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Experimental results with oxygen carriers (GM.1) in aero engines

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I. Introduction: Developments of air warfare during recent years resulted in evergrowing requirements for higher performance of aero engines. As the increase of air or oxygen delivery at high altitudes by means of multistage and exhaust turbo superchargers required new designs, and since it was hardly possible, considering mass production and limited time to re-design the existing types, the idea arose of remedying the power loss above full throttle height due to lack of oxygen by the use of oxygen or oxygen carriers.

The requirements for the oxygen carriers were :-

1. higher specific output
2. lowest possible additional thermal load
3. simpler manipulation, simplified controls and minimum modifications to engines.

Whilst choosing and testing various fuels with these ends in view, O. Lutz and his collaborators at LFA (Brunswick) carried out some profitable pioneer work, and found an additive in the GM.1 oxygen-carrier which promised good results.

After further favorable motor tests with the DB.601 type at LFA Brunswick, and the BMW 132 N type at Rechlin Test Station, BMW Munich did some special work of their own in November 1941 on the BMW 801A and BMW 801D twin radial engines.

II Chemical and physical characteristics: The most important chemical and physical characteristics of GM.1 in comparison with oxygen and air are summarized in Table 1. The most important characteristics for engine behaviour which should be noted are :-

1. The high percentage of oxygen compared with air; 36.4 wt. % vs. 23.3
2. Heat of decomposition about 400 kilo calories
3. Heat of vaporization 45 kilo calories.

(Fig.1 - Boiling curve of GM.1)

The curve in fig.1 shows the two fundamentally different states for the carrier or additive,

1. as pressure fuel at ambient temperature, and
2. as pressureless fuel in supercooled state (cold fuel) temperature -88.7°C at 760 m/m Hg.

In GM.1 a characteristic property which should be specially considered when developing plant, equipment accumulators and valves, is the small difference in temperature between the boiling point and the freezing point.

When the pressure drops below atmospheric liquid GM.1 has a tendency to change quickly into a solid form

Table 1

Physico-chemical properties of oxygen carriers

Gas	Air	O_2 oxygen	N_2O Nitrous oxide
Sp. Gr. gas	0.001225 kg/dm³	0.001311 kg/dm³	0.001078 kg/dm³
" " fluid @ boiling temps.	-	1.131 kg/dm³	1.22 kg/dm³
Sp. Heat c_p gas	0.241 kcal/kg°C	0.218 kcal/kg°C	0.210 kcal/kg°C
$x = \frac{c_p}{c_v}$	1.4	1.4	1.28
Boiling pt.	-193.0°C	-182.97°C	-88.7°C
Melting pt.		-218.8°C	-91°C
Mol. wt.	28.95	32.0	44.02
Latent ht.	50.0 kcal/kg	51 kcal/kg.	45 kcal/kg.
Ht. of decomp.			400 kcal/kg.
Gas const. R	29.27	26.50	19.2
Crit. Temp.	-140.7°C	-118.8°C	+ 37.2°C
" Press.	37 kg/cm²	51.4 kg/cm²	74 kg/cm²
" Sp. Wt.	0.31 kg/dm³		
" vol.	3.23 l/kg.	2.33 l/kg.	2.2 l/kg.

values reckoned at p = 760 mm. Hg.
t = 15°C

III. Test results with GM.1 Pressure fuel:

1. Output increase and specific output.

The first main engine tests of the BMW 801A carried out, first on the ground with throttled engine, then on the altitude test stand at the operating heights of practical interest, were intended to show to what extent engine performance could be increased without excessive overloading.

(Fig.2 - Output characteristics with GM.1 Pressure fuel)

Fig.2 shows that the values in the test depend on the flow of GM.1. Injection of GM.1 took place before the blower, so that a part of the output increase and the gain in the pressure ratio of the blower could be attributed to a fall in the intake temperature.

With a flow up to 180 g/s. the additional power came to about 500 HP, which would correspond to an 80% increase in the combat performance of the type at 10 Km. altitude.

