fig.IV) This first auxiliary chamber had a capacity of 6 cc and was tried out with various outlet sections. Similarly for a second subsidiary chamber having a capacity of 12 cc.

The first chamber with a diameter at the mouth of 6 mm. did not at first give any apparent improvement. Only after increasing the outlet diameter to 12 mm was some extension of the lean knock-free range observed. Eventually the second chamber with an outlet diameter of 12 mm showed the best results. A continuous run of several hours was possible with this subsidiary chamber without having to readjust the mixture strength. Even here, however, the lean mixture range free from knock, remained small. Generally speaking, an improvement was found as compared to the operation without the ante-chamber, since in the latter case, the operation had to be continually watched and the carburettor adjusted. When the subsidiary had been fitted these things became unnecessary.

If a useful engine is to be devised then a further extension of the range would be valuable. This must be left for later investigations.

f) Running Characteristics of knock-free Self-ignition

700 cc engine, side-valve, water-cooled: The particular phenomena connected with the starting of the engine will be discussed later. On the test-stand the engine was warmed up on spark ignition, then adjusted to the knock-free lean range and the ignition switched off. Knock-free self-ignition operation at very low speeds could be obtained only with difficulty when the engine was cold. When the engine was at its operating temperature it could be run knock-free over the whole speed range. Any considerable changes in the operating temperature or large differences in speed demand a corresponding adjustment of the mixture strength.

The cylinder head temperature remained constant in this water-cooled engine even after prolonged operation.

As already mentioned, 10 was the most favourable compression ratio for knocking operation. For the knock-free run practically the same conditions were obtained. The limit of spontaneous ignition was reached when the compression ratio was reduced to 8. A decreased output was observed when the compression ratio was increased in spite of the greater ignitability. This may be explained by the design of the engine (side valves).

Fig. V shows the values of power and consumption obtained from knock-free self-ignition operation with fully opened throttle. The output of 7 H.P. at 2200 revs/min. corresponds to a specific output of 10 H.P./litre. A consumption of ~~200 gms./H.P. hour over almost the whole speed range may be considered to be reasonable for a single cylinder.~~ The values lie near to those usually obtained for Diesel engines. Steady idling could be obtained from from knock down to 300 revs./min. provided a certain minimum temperature was maintained. No indications of corrosion, pitting or the like on the piston or the walls of the combustion chamber could be found with knock-free operation even after long running periods (over 100 hours).

200 cc engine, overhead valve, air-cooled: As with the 700 cc engine, the 200 cc engine could be run knock-free in the lean region. Operation demanded comparatively high cylinder head temperatures, 220° at the seat of the sparking plug. In order to avoid too much cooling, the air-cooled engine had to be cooled intermittently.

According to the results obtained so far, see Fig. VI, the maximum speed of the engine is 4300 revs./min. (5000 revs/min. in the spark ignition engine); below 2500 revs/min. the engine could not be run knock-free. The cause of this has not yet been completely elucidated; probably it is connected with the weakening of the mixture. The values of output and consumption have been given in Fig. VI. The preliminary limits of operation may also be taken from the power curve. The maximum output is 2.5 H.P. at 3700 revs/min (specific output 12.5 H.P./litre); the best combustion is 190 to 200 gm/HP hour. As in the side-valve engine, this is a low value for a single cylinder.

g) Starting Tests

Cold starting with self-ignition may be obtained by the following means:

1) Heating of the intake mixture or increase of compression
2) Increase of ignitability of fuel, for instance by addition of ethyl nitrate for starting
3) Starting with sparking ignition
4) Starting with a glow plug

With the side valve engine (700 cc) the compression ratio could be increased to E = 17. Starting experiments were carried out on the cold engine (plus 15°C) with gradual raising of the compression ratio. This gave a compression ratio of 16.5 for the well tried blend of 60% primary gasoline and 40% RCH fuel for the attainment of cold starting. Below this compression ratio starting was impossible. Preheating of the intake mixture was not investigated. When warmed up, both engines could be started without ignition at a compression ratio of 10.

The ignitability may be enhanced by addition of ethyl nitrate to the mixture. With additions less than 5% a temperature of 25 to 30°C was necessary whereas additions of from 5 to 10% made it possible to start from cold.

As a rule cold starting by spark ignition was used in the experiments.

If a sparking arrangement is to be avoided one can start up with a glow plug, as in Diesel operation. Experiments on cold starting with a glow plug were successful. Only occasionally striking back of the flame into the intake pipe was observed. The simplest means for starting is thus the addition of from 5 to 10% of ethyl nitrate. It should be possible, however, to develop further chemicals.

h) Investigation of the pressure rise and of radiation.

Significant inferences as to the ignition process, the pressure rise and the further course of the pressure and also the radiation in the combustion chamber may be made with the instruments available nowadays.

The course of the pressure was followed by a quartz pick-up, the output being amplified and then recorded by the "Schleifen" oscillograph or cathode ray tube. A quartz window with a photocell was fitted in the combustion chamber. This registered the radiation and thus the first ignition of the gases together with other combustion processes.

