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TESTS WITH THE RING PROCESS AT DIFFERENT COMPRESSION RATIOS

SUMMARY:

It was first established that R 300 and gas oil gave the same power in Diesel operation, provided the nozzles were so selected that injection time was about equal to ignition delay. R 300 (Cet. No. 188) burns more slowly than gas oil (Cet. No.40), so that combustion must begin before top dead centre, becoming earlier as compression ratio rises.

At compression ratio 1:8 the knock behaviour in the ring process an the spark ignition process are equal, while at higher compressions the ring process is superior. If ignition advance and R fuel injection are adjusted to a time which can be considered an invariable for practical purposes, then at λ = 0.7 again in power of 30 per cent is observed at compression ratio 1:8.

At high compression ratios, gas oil is just as suitable for use as R fuel in the ring process as R 300. The power of Diesel engines can be raised to a considerable extent if they are operated according to the ring process on fuels with high knock ratings.

CONTENTS

INTRODUCTION

So far, all tests with the ring process have been carried out at a compression of 1:8. This compression ratio can easily be reproduced in existing types by changing the pistons, it does not make too great demands on the knock rating of gasoline or the ignitability of R fuels at the present stage.

Experience has shown that at the present stage of development the knocking tendency is about equal for engines working on the ring process and those working with spark ignition. We now have to enquire whether the two processes continue to behave in the same way at higher compression ratios, or whether one or the other is superior. One thing was clear from the beginning, that higher compression demands a higher knock rating in fuels, and that higher power cannot therefore be expected. These tests were inspired by the observation by Daimler Benz, that a Diesel aero engine could be operated knock-free on B 4 at a compression of 1:14.

Investigations as to the ignitability of the customary Diesel fuels and the very ignitable R fuels revealed in each case a widely divergent course of combustion in Diesel operation. The object of the tests under consideration was to determine whether there is a fundamental difference between the ignition of gasoline mixtures by gas oil and their ignition by R fuel.

A. Tests on the Diesel Process

1) Selecting the nozzles.

It was first necessary to procure suitable nozzles, as the usual R fuel nozzles are only intended for small volumes, while Diesel operation had to be tested right up to the full load.

a) Conditions of the Tests: As the single cylinder test beds were being reassembled, the tests were made on an I.G. test diesel. The following were the operating conditions for the engine:-

Capacity	1 litre
Compression ratio	1:8 to 1:19
Coolant temperature	80°
R.P.M.	1400
Air temperature	20°
Air pressure	normal aspiration
Injection pump	PE 1b piston 8 mm Ø
Fuel volume	13 to 150 mm³ per cycle
Injection advance angle	Optimum value
Intake	Opens at top dead centre, Closes 43° after bottom dead centre
Exhaust	Opens 48° before bottom dead centre Closes 10° after top dead centre
Method of forming mixture	Carburettor with adjustable nozzle.

The following nozzles were used:-

Bosch pintle nozzle DN 4 S 1 (40° atomisation angle)

Bosch single hole nozzle DLOS 103 (diameter 0.3)

Injection pressure 160 at.

Fuels used were:

Diesel fuel II	(DK II)	Cetane number 40
R fuel	(R 300)	Cetane number 186

In addition to power and consumption, we also observed the pressure change in the cylinder and the needle stroke, in order to estimate the true beginning of injection. The angle of injection advance was set each time for maximum power, which sometimes meant that the engine ran roughly.

b) Results of the Nozzle tests.: The tests were carried out at a compression ratio of 1:14. The results are shown on sheet 1.

The maximum attainable power, without reference to the smoke limit, occurred at a B.M.E.P. of 5 to 6 kg/cm^2. Optimum consumption is at 3000 k.cal/H.P. As the engine operated, not with the pre-combustion chamber provided for normal operation, but with solid injection which was not especially perfected, the figures may be considered permissible.