The specific output increase , represents the performance obtained in one second with 1 g. of GM.1, and is shown in fig.2. It shows a slightly falling tendency when compressed fuel is used with an increasing flow of GM.1 and amounts to 2.7 to 3.1 $\frac{PSes}{g}$. In the make up of the specific output increase, the considerable output gain through the blower as a result of the rising pressure ratio, and the advantage of injection before the blower in comparison with injection after the blower is clearly noticeable.

The dependence of specific output increase on engine operating conditions is shown in fig.3. It shows that the specific output increase with pressure fuel drops considerably under take off power conditions. The influence of altitude and r.p.m. was insignificant. A limited increase with increasing altitude and r.p.m. could be determined.

Life tests were carried out at 8 to 12 kms. altitude for several hours up to 350 BHP additional output and a one hour test up to 450 BHP. Owing to thermal overload when using pressure fuel there was inadequate operational safety when tested at still higher additional outputs.

(Fig.3 - Relation of the specific output increase to engine operating conditions when using GM.1 pressure fuel)

2. Thermal load

Since the principal problem was simply to increase the performance over full throttle height by addition of GM.1 it was to be expected that in any case the mechanical structure of the engine would stand up. Also the increase in thermal load in the combustion chamber should not present bigger difficulties with a sufficient increase of the fuel delivery and up to a certain amount of additive at a given height. It was however different as regards cylinder cooling, which will be dealt with later.
To avoid overheating of cylinders when climbing, counter measures had to be considered from the start as in general margin in engine cooling was not to be depended on.

The course of pressure rise in the cylinder with GM.1 was studied with a pressure indicator. The course of combustions was somewhat more even with GM.1 than without it, especially at high altitudes. With GM.1 the peak pressure at a constant effective output and unaltered ignition was 10 to 20 percent higher. Similarly, with GM.1 a quicker rise in pressure was observed.

When considering the added thermal load on the engine when GM.1 is used, the main point of interest is a comparison of useful output operating under boost, keeping constant the excess air ratio, ignition and the other working conditions of the engine. As fig.4 shows, the added thermal load as a result of higher combustion temperatures increases with increasing injection quantity of GM.1 and amounts to 15 to 20%, corresponding to about 50 up to 150 g/s. flow. This means that the maximum limiting output of the engine under ~~otherwise~~ equal operating conditions cannot be as high as with pure air operation, if the thermal load is to be constant.

3. Course of combustion

The relationship between output, fuel consumption, and cylinder head temperature and excess air ratio is shown in fig.5. It shows that the excess air ratio for the best output and best consumption with GM.1 lies only slightly in the excess fuel region. The economy in using oxygen is practically equivalent to pure air operation.

(Fig.4 - Added thermal load when using GM.1 pressure fuel)

(Fig.5 - The behaviour of the engine with compressed GM.1 as a function of the excess air number λ)

(Fig.6 - knock behaviour with GM.1)

It is worthwhile noticing that in spite of equal useful output the cylinder head temperature is higher with GM.1, which is the result of the higher thermal load, and the favorable fuel consumption as the result of better engine efficiency and the heat of decomposition of GM.1.

As shown in fig.6, further tests have proved that knocking tendency at equal performances is noticeably less when GM.1 is used than with pure air intake. The knocking limit lies about 0.3 atm. higher for equal excess air ratios. It can be assumed that this is due not only to the drop in blower air temperature due to the vaporization of GM.1, but also to the more rapid ignition and burning of the mixture as a result of the higher oxygen concentration, since the improvement is greater than can be accounted for by the drop in blower air temperature alone. However, a tendency to pre-ignition owing to increased combustion temperature is highly probable and requires with large amounts of additive the use of plugs with higher ratings. Later on it became evident that a special finish in cylinders is particularly important when GM.1 is used.

The exhaust gas flame when using GM.1 showed a different appearance. The flame was somewhat longer and more brilliant and changed from light yellow into light red.

With constant ignition and excess air ratio the temperature of the exhaust gas at 100 g/s. flow was about 50°C higher than with air for the same final output.

