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The application to engine conditions of laboratory experiments on self-ignition of fuels.

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In recent years it has been generally accepted that the knock process is the self-ignition of a residual portion of unburnt charge. According to this theory the physical state of the unburnt mixture residue, i.e. its temperature, density, composition as well as the time during which the mixture remains in this state has a decisive influence on the appearance of knocking; so has the tendency of the fuel-air mixture to self-ignition in the given conditions.

Mr. Jost has reported on the self-ignition tests on adiabatic compression of fuel-air mixtures, carried out in the Institut für Physikalische Chemie at Leipzig. The tendency to self-ignition, measured in induction times, of carefully purified paraffin fuels depends strongly on the temperature, but only to a much smaller extent on density and mixture strength. From the data of the preceding report the following numerical function can be indicated as a guide: a 50% reduction in density corresponds to the difference of induction time produced by a 1 to 2% variation of the absolute temperature.

The results of engine tests can be briefly summed up by saying that the effect of temperature, density and mixture strength on knocking is of the same order of magnitude; this only means that it is not permissible to neglect one of the three variables for the other two. In order to investigate the question whether this behaviour of the fuel in the engine can be explained with its self-igniting properties, we should start by considering the physical state of the unburnt mixture residue. The task is therefore to determine the precise value of the various characteristics of the residue.

A first approximation can be obtained by assuming a very fast combustion at top dead centre and neglecting heat transfer, the temperature and density of the mixture residue can be calculated from the theoretical final temperature of the burnt gas, the specific heat of the mixture and the number of mols ratio before and after combustion. As the combustion proceeds, the temperature and density of the unburnt residue rise further above the compression temperature produced by the piston motion. Fig. 1 gives the calculated final temperature of the last (infinitely small) residue as a function of the excess air coefficient λ for a gasoline of mean molecular weight 100 and empirical composition $(CH_2)_n$. The figures for the specific heat of unburnt and burnt gas were taken from H. Kühl's "Dissociation of combustion gases and its influence on the efficiency of gasoline engines", VDI-Forschg. Vol.373.

At λ = 1.05 the mixture reaches the maximum temperature; the temperature decreases steeply with an increasing fuel excess, less steeply with an air excess. For each value of λ in Fig. 1, the compression ratio was calculated to give the same final temperature (Fig. 2). The self-ignition tests gave rise to the assumption that independently of the mixture strength knocking appears at a certain temperature: e.g. if the admissible compression ratio of a fuel at stoichiometric strength has been arbitrarily chosen as 8, the admissible compression ratios for different mixture strengths should coincide with the curve of Fig. 2.

Fig. 3 is used to draw comparisons with operational experiences. Curve b likewise applies to a pure paraffin fuel. Air deficiency and excess allow the compression ratio to be increased to approximately the same extent. From a merely qualitative standpoint the measured and calculated knock-limit curves are similar. For a more accurate calculation other factors must be taken into account, which postulate a connection between the final temperature and the excess air coefficient; among these come first flame propagation velocity and residual gas heat. The former shows a marked maximum at $\lambda \leq 1$, i.e. in the region of moderate over enriching; any reduction of this at constant ignition timing produces a lower peak pressure, and consequently also lower final temperatures of unburnt residual gases. This explains the positive effect of a marked air excess on the knock process. In the engine, knocking is always found to be strongly dependent on pressure. Fig. 4 shows the order of magnitude. The points of this curve have been obtained as follows: the intake temperature was varied, for each temperature the boost pressure was determined at which audible knocking occurred; and from the correlated figures for intake temperature, boost pressure, compression ratio and mixture strength, the density and temperature of the last unburnt residual gases were calculated. The curve shows therefore the corresponding values of theoretical final temperature and final density at the knock limit. According to this a 50% pressure rise would require a 90° temperature drop, i.e. 10% of the absolute value, in order that the knock limit be not exceeded.

The pressure effect can only be discussed if the heat transfer is originally taken into account. Each boost pressure rise increases the thermal stress of the engine, which means the cylinder wall temperatures and the temperature of fresh gas as a result of heat induction. By collecting several experimental engine tests on heat induction we have made an approximate estimate; it shows that a 50% boost pressure rise allows the absolute temperature of the unburnt residual gases to be increased by no more than 3 to 4%.

The knock limit curves, an example of which was shown in Fig. 3, are generally plotted at constant knock intensity. It seems justifiable to assume that an approximately constant amount of energy must be contained in the pressure waves in the gas chamber if a constant knock intensity must be attained. The higher the mixture density, the smaller must be the detonating volume to produce a constant amount of energy in the shape of pressure waves; and consequently the later must the self-ignition temperature be reached in the unburnt portion. A lowering of the initial temperature must therefore be connected with the boost pressure increase, in order that self-ignition actually occurs only at a later stage of the combustion. A rough estimate shows that at very marked knocking a 50% density increase must go together with a 3% decrease of initial or compression temperature, if the energy of the knock vibrations must remain constant.