200 cc. overhead valve engine

Only the pressure could be recorded with this engine. In fig. 7 the course of the pressure in self-ignition with knocking at a compression of 10.2 is given in terms of the crank angle. The sudden, practically vertical pressure rise culminating in a high pressure peak when ignition sets in is characteristic of operation with knock. This indicates a simultaneous combustion of the whole mixture.

Several degrees of crank angle before the pressure rise, a small pressure increase may be found in the diagram. This may indicate a preliminary reaction in the mixture.

The pressure diagram shows characteristics similar to those of the spark ignition engine.

Figs. 7 to 10 show that as the pressure rise occurs later, the knock decreases and finally stops altogether.

700 cc. side valve engine

The course of the pressure, the top dead centre and the radiation were indicated for the side valve engine.

Fig. 11 shows a record of operation with knocking. The pressure in the combustion chamber starts rising steeply at a 8° B.T.C. the maximum rise being about 9 atm/deg. crank angle. At 2.5° crank angle B.T.C. it reaches the maximum pressure of 72 atm. gauge pressure. Between about 2.5° B.T.C. and 9° A.T.C. the pressure is practically constant.

Luminescence of the flame in the combustion chamber sets in at the same time as the steep pressure rise at 8° B.T.C. Operation with knocking always gave a bright white light in the combustion chamber, the radiation of which was easily registered.

The pressure rise occurs somewhat later (9° crank angle A.T.C.) in the knock free lean mixture region with low specific consumption; here the transition is very smooth and the pressure rise considerably flatter (about 2.5 atm / deg. crank angle). The maximum at 17° crank angle A.T.C. only amounted to about 50 atm. gauge pressure.

As the figure shows, special difficulties were experienced in the registration of the radiation in the knock-free region. While, as has been mentioned, a bright white flame appeared with knock, the flame in the knock-free region was of a faint blue and even with a high amplication of the photocell current no deflection of the recording instrument could at first be observed. Attempts were made to intensify the luminosity of the flame and to choose a photocell more suitable for the observed spectral range. This was not however, successful. Then the internal diameter of the windows was considerably increased.

By this means registration of the radiation eventually became possible. According to these measurements radiation in the knock free lean region also sets in simultaneously with the steep pressure increase i.e. between 6 and 9° crank A.T.C.

In the knock-free rich region (fig.13) the steep increase of pressure occurs at 22° crank angle A.T.C. i.e. relatively late. At the same time radiation in the combustion chamber begins.

The pressure peak of about 35 atm. excess occurs about 30° crank angle A.T.C. A preliminary reaction before the steep pressure rise is also noted.

Just as in the knock-free lean region the colour of the flame was a dull blue. The course of the pressure is similar for the two cases, knock-free lean and knock-free rich. This is shown by figs. 12 and 13.

5. Evaluation of Results

a) Glow - residual gas, and self-ignition.

The only object of the initial experiment was to obtain ignition with mixture compression without an igniting spark. The possibility of a so-called pre-ignition was not however excluded. With pre-ignition, some engine parts e.g. the spark plug electrodes reach so high a temperature during the compression stroke that ignition occurs. The first experiments to obtain self-ignition had to be carried out at temperatures so high that glowing of some of the engine parts was sometimes observed. In such cases one may assume glow ignition similar to that in the hot bulb engines or the glow-tube engine of Gottlieb Daimler.

The fact that no knock was observed with this characteristic glow ignition may have two reasons. First that conditions obtain similar to those with spark ignition i.e. propagation of the flame from the hot point traversing the combustion chamber at a definite velocity. Secondly there is the possibility of the practically instantaneous combustion of the mixture only occurring relatively late after top dead centre at the time when the piston is already on the downward stroke, thus increasing the volume of the combustion chamber. The pressure diagrams obtained later confirm that this is possible in principle.

A further explanation of the decrease in knock at very high temperatures has already been given by Dumanois and Serruys. (2)

Peroxides which initiate chain reactions are responsible for the sudden combustion; at high temperatures in the engine these decompose even before the combustion proper. As a matter of fact Dumanois, on raising the temperature of the engine first obtained an increase in knock which however ceased as the temperature rose further.

Residual gas ignition is not likely for a four-stroke engine and can therefore be omitted for the purpose of the above investigation. The conditions of operation determined in the later experiments may thus be considered as pure self-ignition. One may adduce as a proof that cold starting is possible at a compression of 16.5; also, at the operating temperature, starting was possible at a compression ratio of 10. Under these conditions, where the compression temperature is considerably above the temperature of the walls one can no longer assume that ignition occurs at hot points on the wall.