4. Fuel Consumption and Cooling.

In the BMW engines, like any other, fuel consumption is adjusted in the interests of economy to be no higher, both for air combat and climbing conditions, than is required for safe thermal control at this output level for the prescribed period. Consumption of fuel is automatically controlled by the BMW regulator up to very high altitudes set to exactly the prescribed minimum amount. Therefore the richer mixture for high altitudes required by older types is not here necessary. Since there is a higher thermal load on the engine when GM.1 is used an increase in the indicated fuel consumption is necessary. Actually, as the temperature-pressure- and height-sensitive mixture controller does not respond to the increased oxygen content of GM.1 compared with air, there is, as fig.7 shows, a weakening and a further thermal load instead of the relief required for GM.1 addition.

A higher output increase with GM.1 is possible only with a simulteneous additional increase of fuel flow if the engine was not previously set unnecessarily rich. Also the determination of cooling pressure drops and cooling air cross sections are called for by the fact that in modern engines, in order to get the smallest possible drop particularly when climbing, the permissible maximum cylinder head temperature is pushed up to the limit. As bigger quantities of heat have to be removed with GM.1, as fig.7 shows, an equivalent increase in the cylinder cooling is essential.

(Fig.7 - Specific consumption of fuel and cooling air for compressed GM.1)

(Fig.8 - Compressed GM.1 in the Do.217)

5. Flight tests

Following favorable bench tests, flight tests with the Do.217 began. Normal oxygen bottles were used as GM.1 containers. When equally full, The pressure in these containers varied quickly with the outside air temperature, and also at the same temperature altered with the degree of filling to the extent that by vaporisation, strong refrigeration of the remaining GM.1 took place. The strong dependence of the flow of GM.1 on temperature and pressure in the container resulted in considerable variations in output. Fig.8 shows the balance in an endurance test which shows this clearly. Output was measured by instruments. Increase in fuel supply was secured by a device subsequently applied to a mixture regulator which was automatically operated by the GM.1 pressure when GM.1 was injected, thus providing a given adjustable amount of additional injection. In spite of the sudden shocklike increases in power output, when injecting GM.1, over-running of the engine did not take place owing to the automatic speed controller. The unpleasant results of the fluctuations in flow of GM.1 which occasionally led to considerable peak values, required the fitting of a pressure controlled, temperature-insensitive adjustable nozzle constantly regulating the flow.

The engine's behaviour in flight corresponded to the altitude test stand values, especially as far as rise of cylindor headtemperature, blower pressure rise, and fall of boost air temperature were concerned. The specific output proved itself to be better than measured on the test bench. Signs of thermal overload began to appear as on the altitude stand when the output increase was over 500 HP, in particular rise in cylinder head temperature, pre-ignition and valve burning.

Further flight tests were carried out in an FW.190 with the co-operation of FA. Focke--Wulf. The GM.1 containers were insulated to reduce variations in output, the idea being to maintain an even flow of GM.1 by maintaining an even temperature. The best insulation did not give a perfect solution, as decrease in flow and fall of temperature through after-vaporization at the intake could naturally not be avoided. The improvement of flight performance of the FW.190 with a BMW 801D with an addition of 70 to 80 g/s. can be seen in Fig.9.

(Fig.9 - GM.1 pressure fuel in FW.190)

Speed increase was about 80 Km./hour at 9 Km. altitude. The increase in ceiling height on injection at 8 Km. was about 1000 m. It appears that GM.1 flow and output boosting fall before the equilibrium state of the cells is reached owing to the small quantity carried. In order to get an even output increase it proved wise to fill up with GM.1 only shortly before the flight.

6. Operational performance

On the basis of bench test and flight test results, there was proposed for the fighter an addition of 80/90 g/s. GM.1 for 5 minutes at 8Km. altitude. As is shown in fig.10 this corresponds to about 300 HP output increase. The height for switching the GM.1 on is determined by the fact that the thermal loading at combat output and full throttle height must not be exceeded. The effective engine performance at the height of switching on is correspondingly lower than at the full throttle height owing to the higher heat output when GM.1 is used.