The best values were obtained with gas oil (Sheet 1). It is immaterial here whether the pintle nozzle or the hole nozzle is used. The hole nozzle is, however, considerably less satisfactory with R 300. But this finding only refers to the investigations made here into Diesel operation, as the volumes used by the Ring process when idling are in a region in which, as stated, there is no difference in performance between the fuels and nozzles.

The reasons for the marked influence of the type of nozzle when operating on R 300 are clear from Sheet 2. Here the opening and closing of the nozzle needle is represented as a function of the fuel volume, that is, of power. As the movement of the nozzle needle is the surest indication for the beginning and end of injection, it is possible to see from the graphs how long injection lasts, and when it begins and ends. At the same time the instant of pressure rise is shown, so that it is possible to see what proportion of the fuel gets into the cylinder after the beginning of combustion.

It now appears that when working on R 300 with a single hole nozzle, injection must begin very early if the powers shown on sheet 1 are to be reached. The fuel flow is obviously very much hampered by the narrow bore, so that the injection of comparatively large volumes of a fuel of low calorific value takes a fairly long time. Assuming that delivery is uniform, we see that up to the rise in pressure only about 1/3rd. of the volume of fuel is in the cylinder, another third is injected up to T.D.C., and the remaining third gets into the cylinder only during the expansion stroke. This explains the low power of the single hole nozzle in Diesel operation on R 300. The behaviour of the exhaust gas temperature (Sheet 1) indicates after burning. In spite of low power this is fairly high.

Using the pintle nozzle it is possible to inject all the fuel before dead centre, combustion occurring with about half the volume of R fuel. Injection can be considerably delayed, thus curtailing ignition delay. The exhaust gas temperature is comparatively high, being higher than that of gas oil owing to the sluggish combustion. The power and consumption almost attain to the values for gas oil.

These two sets of tests enable us to draw conclusions as to starting. The R engine is started by the Diesel process with the greatest possible volume of R fuel, as the power required is initially very great, and combustion with the engine cold is incomplete. Narrow aperture nozzles, which are favourable to ordinary operation, are not suitable for starting, as they do not permit the supply of comparatively large volumes of fuel in a short time. This bears out our practical experiences. We should therefore always try to make do with as wide nozzles as possible, or else use for small volumes those nozzles which give a solid jet of great penetration, and, for large volumes for starting, those with a wide opening with the best possible atomisation. Bosch were entrusted with the handling of this problem.

The test results shown in sheets 1 and 2 indicate that maximum power is achieved with gas oil if the pressure rise occurs near dead centre. The injection advance angle is therefore about the same as for R 300, in spite of the lower cetane number. This is because R 300 burns sluggishly, and therefore ignition must begin before top dead centre. With the pintle nozzle and gas oil, pressure rise and the end of injection are at about dead centre. Therefore this nozzle gave the best results. With the hole nozzle, pressure rise must occur before top dead centre, because otherwise the proportion of fuel, which does not get into the cylinder until the expansion stroke, will become too great, and so cause faulty combustion. At part load the greater duration of injection of the hole nozzle evidently has a favourable effect on combustion, resulting in favourable consumption and low exhaust gas temperatures (Sheet 1)

In contrast to R 300, about half of this fuel can be injected up to the beginning of the pressure rise, as the calorific value of gas oil is considerably above that of R 300.

2) Comparison between R 300 and Gas Oil in Diesel Operation.

We now made a series of tests to obtain a comparison between the course of combustion in a Diesel engine running on R 300 and on gas oil.

a) Conditions of the test: After we had established that Diesel operation on R 300 was only possible with the pintle nozzle, we made the following tests with the test conditions as under A 1a, but with the pintle nozzle DM 4 S 1, and a compression ratio of 1:16.

b) Results. Sheets 3 and 4 show several combustion diagrams, with their mixture loops. Tests such as these were made at different compression ratios. The results at compression 1:16 were selected as these photographs were the most successful. The conditions at the other compression ratios were essentially the same.

