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Experimental experience with the Ring Process in the air-cooled BMW 323 aero engine

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(1) Introduction

At the beginning of 1940, I.G. Farben suggested the replacement of the usual ignition system of gasoline engines by one which uses ignition-oil injection instead. This was also of interest with regard to aero engines as already at that time an ignition system unaffected by altitudes was wanted. In addition an improvement of the knock-behaviour and of the specific fuel consumption could be expected. It also promised to give us later a chance of creating a workable ignition system for using safety fuels in a gasoline engine.

In order to test this process - which was given the code-name "ring process", in an air-cooled 9-cylinder radial engine of 27 litres capacity, the BMW 323, its general behaviour was examined at first with a single cylinder in order to obtain the necessary data for main engine operation. Such a main engine, fitted with this new device, was subjected to a flight test to gain more experience. For lack of time a type which would embody all the experience so far gained ~~could not yet be made~~. The experience gained by both the flight test and that on the test stand was to be used for the further development of the ring process in the air-cooled radial engine.

(2) Developments

(a) Tests with a single-cylinder engine

For the first tests with a single-cylinder engine the BMW 323 cylinder was fitted with a ring fuel nozzle in place of the sparking plug. Compression was increased from a ratio of 1:6.4 to only 1:8, this being a compromise between ignition requirements and mechanical considerations. The first experiments showed already that, with the operating conditions selected, we could expect approximately the same knock behaviour with the ring process as with the spark ignition engine, which necessitated the use of high performance fuel (CV2 C and later C3). It appeared in the course of the single-cylinder experiments that there was little difficulty in metering ignition-oil "R-300", even when extremely small quantities, e.g., $5mm^3$/stroke, were injected, in spite of the poor nozzle cooling. No difficulties arose as long as the single cylinder tests were carried out with boost air heated above 70°C, but they cropped up at once when part load tests were carried out at boost air temperatures below 50°C. In this latter case fuel consumption became worse and ignition failed sometimes because the final temperature of the mixture was too low. At certain altitudes the aero-engine meets with far lower boost air temperatures (Fig.1). An extensive improvement of ignition behaviour was of a decisive importance under these conditions. It was partly achieved by influencing the temperature of the mixture through the cylinder head temperature.

The first test runs showed that the cylinder temperatures were considerably lower in the ring process using the standard cooling baffles of the BMW 323 than with the normal gasoline engine under the same conditions (Fig.2). We found a difference of 15% in the cooling losses. This fact was used to raise the temperature of the cylinder head and thus that of the mixture by increased baffling of the cylinder head, but with the same cylinder cooling, i.e. by a smaller cooling air delivery (Fig.2 and Fig.3). This resulted in an improvement of the ignition behaviour.

Fig.4 shows the influence of the cylinder head temperatures under the same conditions on the position of the mixture loops, i.e. on the quality of the ignition. In order to develop the ring process with air-cooled engines it appears that not only the cooling conditions should be made worse by decreasing the air delivery but also that the power of the engine should be adapted to the cooling conditions.

This above-mentioned measure by itself was not enough adequately to improve the ignition. A significant improvement was obtained by directing the ignition-oil jet on a hot space in the combustion chamber, viz. on to the head of the exhaust valve. This permitted runs with low loads and at considerably lower boost air temperatures down to 0°C - with practically no deterioration of the knock behaviour at high loads. Examples of this are given in the two diagrams following. Fig.5 shows the improvement in the performance caused by directing the jet on to the valve, both in regard to power output and displacement of the mixture loop. Diagram 6 shows the combustion limits at two different boost air temperatures based on ignition-oil consumption. The diagram shows also the difference in power when ignition fails.

(b) Tests on the main engine at a compression ratio of $\mathcal{E}$: 1:8

Based on those preliminary single-cylinder tests, a BMW 323 main engine with two speed blower was prepared for the same operating conditions, i.e. with a compression ratio of $\mathcal{E}$: 1:8 (1st stage of development), valve overlap 53°, sparking plug with battery ignition as an auxiliary ignition system, a fuel- and ignition-oil nozzle for each cylinder, ignition oil jet directed on to the exhaust valve, cylinder head with reduced cooling air flow, power as on the BMW 323 P standard engine, i.e. take-off power 800 b.h.p. at 2500 r.p.m.