The cooling pressure has to be increased by 70 m/m WS when switching on GM.1 in order to maintain the maximum permissible cylinder head temperature. Enrichment of the mixture is carried out by the enrichment device already described, operated by the GM.1 pressure. The mixture will thus be controlled to some constant indicated consumption as for combat output at full throttle height without the use of GM.1. As a result of the improvement of the general engine efficiency by the use of GM.1, a more favorable specific fuel consumption results than in normal operation, in spite of the enrichening of the mixture.

(Fig.10 - Power characteristics in the BMW 801A with compressed GM.1)

7. Test procedure

It can be briefly said that the GM.1 delivery with pressure fuel was secured simply by the flask pressure. The quantity was determined by weighing and the injection by simple "Lochdüsen" nozzles with various diameters. Mixture control was subsequently by hand. Cooling variations were controlled by an adjustable fan.

In order to use fully the increase in boost pressure, the injection took place in both intake shafts before the blower. As a result of the small temperature difference between boiling point and melting point, a tendency to stoppage developed through GM.1 snow, especially where the pipes contracted and extended, with unsuitable and not absolutely tight cocks, armatures and primary nozzles and elbows. Piping diameters should be generously measured taking into considerations throttle leak. They were in this case N.W.10. The nozzle injection angle used in fitting to the intake-shafts was 30° to 40 °. Smaller diameters such as 1.5 m/m caused uneven flow and icing. The flow of GM.1 proved with fixed nozzles (Lochdüsen) to be strongly dependent on bottle pressure, which altered considerably according to the ambient temperature and the state of filling of the bottle.

Decrease of pressure and flow with discharge can be prevented if the gas-phase of the container is maintained under an external constant high pressure.

There seemed to be no difference either in idling or in operation whether injection was into both suction shafts simultaneously or only one of them, so that it is assumed that the distribution of GM.1 through the impeller was even. Contamination of GM.1 was prevented by interposition of EC high pressure filters. 1000 kg. containers were used for endurance tests.

IV. Test results with cold start fuel

1. Purpose

Tests on injecting GM.1 in the fluid state without pressure, which were carried out by LFA Brunswick, proved that much larger quantities could be carried as the whole layout was not subjected to high pressures of 70 atm. or more. This enabled the desired requirement for raising the output by using GM.1 for a longer period to be taken into consideration. Owing to the low temperature of the fuel an improvement in the specific performance was attributable to increased internal cooling.

2. Power-behaviour

Tests with cold start fuel were carried out on power boosted 801D engines by BMW Munich, in collaboration with the Research Institute for Driving motors and Motor cars of Stuttgart, on their benches and on BMW's own altitude test benches. In comparison with pressure fuel, the several distinct and considerable advantages came to light. The smooth running and regularity of output of the engine was remarkable when GM.1 was used, better than with normal operation or operation with pressure fuel. The specific output was as shown in fig.11 with 3.7 to 4 PSe s/g., 20 to 30% higher than with pressure fuel. As appears in the output balance shown in the figure it is to be attributed primarily to the intensive internal cooling through the use of cold start fuel, which, as fig.12 shows, results in a stronger cooling of the boost air and in a larger increase of boost pressure. Furthermore the good internal cooling has the result that the temperature of the cylinder heads at equal GM.1 flow is no higher with cold fuel than with pressure fuel in spite of considerably higher power output.

(Fig.11 - Power characteristics for liquid GM.1)

(Fig.12 - The increase in the boost pressure and the fall in the boost air temperature due to addition of GM.1)

3. Cooling

The question of the cylinder head cooling within was quite particularly studied in the cold fuel tests. Fundamentally it can be stated that the higher thermal loads with GM.1 can be countered by external cooling, in the sense of a rise of the cooling pressure drop and cooling air intake as well as internal cooling by increasing the amount of injected fuel or by both together. The effect of the two possibilities can be seen in fig.13. The proportional use will naturally be influenced by operating conditions and engine possibilities.