With gas oil DK II (Sheet 3) the pressure rise is very violent as the whole of the fuel is in the cylinder at the moment of ignition. Power and consumption are satisfactory, but the price of this is such rough running as to be impossible in practice. The diagrams therefore show very violent oscillations, so that failure of the quartz transmitter often occurred.

It was clear that the best power was reached when maximum pressure was at dead centre or shortly after it. Although with R 300 the total volume of fuel is in the cylinder at dead centre, combustion is very smooth (Sheet 4) R 300 evidently burns much more slowly than gas oil. As already mentioned, combustion occurs very quickly with gas oil when it begins at dead centre, and there would be violent knocking if, as is necessary with R 300, combustion began before top dead centre. Combustion during the compression stroke means thermal and mechanical losses, so that the power of R 300 is not equal to that of gas oil.

In the ring process the sluggish combustion of R 300 is only important in starting, idling, and warming up. One could deduce from this that a certain time is necessary in Diesel running for the mixture to form, and that with highly ignitable fuels this is not possible, because combustion begins before the fuel is all in the cylinder. Combustion thus begins with a smaller amount of energy, and the pressure rise is determined by the conditions of injection. That this assumption is incorrect is proved by tests, in which with R 300 the use of a larger pump plunger brought about a short injection time. The whole of the volume was then in the cylinder before combustion. In spite of this, combustion was slower than when the same quantity of energy was injected before the beginning of combustion in the form of gas oil. Thus, the cause of more sluggish combustion is only to be sought in the composition of the fuels. It is possible that the oxidation of R 300 passes through numerous intermediate stages, in which frequent breaks occur in the chain, or in which very often CO_2 of H_2O are formed, which inhibit combustion.

3) Tests at various compression ratios

After the tests described above had established the differences which appear between operating a Diesel engine on gas oil and operating it on R.300, we had now to investigate the way in which different compression ratios affected the behaviour of these two fuels.

a) Conditions of the tests: The tests were carried out under the conditions described in Section A 1a, but only with pintle nozzle DM 4 S 1. The compression ratio was altered from 1:8 to 1:19, but with gas oil operation was only possible from 1:11 onwards.

b) Results of Tests: The tests presented in sheets 5 and 6 show that the best powers are obtained with gas oil (Sheet 5) The highest powers were at compression ratios of 1:11 or 1:12, which are out of the question in practice because the engine cannot be started at those ratios.

In consequence of increasing friction loss, the attainable maximum power falls off as the compression ratio increases (Sheets 5 and 6). At 1:11, ignition is uncertain with gas oil, so that higher powers are actually achieved at compression ratio 1:12. For both fuels the optimum consumption is 3000 k.cal/H.P. hour. Only R 300 at 1:8 (Sheet 6) does not reach this figure.

Ignition delays at various compressions are also shown in sheets 5 and 6. As the injection advance angle most favourable to power was only arrived at by trial and error, the variations are very great. The curves have therefore been plotted in their most probable position.

It appears at first that with R 300 ignition delay is not solely dependent on the compression ratio. With gas oil, on the other hand, we observe that the ignition delay is reduced as the compression ratio increases. The reason is, that with gas oil, ignition occurs at dead centre, and that therefore the compression temperature, which is a function of the compression ratio, has a pronounced effect. With R 300 ignition must begin during the compression stroke, because of the slow rate of combustion. The ignition delay is thus in a region where the temperatures of the charges at different compression ratios are not so different from each other as near dead centre. A comparison of the diagrams showed that with gas oil the best position for the pressure rise is at top dead centre, while with R 300 it is obvious that combustion must begin sooner as the compression ratio becomes higher.

B. Tests with the Ring Process

After we had cleared up the question of the conditions obtaining under Diesel operation, the powers and consumptions obtainable at different compression ratios with the ring process were determined.

1) Tests with different R fuel nozzles

Whereas in Diesel operation that which determined the choice of the nozzle was the fact that large volumes of fuel got into the cylinder in a short time, so in R operation it was necessary to find a nozzle which would work with as small volumes of R fuel as possible, and with slight injection delays.

a) Conditions of the Tests. The conditions for the tests were the same as those given in A 1a. We selected the compression ratio of 1:8, which is customary for the ring process. The R fuel volumes were 20 and 35 mm^3 of R 300 per cycle.

