REFERENCE NO. U.5

ORIGIN AND NO. Lilienthal - Gesellschaft für Luftfahrtforschung Report 158, pp. 11 to 19.

DATE: 28th and 29th January, 1943.

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TITLE: Single Cylinder Tests with Internal Cooling.

TRANSLATION

SUMMARY

The problem arose, on consideration of existing research results in the light of basic technical questions of double-fuel running with additional injection of water, water-methanol, and pure methanol, as to the investigation of injection ratio, the determination of the resulting power, the necessary amount of injection material and total consumption, the thermal and mechanical stress of the engine, the sensitivity of operation, etc. The tests are to be continued. However, the results obtained so far, in agreement with full-scale tests in other places, show that through additional injection of these substances, on account of the internal cooling due to high latent heat, a control of the heat load of the engine is possible, that raises the specific power to an exceptional degree above the normal knock-limited performance of spark-ignition engines, as long as the necessary fuel-air ratio is obtainable.

INTRODUCTION

It has been known for a long time that a large degree of internal cooling can be obtained in a spark-ignition engine by water injection, (on account of the high latent heat of vaporization of water), by means of which an increase of knock-limited power can be obtained for a given fuel and engine, and hence increase in boost and power are possible. Tests with water injection on the English Jaguar aero-engine gave a power increase of about 30% with 60% water added to the fuel.

Alcohol and methanol have also been known for a long time, as additions to normal fuels, to raise the knock limit and hence permit a possible power increase. They have very high latent heats as compared with other fuels and have better knock performance. Their drawback is the low calorific value, which implies a high consumption when using them which is known to be higher than when working with gasoline, since the calorific value of the mixture is almost as high as that of gasoline, but the high latent heat causes an appreciable drop of boost temperature during the intake stroke and hence a possible increase in weight of charge. The use of such fuels at take-off, in air combat, etc., for increasing the power of engines operating on fuels of normal octane number for cruising has also become well known through publications.

For example a report is given in ATZ 1941, p. 145, on foreign research, from which fig. 1 has been constructed.

The use of alcohol as an addition to blends for high power, high speed engines is also known. The difficulty here lies in the production of a stable blend. The stability depends largely on the internal composition of the gasoline. It should be better in the presence of benzole. With regard to stability, the blends are especially sensitive to water, and also to temperature. To avoid these difficulties separate injection (as in the above tests) was tried; this is also indicated on grounds of economy. Thus a substantial saving of secondary fuel is achieved, for this is only used when increased power is necessary.

This short summary shows how important is the question of such double-fuel operation for increase of power; existing research results give no exhaustive answer, but incite one to further research.

In fig. 2 are given blending values of water-methanol mixtures. The shape of the freezing-point curve (tg) should be noticed for high altitude engines, as the freezing point of a water-methanol mixture containing less than 50% methanol lies above -50°C.

TEST CONDITIONS.

A water-cooled BMW.116 cylinder of welded construction, 130 mm. bore, 130 mm. stroke, built on a single cylinder test bed, was used for the work. The cylinder had the normal disc-shaped combustion chamber, which is usual for a water-cooled engine with 2 inlet and 2 exhaust valves. The valve timing was normal without unusual valve overlap. The fuel was injected laterally in the cylinder on the exhaust port side. The subsidiary fuel (water, water-methanol, or methanol) for double-fuel running could be injected in the same way opposite the main fuel injection or in the induction pipe about 150 mm. before the inlet valves. Bosch pumps (Pz2/110 V 637/1) and valves (De 40 N 60 M 6) with an injection pressure of 60 atm. were used. The boost air, which could be heated electrically, was delivered by an externally driven compressor.

In order to keep constant the magnitude of the external cooling the heat transmitted to the cooling water of the closed cooling circuit was estimated by measurement of the difference between inlet and outlet temperatures of the engine with a thermocouple consisting of twenty junctions connected together. The constant circulation of the closed water circuit was so arranged that a temperature difference of 6 to 8°C between inlet and outlet was obtained. Since the total water content of the circuit can be made relatively small, the temperature difference measured by the thermo-element is very sensitive to variations of coolant temperature due to changes in the mixture strength in the cylinder or internal cooling by the secondary fuel, and quickly becomes stabilized. The measurements are very reproducible. By this means the heat transmitted to the cooling water was measured in each test, and this gave a measure of the heat load of the cylinder. If the amount of circulating water is kept constant, equal heat transfer to the cooling water in two tests denotes approximately equal heat loads, an increase in heat transfer denoting an increase in heat load.