(Fig.13 - Cooling pressure differences with GM.1 cold fuel, and mechanical enrichment)

(Fig.14 - Necessary rise of cooling pressure increase with GM.1 cold fuel additive for equal head temperature, with constant excess air ratio)

(Fig.15 - Endurance tests with GM.1 cold fuel on BMW 801D)

Based on our experience, we have chosen to control the enrichment in accordance with a constant excess air ratio. As relative value, the excess air ratio corresponding to combat performance at full throttle altitude was taken. Following the improvement of mechanical efficiency this control gave a slight decline in specific fuel consumption with additional GM.1 flow. The necessary increase of cylinder cooling pressure drop for constant cylinder head temperature with this fuel consumption controller is shown in fig.14. At high rates of flow an excessive enrichment to reduce piston temperatures is in any case unavoidable.

At 8 to 12 km. altitudes an engine could be run for many hours at 500 HP output increase by using cold fuel without any disturbances in the engine nor any signs of thermal overload. Fig.15 shows the balance of a series of such trials. As in this case cylinder cooling remained unaltered, the additional thermal load is visible by the rise of the cylinder head temperature.

4. Flight test

High altitude flight tests with a Ju.88 and a 801D engine took place at the Testing base of ORANIENBURG using GM.1 cold fuel. The result of an hourly measuring test with about 60 g/s. GM.1 is shown in fig.16. The speed increase, thanks to GM.1, was 90 km/hr. over 10 km. In level flying this speed increase brought a considerable increase in cooling pressure drop so that in conjunction with the internal cooling, resulting from enrichment no noteworthy rise in cylinder head temperature took place.

(Fig.16 - GM.1 cold start fuel in Ju.88)

It was noticed that with GM.1, engines were running smoother then without it, in flight as well as on the bench. The time required to reach full output was 3 to 5 minutes.

Fig.17 based on bench and flight tests, shows the expected increase in combat and climbing output up to 8 km. as well as the necessary rise in the cooling pressure in climbing flight and the consumption of fuel. (Flow of GM.1 - 50 or 100 gm./s.)

The desired retardation of ignition with GM.1 is provided without trouble by the control gear on enrichment, without requiring an additional device, as in the mass produced BMW control gear; ignition is controlled automatically by the injection volume.

The retarding of ignition with GM.1 addition amounts to 10^{o} crank angle at the moment of starting, and decreases again at a certain altitude.

(Fig.17 - Output of BMW 801D with GM.1 cold fuel)

5. Test procedure

In contrast to pressure fuel a seperate delivery system is necessary when GM.1 cold fuel is used. It consisted of a compressed air plant when operating bench or flight tests, with which, after reducing the air pressure to about 4 to 6 atm., delivery from the GM.1 bottles was secured.

Injection into the suction shafts was provided by a commercial open rifled low pressure atomising nozzle like that made by Richter and Kärcher. Perfect atomisation was essential for smooth running. Speed variations resulted with a nozzle diameter over 3 mm. and a delivery pressure under 2.5 atm. owing to badly atomised granulated GM.1 It was also observed that atomisation was often less satisfactory shortly after switching on, but became steadily better and finer with the increasing cooling of the nozzle. With larger flows a parallel coupling of nozzles proved itself satisfactory. The time of response was 2 to 5 minutes according to the length of the tube. With changes in output uneven running may occur, resulting from the discharge of gaseous or fluid GM.1 simultaneously or alternately. GM.1 was stored in light insulated metal containers and was fed through insulated steel tubes. It was necessary to place the valve as near as possible to the nozzle. On the altitude test bench, if the distance between the valve and the duct was too long, duct became iced, owing to the low pressure lying considerably below the triple point, thus solidifying the remaining GM.1. Flight tests proved that it was important to de-aerate the containers thoroughly.

