DISCUSSION

(pps. 19-27)

E. Schmidt. The incomplete knowledge of heat transfer is mainly responsible for the difficulty in applying engine conditions to tests on other equipment. Little more can be learnt by measurements, because it is difficult to perform on the running engine heat transfer tests with the required degree of accuracy. e.g. we have tried to measure the heat transfer conditions during the inlet on a small engine. It is easy to see that an engine run by an outside drive without ignition and only with air would function as a refrigerator. It compresses air adiabatically and brings it temporarily to a higher temperature than the cooled cylinder walls. In the process the air delivers heat to the cylinder wall, with the result that it issues from the engine at a lower temperature. The test shows however that it leaves at practically the same temperature, perhaps because the piston gets warmer than the cylinder wall, or because it absorbs heat again in the exhaust. This method does not help, therefore, to learn anything precise about heat transfer during inlet.

F.A.F. Schmidt. According to Jost, pressure affects but little the reaction process determining detonation; and the pressure effect observed in the engine is only an indirect one, manifested through the temperature. The evaluation of DVL engine tests show that indirect effects cannot explain the strong pressure effect on engine knocking. The question whether the pressure effect on knocking observed in the engine test is only an indirect one acting through the temperature or a direct action of pressure on the reaction process is important; on it depend the measures to be taken both in engine design and in fuel development, as well as the fuel testing method.

DVL carried out more tests on self-ignition in bombs and in an apparatus for the quasi-adiabatic compression of fuel-air mixtures. This apparatus worked similarly to that used by Jost, and Tizard and Pye. A larger compression volume was used to achieve more precise results (80 mm. cylinder diameter instead of 33 to 50 mm. used by Jost). The fuel vapour-air mixture was compressed with compressed air, to reduce the compression time. The fuels used were the same as in the engine tests, namely BO B_4 and C_2.

The measurements showed a very strong pressure effect on the ignition process. Fig. 1 contains on the left the results obtained in a bomb with the injection of a liquid fuel. The curves show the ignition lag at pressures of about 40, 30 and 20 atm. These ignition lag values take into account the effects of vaporisation and mixture formation. The right hand chart shows the results with the quasi-adiabatic compression apparatus. The curves refer to compression pressures of approximately 6, 12, 15, 23 and 30 atmospheres. The absolute values of the ignition lag are naturally considerably lower than those measured in the bomb, because the effect of vaporisation disappears. It appears that the temperature effect is smaller and the pressure effect comparatively greater as the temperature rises. This result was also found with various other fuels. The pressure effect was always smaller at low temperatures, for the fuels so far used.

To explain the contradiction with Jost's results, the tests were repeated in our apparatus with n-heptane, in operating conditions similar to Jost's but with a wider pressure and temperature range. Similar results were obtained in Jost's range (up to 400°C), where the pressure effect was indeed very small. It became considerable at higher temperatures, though much smaller with n-heptane than with BO and B_4. The ignition lag at different pressures varied generally with the fuels in question as shown in Fig. 2. I wish to recall the tests made at MAN in co-operation with us on gasoline (B O).The temperature range most interesting for practical purposes is that corresponding to an ignition lag between 0.001 and 0.003 sec.; it is here that knocking develops in engines. Jost's tests covered a range corresponding to ignition lags of between 0.003 and 0.01 sec. The results of more DVL tests with n-heptane in this range will be illustrated by Mr.Scheuermeyer.

The adiabatic compression equipment tests together with our practical evaluations led us to the conclusion that at various temperature ranges the pressure and temperature effect on self-ignition of fuels is generally not the same. It will however be possible, at least with an approximation good enough for practical purposes, to characterise a fuel with a single formula in the practical region.

Heptane tests alone do not appear sufficient for general conclusions on the knock process in the engine, especially if these tests were carried out within a temperature range not corresponding to practical conditions.

Jost. Tests with injection should not be taken as a basis for the ignition process. Refer to my Augsburger lecture of 1938 and subsequent publications.[1)]

E. Schmidt. A distinction should be made between tests with injection of liquid fuels and tests with adiabatic mixture compression. The conditions differ so much, that they are not directly comparable. Misunderstandings are caused by the fact that the meanings of "ignition lag" and "induction time" are confused. They should be more precisely defined and kept separate; either it is the chemical induction time proper or the diesel engine ignition lag, which latter includes the time for atomising, pre-heating and vaporising the fuel.