As at that time no piston type was developed for the BMW 323 main engine at a compression ratio of 1:8, we had to make do with a make-shift. This led to difficulties because of the unfavourable friction conditions in particular of the master piston. Only after some time could these difficulties be overcome by development of a suitable piston-type. In order to obtain ignition conditions which were still favourable at part load, the temperature of the cylinders was increased even above those of the normal engine. This resulted in greater thermal demands with greater mechanical stresses and was also responsible, apart from the difficulties with the pistons and piston rings, for the very unfavourable conditions under which the exhaust valve had to work, taking into consideration the fact that this was made worse by directing a jet of ignition oil on it. The consequence was that incandescent carbon deposits were formed on the valve head. This eventually resulted in pre-ignition as is experienced with highly loaded gasoline engines. As a counter-measure we introduced the hard chrome exhaust valve which eliminated the formation of incandescent carbon deposits. The injection system for the ignition-fuel was developed exactly in the same way as that for gasoline.

The injection pump with plungers of 6 instead of 10 mm. diameter was located below the gasoline injection pump and driven by an intermediate gear. It was essential to make the injection pipes for the ignition-fuel of approximately the same length, since the small quantities make deviation in the injection process very noticeable. The engine control was practically the same as for the normal engine, viz. boost pressure controlled with the mixture regulation. The quantity of the ignition-oil was regulated by hand. At the end of the experiments the engine was subjected to a trial run of 25 hours under type test conditions on the ram test stand, as it was found that the distribution of cooling pressure varied too much when tested with an air brake. Lack of time did not permit work on power and fuel consumption improvement with this engine, as the chief object was the flight testing of the process. Performance is the same as that of the BMW 323 P, but with a little lower boost pressure because of higher compression: cruising fuel consumption approximately 210 g/b.h.p; ignition-oil consumption 1.0 to 1.2 kg/hr per cylinder, i.e. 15 to 23 mm^3/stroke: when idling full delivery of pumps about 40 mm^3 per stroke per cylinder.

The results of about 25 hours flight tests with the engine used as centre engine in the Ju.52 showed again very clearly the considerable susceptibility to temperature of the air-cooled engine operating on the ring process. The cylinder head baffling was not sufficient to keep the cylinder heads at the necessary temperature, e.g. when idling or in horizontal flight at low load and high altitude and with small loads, as baffling was only possible up to a certain degree when considering higher powers. That is why regulation of cooling air flow became necessary, which was obtained by a shutter on the intake-side (Fig 7) of the cowling, with which, in connection with the outlet regulation, the necessary cooling air flow could be adjusted. With this arrangement test flights up to altitudes of six kilometres could be made, and the engine worked satisfactorily; also the auxiliary spark ignition system gave no trouble. All these foregoing tests led us to the conclusion that in order to improve the air-cooled engine with the ring process it was necessary to develop better ignition conditions for the ring-fuel. Since heating of the mixture by means of a considerably higher cylinder temperature has the stated disadvantages, an essential improvement of the ignition of ring fuel was not possible in this way, and there remained only an increase of the compression ratio of the engine, which at the same time made it possible to improve the cylinder cooling. Fig.8 shows the considerable influence which a change in compression from a ratio of 1:8 to 1:9 has on the ignition process and the course of combustion. Indicator diagrams are shown for the same operating conditions and the given compression ratios. By increasing the compression the slow start of ignition is obviated and so the rate of the pressure rise is reduced.

In order to get a better knowledge of the processes in particular for comparison with the spark ignition engine, we recommend that the beginning of combustion be examined by means of a photo-cell.

(c) <u>Main engine tests at a compression ratio of ε 1:9</u>

For the 2nd stage of development, a compression ratio of 1:9 was selected for the main BMW 323 engine operated by the ring process. In spite of the fact that the compression was quite considerable for gasoline mixtures the engine ran without knocking through all the various loads from idling to take-off power. An additional improvement was obtained by introducing a certain amount of stratification in conjunction with inferior micro-mixture of the fuel. By means of later fuel injection and adjustment of jet-direction and atomisation of the fuel, the mixture was influenced advantageously. It became possible to operate on the ring process using the cooling effect of the fuel, at high thermal loads (take-off and climbing) which was not possible in the 1st development stage (ε 1:8) because of ignition failures or unsteady running of the engine (Fig 9).