The exhaust temperature was accurately measured as the mean temperature near the exhaust valve by means of a Pt-Pt Rh element.

The following conditions obtained during the tests:-

Cooling water outlet: 85°C (kept constant by means of a thermostat operating on the outlet of the open cooling circuit).

Lub. oil outlet	:	65 to 70°C
Fuel	:	B.4 (O.N. 87)
Lub. oil	:	Red ring
C.R.	:	6:1
R.p.m.	:	2000
Spark advance	:	40°B

Test Results.

The scope of the tests and the first evaluations are shown in fig. 3, where test results on double-fuel operation with additional injection of a mixture of 75% methanol and 25% water are shown, at 120°C B.A.T. and boost pressures of 1.35, 1.615, and 1.91 atm. The external cooling was kept constant at a value corresponding to a rise of coolant temperature of 7.25°C at 1.00 atm. boost pressure and $\lambda = 0.9$. With increasing λ the hourly fuel consumption (B_B) fell, so that the additional injection of the methanol-water mixture, $B_{M(1)}$, must be increased, if the required higher heat load is to be compensated owing to the weaker main fuel mixture. The m.e.p. (pi) reaches its maximum at about $\lambda = 1.2$, corresponding to a value of $\Sigma\lambda$ (main fuel and secondary fuel) of 0.8 - 0.9. Above in the same figure, the mean exhaust temperature, $t_{abg(1)}$, is shown. As mean temperatures of single-cylinder units they are rather lower than normal, and hence give only a qualitative picture, but they are nevertheless important for the examination of double-fuel operation. For constant boost pressure, the exhaust temperature naturally increases with weaker mixtures. With increase of boost pressure, and therefore increase of power at constant mixture strength, the exhaust temperature falls, since the additional mass of secondary fuel has a cooling effect.

In the cylinder described, the knock limit was in the range λ = 0.8 - 1.1 at 1.25 atm. boost pressure. The mixture response curve is an almost horizontal line in this range rising first at very weak mixtures, while any increase at rich mixtures cannot be determined, in contrast, for example, to the BMW. 132 cylinder. A higher heat load is obtained when using this, corresponding to a coolant rise of 8.65°C in the test cylinder. In the same way it was required to know for the knock limit, the necessary additional fuel being determined, why it should give such a curve with corresponding weaker values, only falling at very weak mixtures. The values are not given in the figure. The exhaust temperature

$t_{abg(k)}$, for the mixture response curve in the range λ = 0.8 - 1.0 is related to the boost pressure. It lies higher than the measured temperature $t_{abg(1)}$, but the curve has the same form.

If points are taken from the test results, for example at λ = 0.9, the curve shown in figure 4 is obtained. For λ = 0.9 the indicated power, N_i (HP), (calculated from the brake power), the m.e.p., p_i (atm.), the fuel consumption B_B, (kg/hr.), the secondary fuel consumption, $B_{M(1)}$ (kg/hr.), at a heat load corresponding to the load at a boost pressure of 1 atm., the secondary fuel consumption, $B_{M(k)}$, at knocking conditions, the total consumptions $B_M + B_{M(1)}$ and $B_B + B_{M(h)}$ at corresponding heat loads, the specific consumptions $\sum b_{i(1)}$ and $\sum b_{i(h)}$ (g/HP.hr), and the ratio of secondary to main fuel are plotted against boost pressure. Corresponding to the increase of p_i with boost pressure the heat load increases, which must be compensated by an increase of secondary fuel. In the first case, when the heat load was kept constant at a boost pressure of 1 atm., the secondary injection started at 1 atm. boost pressure. The hourly consumption $B_{M(1)}$ increases from left to right in a straight line. An approximately parallel line, starting at a boost pressure of 1.25 atm., shows the hourly consumption at knock. The curve $\frac{B_{M(k)}}{B_B}$ shows that the additionally injected water-methanol mixture at 2 atm. boost pressure gives an increase of 60% in power at a proportion of 60% of the main fuel. The curves $\sum b_{i(1)}$ and $\sum b_{i(h)}$ show the effect of this ratio on the specific consumption. The first has a value of 300 g/HP.hr at 1.75 and 330 at 2 atm. boost pressure. Since in flight the exhaust gas is made use of in the form of a turbine or the thrust developed by a jet, by means of which the supercharger power or even more can be provided, the mechanical efficiency of the unit alone is very high, if the consumption recorded in these tests corresponds approximately to the effective consumption. Consideration of the airscrew efficiency leads to a consumption of the order of 380 to 420 g/HP.hr. at 2 atm. boost, falling to the normal consumption on knocking at 1.25 atm.