The fuel used was B 4. The power was attained by altering the volume of fuel. The tests showed that it was possible to operate with a small cylinder without pre-heated air, whereas in previous tests on aero-engine cylinders it was always necessary to adjust air temperature to 80°.

b) Results. Comparison of the nozzles revealed the following facts:-

With the pintle nozzle the penetration is obviously inadequate on a volume of 20 mm³ per cycle (Sheet 7) power and consumption improve considerably when the volume is raised to 35 mm³. The reason is, however, not in the increased volume of R fuel, for the single hole nozzle gave the highest value for this series of tests on the smaller volume of 20 mm³. At 35 mm³ there is no difference between the two types of nozzle. It is thus confirmed that in the ring process a hard spray is better, at least where small volumes of R fuel are used. But the softer spraying nozzle is more suitable for starting, as the Diesel tests showed.

The poor combustion experienced when the pintle nozzle was working on small volumes of R fuel results at full load in an increase in exhaust gas temperature, which at overload falls on account of the rapidly decreasing power. Ignition delay is certainly very much greater with the single hole nozzle, so that in this connection the pintle nozzle is better, if we dispense with the use of small volumes. Nevertheless we used the single hole nozzle in the further tests. Diagrams taken simultaneously showed that when we used the pintle nozzle with a volume of 20 mm³, combustion took place with only a small volume of gasoline. Misfiring begins at a B.M.E.P. of 5 kg/cm², but disappears completely with 35 mm³ per cycle.

2) Comparison of Knock behaviour in the spark ignition and ring processes.

Care should be taken that, in comparative tests on knock behaviour, the most favourable conditions are chosen in each case for both Otto and Ring processes. In the first tentative tests (Report 394) we compared the spark ignition process at 32° ignition advance to the ring process with the pressure rise beginning at top dead centre. This procedure is open to question, as the knock limit is determined to a great extent by the timing of the start of combustion. The tests about to be discussed were therefore made in a different way.

a) Conditions of the tests. The task set was, to extract the maximum power at different mixture ratios, using the fuel B.4, which has a poor anti-knock performance. The ignition, or the injection advance angle was always so adjusted, that maximum power or the knock limit was reached. The process which gave the higher power was certain to be the better. The tests were made at different compression ratios, both R 300 and gas oil being used. The R fuel nozzles used were: single hole nozzle DLO S.103, sparking plug W240 T.1 at compression ratio 1:8; at 1:10 and 1:12 type W 300 G, and at still higher compression ratios type W 330 G. R fuel consumption was unchanged at 20 mm³ per stroke. The remaining conditions are set out in section B 1a or A 1a.

b) Results with R 300 at different compression ratios. There was no knocking either in the spark ignition or the ring process when we used B 4 at a compression ratio of 1:8. (Sheet 8 bottom). It is therefore only possible to make comparisons of knocking behaviour at higher compression ratios.

At the compression ratio 1:10 (Sheet 8 top) the ring process is beyond all question superior. This becomes even clearer at 1:12 (Sheet 9 bottom) and 1:14 (Sheet 9 top). At 1:16 and 1:18 (Sheet 10 top) spark ignition operation fails altogether, as too heavy knocking occurs. It is to be noted that at the higher compression stages spark ignition no longer works satisfactorily, because the normal ignition equipment does not deliver the necessary voltage, and the insulation, especially at the sparking plugs, is no longer sufficient.

Audible misfiring was not observed in the tests, but the diagrams show that as the compression ratio increases ignition becomes more uncertain. The photographs taken simultaneously also showed that combustion is always much smoother in the ring process.

Sheet 10 contains a summary of all the tests, except those carried out at compression ratios 1:16 and 1:18.

