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New tests for the determination of individual factors affecting engine knocking.

by F.A.F. Schmidt.

DVL carried out tests in a bomb, in a compression equipment and in a special apparatus, to explain the causes of engine knocking.

The tests were planned so as to allow a far reaching separation of the individual factors affecting the processes in the engine. For this reason also atomisation, vaporisation and mixture distribution, as also the chemical reactions were investigated in very clear conditions.

For the evaluation it was assumed that within a limited temperature range the reaction can be represented by a mean equation; for the purpose of a quantitative study of the combustion processes, it was initially assumed that the reaction velocity of a certain fuel-air mixture depends only on pressure and temperature; further that in the temperature and pressure range involved it can be rendered by:

$$\frac{d(B)}{d_3} = \frac{p^n d}{e^{b/T}}$$

from which we obtain for the ignition lag

$$z = \frac{e^{b/T}}{p^n} a \cdot \beta .$$

In these equations b, n and a are empirical constants; in contrast to the constants of the corresponding equation derived from considerations of the kinetics of the reaction they have no special physical meaning. β results from the integration and represents a function of temperature and of b. If we want to neglect β , and use an empirical equation for the ignition lag: $z = \frac{e^{b/T}}{p^n} a'$, the values of a' and b' would differ from those used in the reaction velocity equation.

In these early comparative tests on ignition lag and knocking it was further assumed that knocking sets in as soon as a very high reaction velocity is reached. It was found that the curve of engine knocking in terms of compression, pressure and temperature of boost air, and ignition timing for a given fuel at constant air excess can be reproduced by a single formula, using the above empirical expression for the reaction velocity. The engine results well agreed qualitatively with the ignition lag tests.

The constants of the reaction velocity equation can be approximately estimated from the knock tests. Even if there are some uncertainties in the determination of the temperatures in the engine, and the results are conditioned by cylinder wall effect and the practical engine operation, the figures obtained may not be highly accurate but their order of magnitude will always be correct. The constants obtained for various fuels in bomb tests agreed with those from engine tests both in their order of magnitude and in their relative variation. So far the evaluations did not prove whether the reaction velocity is a unequivocal function of the instantaneous pressure and temperature, nor to what extent the temperature rises during the ignition lag. It could however be concluded that within a restricted pressure and temperature range knocking can be explained by a reaction, the velocity of which can be reproduced in its order of magnitude by the reciprocal value of a pressure power and an experimental function of the temperature. The properties of the fuel as regards pressure and temperature effect on the reaction process, as they are expressed by the constants obtained from ignition lag tests, were of the same order as those resulting from the engine tests.

The engine tests on the effect of boost pressure and boost air temperature on knocking could only be explained by admitting that the pressure effect is far more important than the temperature effect. This result contrasts however with those of other physical tests; in particular Jost (1) reached the conclusion that the knock reaction velocity depends appreciably only on temperature. According to him the strong pressure effect introduced in our evaluations, according to which temperature variations of as much as 100°C corresponded to a 50% pressure variation, was quite incompatible with the kinetics of the reaction (2). In Jost's opinion the effect of the boost pressure on engine knocking in fact is mainly an indirect temperature effect, because the cylinder temperature must go up for various reasons with the supercharge. If this effect is present to the smallest extent, it seems quite impossible even approximately to explain the pressure and temperature effect on engine knocking and the results of DVL bomb tests with the figures Jost gives for temperature and pressure effect on reaction velocity.

Further tests were undertaken, especially on the pressure effect on knocking, in order to explain these contradictions and to determine the physical fundamental reactions which characterise knocking. Parallel tests were started with the same fuels on two apparatus and on an engine to determine the self-ignition characteristics, as follows:

1. Ignition lag tests at various pressures and temperatures in a heated bomb with injection of liquid fuel.

2. Ignition delay tests at various pressures and temperatures in an apparatus for the quasi-adiabatic compression, according to the procedure of Tizard and Pye (3) or Jost and Teichmann (4).

3. Engine tests at different boost air pressure and temperature.

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(1) Bericht der Lilienthal-Gesellschaft für Luftfahrtforschung über die Tagung " Power material for high performance engines", Feb. 1939 in Bremen.