The fitting of nozzles in the suction shaft was arranged to provide the largest possible air space, before the jet met the surrounding walls. In fitting the nozzles it was to be observed that the orifice of the nozzle should penetrate to a small amount (about 1 to 2 mm.) freely into the suction shaft and should be well washed by boost air, because otherwise GM.1 would deposit on the nozzle in a solid form. The crumbling away of these deposits led to dangerous power oscillations. The flow of GM.1 was determined in the usual way by scale tanks or calibrating curves.

V. Use of GM.1 with internal cooling

As Stieglitz has reported in detail, BMW for a long while were carrying out tests on internal cooling with additives, particularly alcohol or alcohol-water mixtures, which indicated possibilities for output increase and relief of thermal loading.

As altitude bench tests have shown, power at altitude was thus increased. It had now to be investigated whether this method could be coupled with the one using GM.1, particularly as the two methods respectively complement one another, as fig.18 shows. The figure shows the results of tests of a BMW 801D main engine at 10 km. altitude, and shows first that when using binary fuel a larger overenrichment was possible without loss of output, than in normal operation, which means in countereffect to the thermal overloading with GM.1, simultaneous alcohol-injection caused a larger relief of thermal load through internal cooling without impairing the specific output increase with GM.1. Thus an additional output increase as a result of latent heat or combustion properties was possible.

(Fig.18 - Output of BMW 801D with or without alcohol related to λ).

As can be seen from this figure an advance of ignition is useful with richer settings and this is necessary to an even greater extent when alcohol or water-alcohol mixture is used. On the contrary, when GM.1 is used, taking into account the quick rise of pressure, a retarded ignition is desirable to avoid peak pressures, as already noted. Our comparative tests and experience show that with simultaneous injection of GM.1 and alcohol a satisfactory compensation could be expected and the advantages were secured without special timing.

Alcohol injection can also be used to take care of part or all of the necessary additional enrichment so that the attachment otherwise required on the mixture control can be dispensed with or simplified.

It can be further assumed that injection of alcohol effectively eliminates the deposits of GM.1 snow on the nozzle in the suction shaft which may lead to engine trouble.

Development and mounting of nozzles was thus simplified and facilitated.

Quite recently we began to try increasing the take-off power by addition of GM.1 cold fuel. In testing the 801D type an increase of take-off power for the type from 1800 HP to 2100 HP could be reached so far. The thermal conditions for sparking plugs in particular, were high but within controllable limits.

In order to reduce the thermal load further tests were made using GM.1 and alcohol simultaneously and brought the desired results, as shown in fig.19. As the alcohol quantity was only of the same order as the GM.1 quantity it is expected that during further tests on these lines, better improvements with larger alcohol quantities can be expected. Thus alcohol can serve either to reduce the thermal load at constant additional output or increase the output at constant thermal load.

(Fig.19 - Take off power increase in BMW 801D with GM.1 cold fuel)

VI. Limiting outputs with GM.1

In view of the state of technical development of the equipment, in the interest of simple subsequent equipment and constructional considerations, it is proposed at first for the practical application, to provide constant rates of addition of GM.1 with height (perhaps however 2-stage addition) and thus to get constant increase of power. Assuming sufficient cooling and a sufficient supply of fuel the following question arises: is it possible to obtain a higher additional output at high altitudes when the output is low, or in other words, to what extent does the original output which falls with increasing altitude, permit of an increase of the output due to GM.1 addition without an accompanying increase in the thermal loading.

It was mentioned before that our tests with large additive quantities gave an overload of about 30% when GM.1 is used compared with air operation. If one takes the engine's output at full throttle height as the thermally limited output, then for the height at which the engine's initial power is just zero, there is still with GM.1 addition a possible output of about 70% of full throttle power. Fig.20 shows the corresponding variation of output at altitude with GM.1 addition over full throttle height. Furthermore the figure shows the variations of cooling air pressure and fuel consumption corresponding to this theoretical limiting power.

A steady over enrichment at altitudes was attributed to internal cooling, however, only within the range where no decrease in output took place due to rich mixture. The realization of this theoretical GM.1 output curve would in any case depend upon an altitude control of GM.1 additive, fuel enrichment, cooling air pressure drops and eventually also ignition. It is obvious that the attainment of high cooling air pressures will cause difficulties.