From this it may be concluded that pure self-ignition occurs under the conditions set up later. This self-ignition does not, in all probability proceed from the wall, but from the warmest interior regions of the gas, which transfer least heat to the walls.

b) Further Problems

Within the scope of this investigation at the necessary conditions for spontaneous ignition with mixture compression have been elucidated from the point of view of the engine and particularly from the point of view of the fuel. The difficulty of too heavy knock occurring simultaneously with the combustion was overcome by making it possible to run the engine with knock-free self-ignition over a wide range of speed and load. One obstacle in the way of developing a practical self-ignition engine is the comparatively narrow range of mixture strength over which knock free operation is possible. Therefore the first task is to extend this knock-free range. Furthermore, a precise instrument must be developed for the control of the correct air-fuel ratio. Besides these problems, work must be carried out on the questions which arise in the operation of the multicylinder engine, namely starting and reliability.

The observed fuel consumption of 200 gm/HP hour is low for a single cylinder engine. It is nearly equal to the consumption of the automotive Diesel engines in present day use.

The observed specific output is also of the same order of magnitude as that of the Diesel engine. On account of the low consumption and the possibility of a more economical exploitation by the engine of low boiling low anti-knock fuels, the development of a self-ignition engine seems advisable even from the economical point of view. Such a development would also serve to produce further valuable information on the process of combustion.

The specific power output is relatively low; in all probability this may be remedied by supercharging the engine and using a greater engine speed.

6. Summary

The present report deals with fundamental investigations on the self-ignition operation with mixture compression. This method is to be considered as a new method of operation of engines.

Practical experiments on self-ignition were carried out with two different single cylinder engines of capacities 200 and 700 cc.

Synthetic fuels were tried out and a fuel blend of 60% low boiling primary gasoline and 40% RCH Diesel fuel was found to be particularly suitable.

According to the present state of knowledge it was expected that the reaction of the fuel in the engine in the case of mixture compression self-ignition would occur nearly instantaneously, i.e. with vigorous knocking.

The first experiments on engines did in fact give this result.

An investigation was made into the means of suppressing the heavy knock. It appeared that when fuels were chosen which were less ignitable, only the tendency for spontaneous ignition was diminished, and the knock could not be eliminated. Changes in the combustion chamber, did not result in either a diminution or elimination of the knock.

Experiments on various compositions of the fuel air mixture demonstrated that there was a knock-free region of self-ignition for very rich and for very weak mixtures. With normal mixture strengths vigorous knocking occurred.

Ante-chambers were fitted to the combustion chamber in order to extend the knock-free lean mixture range. This effected some improvement. The values of power and consumption measured in the lean knock-free operating range roughly corresponded to those available in the automotive Diesel-engine.

In the knock range the pressure rise was very steep, the maximum being 72 atm. gauge pressure. In the knock-free range a flatter rise was observed with a smoother transition and a maximum pressure of 52 atm. gauge.

In the knock free lean range the engine could be run over the whole speed range with and without load. The temperature of the hottest point of the cylinder remained constant and relatively low at 150°C during a continuous run of several hours. The most favourable conditions were obtained at a compression ratio of 10. Starting of the engine from cold is also possible.

A problem remains of developing a control instrument which will adjust the mixture to knock free operation for the various engine conditions. This task will be facilitated if it is possible to widen the knock-free range by modifications to the engine. An increase of the specific power output may be expected from supercharging and an increase of engine speed.

Figure headings.

Fig. 1. Effects of knock on pistons.

Fig. 2. Power N and consumption b in the spark ignition engine and with mixture compression self-ignition knocking operation in the 200 cc. engine.

1. Spark ignition engine normal $\varepsilon = 6.3$, fuel Aral
2. Knocking self-ignition, $\varepsilon = 10.2$, fuel 60% primary gasoline + 40% RCH Diesel fuel.

Fig. 3. Output (H.P.) Consumption (g/H.P.hour) and mixture strength for knocking and knock-free self-ignition operation in the 700 cc. engine $\varepsilon = 10.0$ fuel 60% primary gasoline + 40% RCH Diesel fuel.

Fig. 4. Arrangement of ante-chamber.

Fig. 5. Power and consumption of the side valve 700 cc. engine for knock-free self-ignition and lean mixtures.

Fig. 6. Power and consumption of the 200 cc. engine for knock-free self-ignition in the lean range ($\varepsilon = 10.2$, fuel 60% primary gasoline + 40% RCH Diesel fuel.)

Figs. 7 to 10.
The course of the pressure in the 200 cc. engine with self-ignition. Diminution of knocking with later pressure rise (small load, about 3,500 revolutions /min.)

Fig. 11. Pressure and radiation diagrams for mixture compression self-ignition, operation with knock. $\varepsilon = 10$, 2000 revs/min. Maximum load, 700 cc. engine.

Fig. 12. Pressure and radiation diagrams for mixture compression self-ignition knock free operation in the lean range $\varepsilon = 10$, 2000 revs/min. Maximum load, 700 cc. engine.

Fig. 13. Pressure and radiation diagrams for mixture compression self-ignition and knock free operation in the rich range. $\varepsilon = 10$, 2000 revs/min. Maximum load, 700 cc engine.