To complete the picture, Sheet 11 shows a test made on a DB 6001, in which the knock behaviour of B4 was determined from the permissible boost. Here we made use of the ignition advance of 38° which is customary for the DB engine, while in the ring process we used an injection advance of 70°, which is the best in almost every case. If we compare the working of the two processes under these conditions, which are those occurring in practice, then the ring process is seen to be superior at a compression ratio of 1:8. The increased power occurs in the take-off region [illegible], being about 30% above the spark ignition process. In the tests described in report No.394 the increase in power of an air-cooled aero-engine cylinder (BMW 132) showed itself mainly in the cruising power range. Admittedly we operated here with variable injection advance.

c) Results of tests to compare the suitability of R.300 and gas oil as R-fuel

It was important to decide whether, when gasoline was ignited by gas oil the knock behaviour was different from that when it was ignited by R.300.

As stated in Section 13, gas oil ignites in Diesel operation at a compression ratio of 1:12. If the gasoline which is injected during the suction stroke lowers the compression temperature, ignition is no longer possible. The tests were therefore made at a compression of 1:14.

We used the single hole nozzle for these tests, so that as already shown in section A(a) in Diesel operation we achieved lower powers on R.300 (Sheet 12 bottom) than on gas oil (Sheet 12 top). Starting from points on the Diesel curve, corresponding to 13, 20, 35 and 60 mm³/cycle, we plotted the curves for the ring process by adding B_4. As the knock limit was approached knocking was avoided by retarding injection. The curves were plotted up to the point where injection must take place close to dead centre.

It appeared that the two R-fuels gave practically the same power and the same consumptions. Tests with gas oil at 60 mm³/cycle show clearly that the maximum power which is permitted by knocking considerations falls as the volume of R-fuel rises. It is thus possible to plot a limit curve which begins at the highest power attainable in the ring process with the most favourable volume of R-fuel, and runs into the curve of pure Diesel operation. Tests were also made with fuels having better knock rating, and thereby higher powers were achieved; thus Sheet 13 shows an example in which the BMEP of the Diesel engine was raised from 5 to 9 Kg/cm². In a carefully and fully developed Diesol engine the BMEP's are in the region of 6 to 7 atmospheres, yet power increases of 20% may be expected through the injection of gasoline. Whether they can be exploited depends on the power unit, especially on the piston, and above all on their being available a fuel of such high anti-knock properties, that it will not knock even at the compression ratio of a Diesel engine.

SHEET 1

Diesel Tests with Different Nozzles

Pintle nozzle DN 4 S 1, single hole nozzle DLOS 103
Diesel fuel II Cetane number 40, R 300, Cetane Number 188.
Compression ratio 14:1.

SHEET 2

Injection conditions with various nozzles and fuels.

SHEET 3

Diesel process: Compression ratio 18:1
Fuel: Diesel fuel II

SHEET 4

Diesel process: Compression ratio 16:1
Fuel R 300

SHEET 5

Diesel tests at different compression ratios
Diesel fuel II, cetane number 40.

SHEET 6

Diesel tests at different compression ratios
R 300; cetane number 188.

SHEET 7

Ring process with different R fuel nozzles
Fuel B.4, R fuel R 300

SHEET 8

Comparison between the Otto and Ring Processes at different compression ratios.
Fuel B.4

SHEET 9

Comparison between the spark ignition and ring processes at different compression ratios. Fuel B.4

SHEET 10

Comparison between spark ignition and ring processes at different compression ratios. Fuel B.4

Combination of Diagrams 8 and 9.

SHEET 11

Comparison between the Otto and Ring processes
Fuel B.4

SHEET 12

The Ring Process on different volumes of R fuel.

Fuel B 4, R fuel nozzle Bosch DLOS 103.
Compression ratio 14:1
R fuel (1) Diesel fuel II, (2) R.300

SHEET 13

Increase in power of a Diesel engine through the addition of gasoline

Fuel ET 110 + 0.12 per cent tetra-ethyl lead. R fuel: Diesel Fuel II.