(Fig.20 - Limits of output of BMW 801D with GM.1 cold fuel)

The experimental values obtained with our BMW 801D type as drawn in this figure show that up to 6 km. over the full throttle height it was still possible to follow the theoretical curve. The problem for current tests is to establish to what extent at still higher altitudes the theoretical limit value could be reached.

VII. Problems for further developments

So far test results and experience indicated that by adding GM.1 to high altitude engines with and without exhaust blowers over the full throttle heights, also for periods of additive injection, considerable output increases could be expected and that the better performances so far obtained could still be improved upon. In order to obtain this and also to develop with good efficiency and on a firmer basis the already proven advantages of the GM.1 injection, it seems important to us to try to fulfill urgently the following important requirements :-

1. Carrying on of research on necessary properties of the material of all parts which come in contact with GM.1, the most effective insulation material, and suitable improvements of armatures. Shortening the time of response with GM.1 cold fuel by corresponding improvements of the layout.

2. Enlargement of the production base for nozzle equipment, armatures, piping, metal hoses and electrical circuit breakers as well as their further improvement. Owing to scarcity in supply of these parts, development work is considerably retarded.

3. Supply in larger quantities of GM.1 tanks of 100 to 12000 kg. capacity, GM.1 tank carriers for rapid GM.1 supply and wheeled filling devices for refuelling. Further improvement in insulation of tanks in order to lessen losses through evaporation.

4. In new engine types for GM.1 operation a mass produced attachment for the mixture control should be considered; this scheme should permit when necessary under the present status of development a 30% increase at altitude over the normal maximum injection volume. To obtain sufficient cooling in aircooling engines, an increase of 100 to 200 mm. W.S. in the cooling air pressure should be considered.

To realise the above requirements and to get a further increase in the performance of our engines, especially regarding the full throttle height, we have set ourselves the following problems for the further development of GM.1 :-

1. Further output increases in particular at low initial output by GM.1 addition over 150 g/s. to establish how near the theoretical limiting value we can come, namely at the height where the effective useful power is normally zero, by addition of GM.1 to give 70% of the output at full throttle height.

2. Research as to how far the thermal load at large GM.1 intakes

could be counteracted -

a). by adjusting the ignition timing.
b). by raising the internal cooling by means of a richer mixture setting.
c). by adding substances of high latent heat such as alcohol or water-alcohol mixture.

3. Research on possibilities of increase of take off power by GM.1 in available blowers.

4. Experiments to increase the output with GM.1 in engines with exhaust blowers first of all above the full throttle height.

VIII. Summary

Test Results with BMW engines using GM.1 additive as oxygen carriers were reported. The possibility of a considerable rise in the altitude, performance over full throttle height is proved to be safe in operation and thermally controllable. In the case of GM.1 cold fuel the achievement of a still larger output gain can be expected

Discussion

Held: As already mentioned an important part of the knowledge about the application of GM.1 in BMW and Daimler Benz aero engines, the Willick and Pauling described, was gained in close co-operation with the Research Institute for Aero Engines attached to the Technical High School Stuttgart using their test bench. The Institute can congratulate itself on producing some interesting results of its own.

(Fig.1 - Engine data with injection before and after the blower)

Fig.1 shows the comparison between GM.1 injection before and after the blower in a DB 601Q type engine. Depending on GM.1 quantity G_x the most important operating data are shown in both cases. The differences are dependent upon the gain in the blower, which is the result of cooling of the intake air when the injection takes place before the blower. At full vaporization of the injected GM.1 quantity before the blower, the intake air temperature must fall linearly and similarly the blower pressure increases linearly. In fact the GM.1 quantity vaporized before the blower decreases with increasing quantities of GM.1 owing to the short period and small heat supply of the intake air. That is the origin of the crooked course of the boost pressure.

With injection behind the blower, the direct rise of boost pressure conditions owing to cooling is lost. Boost pressure remains unchanged until it is affected by the variation of the flow quantities which move the operational point in the area of the blower.