(2) Vol. 9 Schriften der Deutschen Akademie der Luftfahrforschung, Berlin 1939, p. 259, "Physical and chemical events in connection with engine combustion".

(3) H.T. Tizard and D.R. Pye, Phil. Mag. (6) 44 (1922) 79; (7) 1 (1926) 1094.

(4) W. Jost, Zs. Elektrochem u. angew.physikal. Chemie 47 (1941) 262; H. Teichmann, ebenda, 47 (1941) 297.

The object was to compare on a common basis the characteristics obtainable from these three test series. The bomb built by my co-worker Franke (Fig. 1) mainly differs from so far known test equipments in the fact that it allows temperatures up to over 1000° abs. A uniform temperature level was obtained by enclosing the bomb in a large oven. The fuel can either be injected in liquid form or pumped in as a gas. The ignition process could be followed with a photo-electric cell and by pressure measurement. Accurate measurements were obtained by a careful design of the release devices and measuring apparatus.

Fig. 2 illustrates the apparatus for quasi-adiabatic compression developed by Scheuermayer and Steigerwald whilst Tizard and Pye used a crank mechanism to actuate the piston, the latter being disconnected and fastened at the T.D.C., and Jost a drop weight, here the piston is moved by compressed air (5). This arrangement allows very accurate operation with a simple design and very short compression times. The cylinder wall effect is reduced by the comparatively large cylinder diameter of 80 mm (Jost worked with 30 to 53 mm. bore). Measures were taken in the new apparatus to ensure a very accurately defined initial condition. The equipment could be pre-heated and the pressure could be adjusted above and below atmospheric pressure, which allowed wide pressure and temperature variations. Lonn and Steigerwald will report in detail on the tests.

In both arrangements provisions were made to reach the operational pressure and temperature region; all the results obtained can therefore be directly compared with engine tests. Fig.3 shows the diagram of an ignition test under adiabatic compression. Start and end of compression as well as ignition lag are indicated. The ignition occurs suddenly at the end of the ignition lag.

Fig. 4 contains the diagrams for three different compression temperatures at constant pressure.

In Fig. 5 the temperature is constant, for three different pressures. The top graph shows clearly a slower ignition onset at 10.6 atm. than at higher pressures. The ignition does not set in suddenly but gradually; i.e. with very low pressures and long ignition lags the sudden ignition changes gradually into a slow ignition start. It is therefore possible to detect a gradual transition from the knock-like ignition start proper to slow combustion.

The pressure curve during the ignition lag affords certain deductions on the course of the reaction. It was pointed out before that the reaction curve and the temperature increase during the pre-reaction need not correspond with the reaction velocity variation obtained from the effect on ignition lag of pressure and temperature; in fact it is doubtful whether the mentioned assumption, that the reaction velocity is a unequivocal function of instantaneous pressure and temperature, is correct. Actually, according to the theory of chain reactions, the chemical transformations in the mixture, which occurred before the moment in question and depend on the pressure and temperature variations before that moment, have a decisive effect on the reaction velocity. Fig. 4 and 5 show conclusively that this is the case. Certain differences can be due to the fact that the process varies from point to point of the combustion chamber. Earlier Zeise (6) pointed out that, in certain cases, a distinction must be

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(5) After the same principle as a trial apparatus built earlier at the Nusselt Institution in München under instructions from the DVL.

(6) H. Zeise, Zs.Elektrochem. u. angew. physikal. Chemie 47 (1941) 779.

made in the ignition process (in analogy to observations in tubes) between a stage corresponding to the slow pre-reaction and a second stage corresp nding to the varying ignition reaction. The spontaneous ignition proper is prepared by the pre-reaction, during which only a small temperature rise takes place.