Zeise. In reference to the notice to the remarks of Schmidt and Jost I must mention that numerous tests on tubes and bombs, and engine tests by various authors with different methods and within varying pressure and temperature ranges point to a considerable pressure effect on the ignition lag. The theory also shows that pressure as well as temperature plays a considerable part as I showed at Frankfurt am Main (Bunsentagung) and will repeat later. On the other hand only few tests by Jost show that the ignition lag is mainly dependent on temperature and little if anything on pressure; in some of these tests the initial pressure had been increased from 1 to 2 atm. The supplementary tests refer to a region in which ignition lags are relatively long and a strong pressure dependence can be expected. Sokolik distinguishes three temperature ranges: a bottom one with long ignition lags, where there is practically only a temperature dependence; a medium one - about 400°C to 600°C - with a pressure dependence alone, and a top one over 600°C with both effects. The medium range is not always present to the same extent nor equally marked. It is also remarkable that Stern, Kravetz and Sokolik found that their tests on H_2 oxidation with air between 1/3 and 15 atm. and between 480° and 700°C, apart from those at the lowest pressures, can only be explained with the pressure effect. The mixture strength, i.e. the hydrogen content, is another parameter. If we plot the ignition lags measured for a certain hydrogen content against the pressure, we obtain a single curve, irrespective of temperature, and a different curve for another mixture strength. This also proves the great importance of the mixture strength, as it appears in tests by Russian and English authors. I

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1) At this point in the discussion, I have also mentioned the authorship from which the works in this field are compiled. I dislike footnotes, and have consequently omitted them in publication.

shall only mention Townend and Maccormac, who found a strong dependence of the ignition lag on the mixture strength, e.g. a very strong influence of very small H_2 additions to CO-air mixtures, which lower the ignition temperature by about 150°C.

It depends entirely on the operational range whether the dominating factor is pressure, temperature or both together.

On the one side there are very many tests and theoretical considerations, on the other few tests with a relatively small (20%) pressure variation; it is not difficult to decide which has greater weight. Even Jost's last theory, that changing the material of the cylinder head would produce a change decisively pointing to the exclusive temperature dependence, does not seem quite conclusive.

Naturally the heat conductivity of the cylinder head affects the temperature conditions available at the compression end. The cylinder wall in its turn has a different effect. E. Schmidt mentioned earlier that during the ignition process the cylinder wall can have particularly hot or active spots, according to their position. Recent reaction kinetics tests, e.g. on the oxyhydrogen reaction, which for a long time had been explained with the theories of Kassel and Storch and Lewis and von Elbe, have given rise to doubts as to their mainly homogeneous character. Cylinder wall effects have recently proved to be a very important, though it is impossible to say a priori whether this applies to the engine too in the other conditions. Until the contrary is proved, this inference that the change of cylinder head material affects/pressure and temperature cannot be considered as conclusive.

Finally I should ask Jost and Rögener whether in their calculations they have taken into account the considerable pressure effect of $\varkappa$ present within wider pressure ranges.

Scheuermeyer. Ignition lag measurements were also carried out at DVL with n-heptane-air mixtures in an adiabatic compression equipment at stoichiometric mixture strength. These dealt with the measurement of the ignition lag in quasi-adiabatic compression gas mixtures, in which the fuel is already vaporised at the compression outset; the effects of atomisation, vaporisation and heating of the droplets therefore disappear. Fig. 3 shows the comparison with Teichmann's (1) results.

As usual, the compression temperature T (2) is plotted in a scale of reciprocal values (1/T) as abscissa and the ignition lag z in logarithmic scale (1/10, 1/100, 1/1000 sec.) as ordinate. Teichmann's values are plotted on the left in the region of lower compression temperatures, DVL's on the right for 23 and 16 atm. compression pressures. The graph shows a steady transition, though the curves are considerably less steep in the higher temperature range. Whilst Teichmann's tests show an apparent activation energy E of about 35 Kcal, in the temperature range prevalent in the motor it is considerably smaller (of the order of magnitude of up to 10). It is evident that the extrapolation of Teichmann's results (broken line) is inadmissible in the region of higher temperatures prevalent in engines. The graph shows further the pressure dependence of ignition lag, which falls off with lower terminal temperatures. The pressure dependence of the ignition lag for various fuels in the operational pressure and

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(1) H. Teichmann, Reaktionskinetische Untersuchungen zum Klopfvorgang, II. Zs. Elektrochm. Bd 47, Nr.4, 1941, S.297.

(2) Calculated from the initial temperature and the compression ratio with the precise values of specific heat.

temperature range will be dealt with in F.A.F. Schmidt's report.

Although n-heptane tests are not concluded, the results available are similar to those found in many tests on other fuels.

The tests on the pressure dependence of the ignition lag were carried out at initial pressures varying over a wide range (1 : 5), the other conditions being the same.

Kamm. The realisation of self-ignition operation in a mixture compression engine offers the advantage of a considerably simplified engine design; it must therefore be considered a prerequisite for the use of many cylinders at high speeds.

We shall report below on tests carried out by Flugmotoren-Instituts Stuttgart on instructions of the Auftrag des Reichsamts für Wirtschaftsausbau. The work covered only engine tests.