The values of external coolant heat Q_k and the internal vaporization heat corresponding to coolant heat Q_v are given in fig. 5. Plotted against λ are the indicated power Q_i in kcal/hr. corresponding to the load at 1 atm., the internal coolant heat corresponding to the vaporization heat Q_v for the main and secondary fuel, and sum of external and internal coolant heats $Q_k + Q_v$, the relationship to indicated power $\frac{Q_k + Q_v}{Q_i}$ which lies in the range 0.4 - 0.6 and which will be designated normal, and the ratio of internal to external cooling $\frac{Q_v}{Q_k + Q_v}$, which has the value of 0.4 at high boost and the weak mixture λ = 1.2, i.e. about 40% of the internal cooling is taken up in the utilization of the vaporization heat.

Taking values at λ = 0.8, 1.0, and 1.2, and plotting them in the form of curves gives fig. 6, in which are given values of Q_i, $Q_{k(1)}$, $Q_{v(1)}$, $\frac{Q_v + Q_k}{Q_i}$, $\frac{Q_v}{Q_v + Q_k}$, $\sum \lambda$, (the air ratio calculated from main + subsidiary fuel), and the exhaust gas temperatures $t_{abg(l)}$ and $t_{abg(k)}$, plotted against boost pressure. The line $Q_{k(l)}$ = 14100 kcal/hr. corresponds, as has been mentioned, to the heat load at 1 atm., running on the main fuel. It will be seen clearly that the internal cooling rises with increasing power.

The test results for 100% methanol, 50% methanol + 50% water, and 25% methanol + 75% water will be evaluated in the same way, and will be given for injection of these secondary fuels into the induction pipe (start of injection 100° A.T.D.C.) and also into the cylinder, in which case the injection is in about the middle of the compression stroke. While 100% methanol and 75% methanol + 25% water are insensitive to the place of injection, the 50/50 mixture shows only a small difference from the 75% methanol 25% water mixture, whether the mixture is injected into the induction pipe or into the cylinder; (the latter gives at the most a slight power decrease, since the mixture injected in the compression stroke displays no effect of temperature drop due to its latent heat); with increasing water content larger variations are obtained, and it is no longer a question of indifference whether the secondary fuel is injected into the induction pipe or the cylinder. From this the following conclusion may be drawn; with decreasing methanol and increasing water content the high anti-knock effectiveness of methanol decreases and with pure water the effect of latent heat alone obtains, but on the other hand the cause might be sought in a faulty preparation of the secondary fuel as to the water content. As fig. 7 shows, (25% methanol + 75% water in induction pipe), a difference from the other mixtures is not apparent when considering $B_{M(l)}$. If the heat loads at the original knock conditions at 1.25 atm. are compared with those at higher boost pressures, then a falling heat load is obtained with low methanol content (c.f. Δt_k in fig. 7 and the same quantity in fig. 4). The internal cooling must be increased with falling boost pressure, whereas with the more usual mixtures it can be kept constant or even slightly increased on account of the high anti-knock property of the secondary fuel. The original cause must be sought, as has been mentioned above, in the decreased anti-knock properties of the mixture, and in the difficult control of the preparation of the mixture on account of the high water content at the above injection ratios.

These considerations are confirmed by fig. 8, in which results obtained for the same mixture injected in the cylinder are given. As the shapes of the curves show, an improvement results.

The tests with pure water as secondary fuel, shown in fig. 9, complete the work, as a controlled test of injection in the induction pipe with the above liquid-cooled cylinder was practically impossible, despite the comparatively high boost air temperature of 120°C. It was possible to carry out tests with injection in the cylinder. The above injection ratios gave a good range of injection during compression, which was about 150° B.T.D.C. for the start of injection. It was thus possible also to increase the power with water. Of course, as the figure shows, the necessary quantity of injected water increases greatly in spite of the high value of the latent heat, which must of itself cause a reduction in the amount of secondary fuel injected. The proportion of internal cooling at knock is relatively very high and increases greatly, as the curve of Δt_k shows. The reason must again be sought in the faulty preparation of the water blend and in the poor distribution of water vapour in the cumbustion chamber, which probably cools some parts very well and others less, and at full power the distribution in the combustion chamber must be approximately equal. This unequal distribution can be shown by measurement of spark plug base temperatures, which differ markedly from each other and no longer show a fixed relationship with water injection. The relationship can only be shown by observation of the coolant heat. This was also the basis by which for all the tests the heat load was calculated, not from the spark plug temperatures, but from the external coolant heat.