The comparison of the results of Fig. 6 shows that pressure and temperature functions obtained both in the bomb and in the compression apparatus agree fairly well with figures deduced from early rough calculations based on engine tests. Owing to the difficulty of controlling the effects of heat transfer, to the uneven distribution of the mixture in the cylinder and to the influence of special constructional details of the cylinder design etc., this good agreement could not be expected; it was enough that the characteristics agreed in their order of magnitude. First of all the tests showed that the pressure dependence too is of decisive importance for the reaction process. Fig. 6 shows for instance that in the pressure and temperature range within which knocking occurs in the engine, doubling the pressure corresponds to a 0.4 : 1 variation of the ignition lag. A temperature variation of over 100°C thus corresponds to a 1 : 2 pressure variation. The results shown in Fig.7(7) confirm the fact that the main properties of a fuel as regards the pressure and temperature effect on the reaction process are mainly unchanged by an addition of lead; that however over the whole range the reaction velocity falls off as a result of a lead addition.

These tests are in open contradiction to the results of Jost's and Teichmann's tests; they proved a very great temperature effect and a small and roughly negligible pressure effect.

In the study of knocking it is of decisive importance whether the pressure effect measured during the knocking is mainly an indirect temperature effect, or a direct pressure effect connected with the reaction process of the fuel in question; in fact the fuel assessment changes entirely whether we assume that knocking is affected only by the extent of the activation heat or also by the pressure function of the reaction process. The measures to be taken on the engine also vary according to whether we assume an indirect effect of temperature on the reaction process or a direct effect of the mixture pressure.

We can conclude from the present tests that the different pressure effect with various fuels is not due to an indirect temperature effect (see Fig. 8). Even considering all possible limits of error, checks on the engine process afford an explanation of those curves only if we assume that the pressure effect is closely connected with the reaction process. The proportion of residual gases also affects engine knocking. It is low when there is a valve overlap and high in engines without it. Ignition lag tests with the addition of inert gases were carried out in the bomb to explain this question. It was found that the partial pressure of oxygen is generally the decisive factor of ignitability. At constant total pressure a nitrogen addition results in a decline of the partial pressure of the oxygen and in a lowering of the ignitability. Under constant partial pressure of the oxygen a CO_2 addition produced only a small effect.

Further tests are under way to separate as completely as possible the thermal effects and the action of vapourisation from the chemical process. Apart from the investigations on droplet vapourisation, on which we reported earlier, the comparison of the results in the bomb and in the compression apparatus vastly contributes to determine the

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(7) F.A.F. Schmidt, VDI-Forschgsh. 392, p. 12.

influence of the vapourisation process; the other conditions being similar, liquid fuel is injected in the bomb, whilst vapourised mixture is used in the compression apparatus.

In the comparison it is important to introduce correctly the temperature effect of the evaporation heat. A superficial examination shows that the character of pressure and temperature effect of a given fuel remains the same in both cases; the ignition lags in the bomb become however considerably longer, mainly due to the vapourisation process (Fig. 9).

Fig. 8 shows that the pressure and temperature effects, which are apparent in the bomb and compression apparatus, manifest themselves similarly in the engine. It can therefore be expected that in future development it will become increasingly possible to characterise the fuel properties, the test conditions remaining the same, by the constants in the formula

$$z = \frac{e^{b'/T}}{p^n} \cdot a'$$

one or a few (1) engine tests, together with the constants determined with physico-chemical apparatus, would then be sufficient, without the need for long test series, to determine the fuel characteristics in the engine. Engine tests should be restricted to the region most important for practical engine operations.

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(1) Owing to the excess air effect.

Fig. 1 - Test bomb for the investigation of self-ignition of fuels.

Fig. 2 - Testing apparatus for the investigation of self-ignition of fuel vapour-air mixtures (quasi-adiabatic compression.

Fig. 3 - Test for the determination of self-ignition.

Fig. 4 - Ignition lag and compression temperature.

Fig. 5 - Ignition lag and compression pressure.

Fig. 6 - Ignition lag to B_4 as a function of pressure and temperature.

Fig. 7 - Ignition lags of B_0 and B_4 measured in a compression apparatus.

Fig. 8 - Knock limits at various temperatures and pressures of the admission air for engine methane and aviation gasoline.

Fig. 9 - Ignition lag to B_0 in terms of pressure and temperature.