The advantage of increased fuel consumption at high powers is obvious for mechanical reasons. The maximum pressure of 110 atmospheres at take-off power represents the stress limit for the unaltered structural components and also for the moving parts. Use of rich mixture and the choice of a favourable ignition fuel injection timing led to a decrease from 110 to 95 atmospheres, i.e. only 10 - 15 atmospheres above those of the standard BMW 323 engine. The data for the main engine with a compression ratio 1:9 are as follows :- BMW 323 power unit: cylinders with a fuel and ignition-fuel injection nozzle each: sparking plugs for auxiliary ignition: standard cowling: piston type for a compression ratio of 1:9: chrome exhaust valves: auxiliary ignition system with battery and distributor: automatic regulation of fuel quantities as well as controlled boost pressure: performance approximately equal to that of the BMW 323 at correspondingly lower boost-pressures, fuel consumption for cruising power about 185g/bhp hr: ignition-fuel consumption 18 to 23mm^3/stroke per cylinder: when idling about 40 mm^3/stroke each cylinder. As the endurance run of the engine was successful the following questions should be investigated in flight tests with the Ju 52:- Performance and fuel consumption at various altitudes, also the necessary air cooling flow by means of the air cooling control mentioned above, checking of the complete control system, operation behaviour and behaviour of the auxiliary ignition system. When the test flights have proved the engine completely serviceable, high altitude flying shall be undertaken with the single engine airframe of the HS 126 in order to establish the greatest advantage of the ring-process, viz. the fact that the ignition system is not affected by high altitudes.

(3) Various questions

Now some items will be discussed which are of particular interest in connection with the ring-process.

We have already said that the knock-behaviour with an engine of compression ratio 1:8 is about the same as with a gasoline-engine under the same conditions. It is altered in favour of the ring process when the compression ratio is 1:9, if suitable measures are taken, e.g. stratification and modified fuel delivery (retarded start of injection, direction of jet and inferior micro-mixture of the fuel). We will then find special advantages with regard to the cruising power. At about the same mechanical loads (peak pressures), the spark ignition engine has a comparable compression ratio of 1:8. A further advance is the use of a large valve overlap since, apart from the increase of blower horse power, a greater anti-knock performance is achieved (Fig 10). This affects chiefly the region of lowest fuel consumption, since this may increase because of the position of the regulating curves in relation to the knock limit. In addition ignition conditions are improved at low loads and idling because of the flow back of exhaust gas into the cylinder.

We may expect a minimum fuel consumption of 185 g/bhp hr. at ground level (155 g/ Ihp.hr) which always includes the ignition fuel. Attention is drawn to the fact that oil consumption is also included in the fuel consumption. Their sum is approximately constant. The data relate to 3 to 5 g/bhp hr. An advantage over the spark ignition engine is the fact that weak mixtures can be used in the ring process without ignition failures and, in spite of inexactitudes in control, may be considered for economical operation. These facts and the comparable compression ratio of the spark ignition engine ~~(1:8)~~ mentioned above in connection with knock behaviour, allow us to expect an economical fuel consumption which for the ring process is 5% lower.

We mentioned already that cylinder cooling has a much greater influence on the engine operation than in the spark-ignition engine, as the start of ignition is limited by a definite minimum charge temperature. The working range may be increased by suitable measures: direction of the ignition fuel jet on to the hot exhaust-valve, increase of the ignition fuel quantity and its retarded introduction in the lower power ranges, and most of all, air cooling control which keeps the cylinder head hot at low power outputs. The latter is much easier with the water-cooled engine than with the air-cooled. The cooling air-heat loss is about 15% lower for the ring process than with spark ignition. This is an advantage of the ring process, considering the cooling difficulties of air and water cooled engines at high altitudes. We cannot give the reason for the lower cooling air losses because we have not made suitable tests. We believe that the heat transfer from gas to the cylinder walls decreases because of the smaller gas movement arising from the changed combustion process. The reduced cooling air flow also results in a smaller power loss to the cooling air.

As to behaviour at altitude, the ring process provides ignition unaffected by altitude whilst, even at low altitudes, spark ignition is only possible with special altitude ignition systems, altitude sparking plugs with a suitable cable-screening, air pressurising etc. In this connection we must also mention that the ignition system of the gasoline engine is at present still very susceptible to failures in spite of the present development, and it causes a considerable number of engine failures, whilst the injection system of the ring process may be considered more reliable.

Starting is the most difficult problem of the ring process. At first we used the auxiliary ignition system described above which operates a series of sparking-plugs from a battery via a distributor. The sparking-plugs remained completely serviceable although not in constant use. Starting aids, e.g. starting charcoal or an admixture of exhaust gas with the intake air failed. One way seems possible. It may well be that the ignition-limit for the ignition fuel could be reached at low intake air temperatures by using a gasoline starter motor and cranking for some time with ignition fuel quantities above 100mm/stroke, if possible, and a retarded injection (starting 30 to 40 degrees before top dead centre) as well as admixture of the exhaust gases of the starting engine with the intake air, given an engine with 100° crank angle valve overlap.