Correspondingly the specific consumption increased to more than 500 g./HP. hr. for 2 atm. boost pressure, and it was then 50% higher than the highest value of methanol mixtures. But it has the property, also displayed by the 75% mixture, that it can scarcely be avoided that a portion of the injected water reaches the crankcase between the piston and cylinder, mixes with the lubricating oil, and unfavourably affects the properties of the oil. (If the injection and blending ratios for water are improved, and furthermore if the conditions for the hot air-cooled motor are not so severe, then water hardly comes into consideration for practical use in aero-engines on account of its freezing point of 0°C.)

Fig.10 shows as an additional evaluation the comparison of specific fuel consumptions of various mixtures with injection in the induction pipe at $\lambda = 0.9$. The faint lines correspond to the heat load at 1 atm. boost pressure and working on main fuel alone; the heavy lines are knock-limited curves. It shows that the optimum ratio is 75% methanol. Methanol alone and 50% methanol lie somewhat above. The 25% methanol blend lies very much higher, while water alone was impossible in practice.

Fig.11 shows the same quantities with injection of the secondary fuel into the cylinder. For the high valued mixtures the quantities are about the same, but the values for 25% methanol are lower, and pure water attains a reasonable figure.

These values for pure methanol to pure water are valid not only for $\lambda = 0.9$, but for a range of 0.8 to 1.1. The optimum lies between 50 and 75% methanol. This relationship is easily seen in fig. 12. Plotted against the air ratio λ for a boost pressure of 1.91 atm. is the hourly fuel consumption $B_{M(1)}$ for the various mixtures, at a heat load corresponding to normal running at 1 atm., with injection in the induction pipe. From these values are derived the total hourly consumption $\sum B = B_B + B_{M(1)}$, and by consideration of the powers, corresponding to the p_i curves, the specific total consumption $\sum b_i$. The smallest consumption is attained by the 75 or 50% mixture. The best range of the mixture ratio lies between $\sum = 0.8$ and 1.1; above that the specific consumption is greater. In practice the range under 0.9 does not come into consideration, since smooth running is not obtained. The range in which the engine just reached smooth running on the main fuel is over 0.9, and is then limited on weakening the mixture by addition of the secondary fuel. With 100% methanol the air ratio calculated on the fuel can be greatly weakened up to $\lambda = 4$. Pure methanol running without fuel cannot be achieved however, conditioned by the temperature ratio of the liquid-cooled test cylinder. As the figure also shows, using pure methanol as secondary fuel increases the power in the same range. Weakening off is much less possible for 75 and 50% mixtures, and is confined to the normal value for running on the main fuel alone with the 25% mixture and pure water. The effect of latent heat with 100, 75, and 50% methanol on the drop of inlet mixture temperature results in an increase of boost and hence p_i. For 25% methanol and pure water only a corresponding smaller effect of latent heat at an air temperature of 120°C results in a decrease of inlet temperature (also the effect of faulty blending, as already mentioned, must be allowed for), so that a correspondingly lower value of p_i is obtained.

The results given so far refer to an air temperature of 120°C. In order to investigate the sensitivity, corresponding tests were carried out at boost air temperatures of 40 and 80°C. A section of these tests is given in fig.13, for $\lambda = 1$ and a boost pressure of 1.65 atm. The hourly fuel consumption B_B, the hourly secondary fuel consumption $B_{M(k)}$ on the mixture response curve, the coolant heat Δt_k as a measure of the heat load, and the ratio $\frac{B_{M(k)}}{B_B}$ are plotted against boost air temperature. The tests showed (not apparent in the figures) that the effect of latent heat on the temperature drop of the boost air was small with falling air temperatures. ~~The power~~ was proportional to somewhat less than the first power of the absolute temperature of the boost air. It should be noticed that the ratio $\frac{B_{M(k)}}{B_B}$ falls with falling B.A.T. $B_{M(k)}$ at knock is unrelated to the B.A.T. and is dependent only on the boost pressure. For control of the secondary fuel at the knocking point, boost pressure only is effective, but not the B.A.T.