The airflow rises with increasing amounts of GM.1 with the injection before the blower and sinks comparatively steeply when the injection is after the blower.

In every case the GM.1 quantity is completely vaporized inside and after the blower, because of the considerable heat in compression, and therefore the temperatures taken before the valves fall linearly. The fall is larger with injection after the blower, because firstly, with falling air volume the GM.1-air ratio alters to the advantages of the GM.1 itself and secondly the increase of adiabatic heating which is connected with the rise of boost pressure conditions when injection is before the blower, is lacking.

The effective power rise is slower in relation to various rates of air flow, with injection after the blower than with injection before the blower; the corresponding output increases, i.e. the power increase per quantity of GM.1 per unit of time are in the first case 2.6 to 2.7 HP s/g. and 3.0 to 3.4 HP s/g.

Further development was limited to injection before the blower. Metering of fuel must be adjusted to the increased oxygen flow when GM.1 is used in a manner to get the best output.

(Fig.2 - Influence of the mixture strength)

This figure shows the output obtained against oxygen excess λ for a DB 601Q at 10 km. altitude at 2500 r.p.m. with 80 g/s. GM.1. For comparison, the maximum output without GM.1 was measured altering the pressure before the engine to give otherwise equal conditions. The most favorable mixture strength is the same in both cases. Exhaust temperature and temperature at sparking plug seats are as expected higher with GM.1 than with air operation, but the running apart from that was similar.

In the course of experiments the influence of the ignition timing was also investigated. For this three output courses were considered at 10 km. altitude with different ignition timing points.

1. Normal performance
2. With increased output obtained with the addition of 105 g/s. of GM.1
3. With equally increased output with pure air operation obtained with a higher pressure before the engine.

(Fig.3 - Influence of ignition timing)

It appears in fig.3 that the timing point for test output with GM.1 additive is about 10° crank angle retarded. Correspondingly, the combustion peak with GM.1 additive moves with constant ignition timing point to 10° crank angle advance. Both graphs point out that the course of combustion is accelerated by the presence of free oxygen resulting from the free energy of the disintegrating GM.1. As fig.3 further shows, the course of combustion with GM.1 at equal ignition timing leads to higher peak pressures. Whereas with the best ignition timing with GM.1 a substantial pressure drop appears as against an equal performance with pure air.

Fig.4 shows three indicator cards which were all taken at the same ignition timing points. One notices a steeper pressure rise and advance of the combustion peak in the middle diagram operating with 105 g/s. of GM.1 additive as against the diagrams for pure air operation, one for the initial output at 10 km. altitude, the other for an equal output as with GM.1 operation.

The observed acceleration of the combustion also influences the knocking behaviour. In order to make this clear, knocking measurements were conducted by means of an FKFS fuel test engine. In fig.5 various throttle positions and power outputs are plotted against fuel flows for operation with or without GM.1. The various knocking limits are specially indicated. One reckons that the knocking limit with GM.1 additive is considerably higher than when pure air is used.

(Fig.4 - Indicator card with and without use of GM.1 at fixed ignition timing point, 35° crank angle before T.D.C., engine DB 601Q, no. of revs n = 2.500 min. altitude 10 km.)

This effect is explained on one hand by the low load temperature and on the other hand by the higher speed of combustion which also results in controlled burning of the knock-susceptible residue of the cylinder charge. In this relationship it is pointed out that the indicator cards of a multi-cylinder engine with use of GM.1 were essentially more even than with air, which is explained by a quicker and more even burning of the charge.

As regards the thermal load of the engine when GM.1 is used, measurements of piston temperatures in Diesel engines are available. Measurements by means of fusible plugs gave 350°C. at the piston centre at full load with pure air operation. With about 35% output increase due to supercharging with a blower the temperature rose to around 420°C., and at equal output increase by GM.1 additive to 500°C. These values indicate clearly a substantially more severe rise of thermal load with output when using GM.1.

(Fig.5 - knocking behaviour)