Satisfactory idling and low powers can be obtained at low outside temperatures by adding exhaust gases to the intake air.

The cost of the ring process is a little greater than for the spark ignition engine. The ring process uses the injection system with a second injection pump, ignition-fuel nozzle, injection pipes, container, auxiliary ignition system as an intermediate solution and the ignition fuel as supplementary fuel, whereas the spark-ignition engine needs a complicated altitude ignition system, viz. magnetos, cable-screening sparking-plugs, air pressurising and safety devices.

For control of the ring process as described, the following are necessary :- Power regulation as for the spark ignition engine, viz. by boost pressure and mixture control, as well as regulation of the ignition fuel quantity, which will perhaps require a two position adjustment; furthermore, by changing the injection timing of the ignition fuel for idling and small loads by suitable construction of the pump plungers, regulation of the cooling air flow from zero to full flow, exhaust gas admixture to the intake air for idling or low loads at low outside temperatures (e.g.) at high altitude)

We had no difficulty with the ignition fuel pump, only care must be taken that the delivery quantities of the individual pump plungers are exactly controlled. We found with the ignition fuel injection nozzles that the open types gave coking of the nozzle, and the closed nozzles gave trouble during the injection process because of irregular spill. But developments so far allow us to suppose that in time nozzles of both the open and the closed type will work efficiently even in their standardised form.

Ignitability of the ignition fuel R 300 can be taken for granted. No corrosion was observed. Its low calorific value has an unfavourable effect on economic consumption (about 3% loss) as it includes the consumption already mentioned. Consumption from cruising power to take-off power is 5 to 10% of the fuel consumption.

4) Advantages and disadvantages of the ring process

In summing up we may say that the main advantage of the ring process as compared with the Otto process of aero engines is the following :- "It gives us an ignition system which is not affected by altitude, in other words, we may dispense with an electrical ignition system which very easily fails and the use of which at extreme altitudes has not been sufficiently developed.

Further advantages are, in particular, the more favourable cooling conditions for high altitude engines at high loads, and at very great altitudes, also the general insensitivity of the weak mixture operation to inexact mixture regulation and also the reduction of the economic consumption by about 5%/ when compared to a spark ignition engine of otherwise similar type.

In order to give a complete account we should mention also that the knock behaviour is a little more favourable, that the ring process is more reliable and that at higher loads over 1.2 atmospheres boost pressure there is still a gain in boost pressure and nominal power when compared to the spark ignition engine. There is also the possibility of using safety fuels but this was not examined.

Disadvantages are the necessary regulation of cooling air, the starting problem which is not solved yet, especially at low temperatures, and the auxiliary ignition system, the regulation of the exhaust-gas mixture for special operating conditions (e.g. idling at high altitudes) and the somewhat greater cost in comparison to the spark ignition engine.

5) Conclusion

In conclusion we may say that after 2½ years' development an air cooled radial aero engine was constructed to operate on the ring process and developed to a practical stage. Special qualities of the air cooled radial engine and of the ring process, viz. the greater susceptibility to temperature of the latter and the high mechanical loads of the former caused the development to take place in very unfavourable circumstances. By being able to design an engine for practical use we gained an experience which, if necessary, would enable us to use the ring process also in other engine types.

Translation of diagrams, etc

Fig.1) Boost air temperature of the BMW 323 P.
Fig 2) Cylinder temperatures for the Otto and ring process in the BMW 323 single cylinder engine.
Fig.3) BMW cylinder with standard cooling baffles and with special cooling baffles for the ring process.
Fig 4) Influence of the cylinder head temperature on the fuel consumption in the ring process.
Fig.5) Influence of the jet direction of the ring fuel nozzle on power and consumption.
Fig.6) Limitations due to ignition failures with the ring process.
Fig.7) Air cooling regulation for the test flights in the Ju 52 with the ring process.
Fig 8) Indicator diagram for the ring process for different compression ratios
Fig.9) Changes in the operational behaviour through mixture stratification in the ring process at C.R. ε : 1:9
Fig.10) Performance range of the BMW 323 with control curves for the ring process at 53° and 100° valve overlap (ε : 1:9).

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