Pure self-ignition as a result of mixture compression can always be achieved simply by a corresponding increase of the ignitability of the fuel. The compression warms up uniformly the whole charge, which burns away practically at the same time as it is inflamed. Consequently strong detonations occur. Fig. 5 shows the effects of this detonating self-ignition operation on the pistons of a 200 cu.cm. engine. The effects of this strong knocking cannot be prevented from acting on pistons and cylinder walls; it is therefore only possible to realise self-ignition in a mixture compression engine if knocking itself is eliminated whilst maintaining the necessary fuel ignitability.

Of all known means to reduce knocking, the addition of anti-knock ingredients in a proportion sufficient effectively to hinder knocking has a negative effect, as it lowers the ignitability below the permissible limit.

Experiments to attain a sufficient control of the combustion process by sectioning the combustion chamber and thus eliminate knocking likewise failed.

The combustion process can however be affected by varying the fuel-air mixture. If we vary the fuel-air ratio of the inlet mixture in a self-igniting engine, the first result is that the engine will function within a considerably wider range of mixture ratios than the conventional ignition engine. Strong knocking appears over the largest part of the range. The boundaries are formed by a comparatively narrow range of knock-free self-ignition, both on the rich and on the lean side.

Fig. 4 shows these conditions in a water-cooled single-cylinder 700 cu.cm. engine (compression 10, octane number ~ 5). e.g. at 2,000 rpm it is impossible to operate with a very rich mixture below an air-fuel ratio of 7 whilst no knocking appears between 7 and 11. Strong knocking occurs in self-ignition operation at mixture ratio 11 to 25. Knock-free operation appears again between 25 and 28, i.e. below the mixture strength currently used in gasoline engines. Beyond 28 operation was impossible.

A 10 to 12 HP/lt. volumetric output was achieved with this engine in the knock-free lean mixture range. Consumption figures are nearly constant over a large speed range at approximately 200 gr/HP/h. For rich knock-free operation the output is rather higher and consumption rises to 400-800 gr/HP/h. In the knocking operation the measured output figures corresponded approximately to those of rich knock-free self-ignition operation.

The graph of the combustion process with knock-free lean operation (Fig. 6) shows the pressure rise at ~ 9° crank angle after top centre with gradual transition and an increase of about 2.5 atm/° crank angle. The peak pressure of 50 to 55 atm. occurs at ~ 17° crank angle A.T.C. ($\varepsilon = 10$ at full load).

The knock-free lean mixture region can be used for economic self-ignition operation. For practical applications of knock-free self-igniting engines it would be desirable to extend the narrow knock-free region, so far obtainable to only a small extent, by designing supplementary chambers.

As it is not expected that the knock-free region will be extended so far as to utilise carburettors in their present form, one of the most important future tasks will be to develop a suitable controlling device, which delivers the necessary mixture strength at any moment.

Jost. I cannot comment on Scheuermeyer's tests; first of all he gave no details of his methods, e.g. on self-ignition determination, secondly his tests deal with a field in which we have not worked.

Turning to Zeise's remarks. Serruys' tests have nothing to do with catalytic effects. As a precautionary measure Serruys covered the inside of a cylinder head with various metal coatings without producing noticeable differences. Tests with H_2O have shown that the kinetics of CO reaction is strongly affected by small quantities of H_2 or mixtures containing hydrogen. This would be completely outside our field and has nothing to do with it. Tests on the kinetics of hydrogen oxidation are made only at low pressures. Moreover there is the cylinder wall effect, producing an entirely different temperature dependence because active gas particles diffuse on to the cylinder wall and vice versa. This is not at all comparable with engine conditions. In Townend's tests, gases were introduced in pre-heated containers at induction times varying from seconds to hours. As far as I know Sokolik too proceeded in this way. It is also known that a change of the material used for the container affects the test results. When 7 or 8 years ago we started occupying ourselves with the kinetics of the knock reaction, we tried to take measurements in the most convenient manner in the laboratory, i.e. at normal pressure by introduction into a container or in a flow equipment. We found that this is not the way to approach engine conditions and thus we went over to adiabatic compression. The experimental results were entirely different from anything published. Finally we found that Tizard and Pye knew it beforehand; a great part of knock research had therefore been useless.

Fig. 1 - Ignition lag of B4 as a function of pressure and temperature.

Fig. 2 - Graph.

Fig. 3 - Ignition lag z of n-heptane-air-mixtures as a function of compression temperature for various compression pressures (provisional test results obtained in a quasi-adiabatic compression equipment).

Fig. 4 - Output, consumption, mixture strength, knock behaviour in self-ignition
$\varepsilon = 10$
700 cu.cm. capacity.

Fig. 5 - Piston wear with knocking self-ignition.

Fig. 6 - Pressure variation and radiation with knock-free self-ignition. $\varepsilon = 10$; $n = 2.000$ rpm; full load - 700 cu.cm. engine.