Figs. 14 and 15 give a summary of the test results for injection into the induction pipe and into the cylinder at a B.A.T. of 120°C and $\lambda = 0.9$. The x-axis gives increase of power expressed as a percentage above knock-limited power, and the y-axis gives the total consumption and the ratio of secondary to main fuel for the mixtures tested. As has been shown previously, the values are valid up to about $\lambda = 1.1$. With falling B.A.T., and for constant heat load of the cylinder, the proportion of secondary fuel first falls, but later increases again.

Pressure diagrams were taken with a quartz pick-up for all tests. In fig. 16 are given mean combustion pressure p_{zm} and peak pressure p_{zh}, for each mixture, plotted against boost pressure. In order to be of some use, these points were so obtained that at least 100 pressure diagrams were used for one combustion pressure curve. From these were calculated the mean, p_{zm}, and maximum, p_{zh}. An unequivocal relationship between the combustion pressure and the composition of the secondary fuel is scarcely determinable. The combustion pressures increase with increasing boost. The scatter shown is normal for spark ignition. Perhaps there is an effect, not apparent in these figures, in the direction of a decrease in combustion pressure with increasing internal cooling and decreasing heat load of the cylinder.

In opposition to the previous tests, results are given in fig. 17 of methanol mixed with the fuel itself. The blend, consisting of 66.7%$_v$ methanol and 33,3%$_v$ gasoline, was stable. The curves show the previously mentioned effect of high consumption at low boost pressures. On the other hand light knock was encountered even at 1.75 atm.

The research results give a clear picture of the operation and possibilities of double fuel running by means of additional injection of water/methanol mixtures. The results, apart from higher consumption due to the insensitivity of operation with mixtures of high methanol content, are almost wholely advantageous. However, as a result of work elsewhere it has been shown that the difference in corrosion between technical water-free alcohol blends and other fuels can be neglected, but that with increase of water content increased corrosion is to be expected. It will be necessary to keep an eye on these troublesome effects.

CONCLUSIONS

(1) Secondary injection of methanol/water mixtures and also of pure water in addition to the normal fuel of a spark ignition engine make possible an increase of power, on account of the effect of the high latent heat on the internal cooling, the upper limit of which could not be determined. An increase of 85% over the knock-limited power can be attained at a constant speed by increase of boost up to 2.3 atm., without knock resulting.

(2) In particular water/methanol mixtures with more than 50% methanol are suited for double fuel operation on account of the good freezing properties and the insensitivity of operation. Pure methanol is only slightly less suitable.

(3) The ratio of secondary to main fuel increases approximately in proportion to the power increase above the original knock limited power.

(4) The heat load of the cylinder remains almost constant with increase of power on account of the internal cooling.

(5) The mechanical stress increases on account of the increase of combustion pressure.

(6) The exhaust temperature falls with increasing power.

The possibilities of the use of double-fuel operation for power increase of aero-engines are given in fig. 18, which shows a schematic altitude power diagram. The power limit for a normal boosted engine is given by the line 1-2-3 where the fall from 2-3 is caused by the impossibility of increasing the supercharger pressure ratio. If enough combustion air is obtainable, the power limit would be increased to 2-4. By additional water/methanol injection an increase is possible at equal heat stress given by the line 1^1-2^1-4^1. On account of the existing limitations on the engine (full open throttle and max. super-charger speed), an increase given by the line 1^1-2^1-3^1 is possible on account of the favourable effect of latent heat of the methanol blend on the charge density. A further increase with increasing altitude is possible to

11-211-311 by using a supplementary supercharger. In the same manner an increase in altitude power is possible with methanol/water by the use of oxygen or oxygen carriers in the range above full power altitude; the power limited only by heat stress is given by line 2-4.

For the requirements of the Luftwaffe the decrease in power above full power altitude is of decided interest, and also the power increase from take-off to full power altitude. This is to a large extent possible by the use of double-fuel operation together with oxygen carriers or supplementary blowers. Further tests on the possible duration of such power increases can be carried out on the basis of the test results.

The internal cooling obtained by use of the secondary fuel cannot replace the external cooling. It is in this direction that development must proceed in the future, to improve the external cooling. And in the corresponding manner that the external cooling improves the internal cooling can be reduced or at the same internal cooling an increase of power can be obtained. It is plain that the work is not completed.

9th November, 1945.
JH/SIL/MAi.