Summing up the action of heat induction and of density effect on knock energy gives the result that a 50% pressure rise must be coupled with a 6 to 7% temperature drop if knocking is not to increase. Engine tests showed that temperature must be lowered by about 10% to balance the same pressure rise. The order of magnitude of indirect pressure effect is therefore quite comparable with that of observed pressure effect. The question whether there are other indirect pressure effects on the self-ignition of unburnt residues in the engine cannot be answered as yet. Even if self-ignition were based on a different temperature and pressure law from the one assumed by us, the indirect pressure effects mentioned had to be considered when the material obtained from engine tests was discussed.

The comparison between knocking and self-ignition of fuels can be concluded with the result that important features of the reaction of fuels in the engine can be explained with the principles regulating self-ignition. A more thorough quantitative explanation requires still more detailed data on the self-ignition process ~~especially at shorter induction times~~, as well as over the state of the unburnt residual gases in the engine.

The decisive factors as regards knocking, such as final temperature, final density of the unburnt part and time available for the mixture distribution can be determined in the engine by indirect as well as by direct methods; this is done by calibrating an engine with various fuels. The fundamental concept of this process can be explained as follows: it is assumed that the onset of knocking in the engine depends on three factors, final temperature T, final density ρ, time available τ. Knocking occurs for certain correlated values of the three variables, the knock limit can therefore quite generally be expressed by $f_1 (T, \rho, \tau) = 0$, the index 1 meaning that this knock limit surface refers to fuel 1. The variables can be taken as axes of a right angle co-ordinate system 0.

If we calculate the same factors from engine tests, the values will present a certain systematic difference; we shall therefore call them T', ρ' and τ'; if we likewise plot T', ρ', τ' as axes of a right angle system I, the points with the same co-ordinates do not correspond in the two systems; i.e. the calculated and the real values of the three factors do not coincide; or in other words we attribute quite different values in different engines to the same true values. In the system of true values one point can be determined by the knock limit surfaces of three suitable fuels, which intersect each other at this very point. If we pass to the system of calculated non-corrected values, this point P appears as P_I, the three knock limit surfaces meeting in P must intersect each other now also in point P_I of system I, as well as in point P_{II} corresponding to P for an engine II. The points of intersection of the knock limit surfaces of three fuels for different engines indicate then that in these points of intersection the three factors T, ρ, τ assume the same true value. Theoretically, by repeating this procedure in the three-dimensional system of the various engines, the equivalent points could be co-ordinated. If then we plot for an engine the knock limit surface of a new fuel, this surface can be calculated in advance for other engines by plotting it on the points equivalent to those of the first engine.

In this system we use the fuels themselves to "indicate" a certain physical state in the unburnt residue, by physical state meaning all the factors decisive for the knocking. We assume that the differences in the behaviour of different engines with the same fuels are due to the different physical state of these engines; this state is determined by the constructional features of each engine and to a certain extent the various fuels find it there. In fact however the various fuels will contribute to determine this physical state; if this influence grows beyond a certain limit, the described system naturally loses its fundamental accuracy.

We shall add a qualitative comparison with engine test results. Fig. 5 shows knock limit tests for two engines and three fuels, undertaken in the Institut für Betriebsstofforschung of DVL. The variables are intake temperature and boost pressure; they could be converted into final temperature and final density, leading mainly to a distortion of ordinates and abscissae; qualitatively the picture would be the same.

The difference between engine I and II is that all curves are displaced in the same direction; their opposite orientation, roughly characterised by the sense of rotation of the triangle enclosed by the curves, does not vary; the curvature changes in the same sense in all curves. This qualitative result should however signify that in effect the fuels find quite a different physical state in the two engines, even if the same state would result from calculations based on intake temperature, boost pressure etc. It must however be stressed that the figure apparently obeys a comparatively simple law. The co-ordination of the points can also be effected so as to produce an inversion of the sense of rotation of one of the triangles formed by the knock limit curves. It must also be considered that the whole theory must be plotted on a polydimensional space, in case more than three variables characterize the knocking process.

It seems to us that in a discussion on the possibility of transfer of the test results of one engine to another that these main considerations must be wholly borne in mind.

Fig. 1 - Calculated final temperature of unburnt mixture as a function of excess air coefficient.

Fig. 2 - Calculated compression ratio producing a constant final temperature.

Fig. 3 - Influence of excess air coefficient on admissible compression ratio. (F. Seeber)

Fig. 4 - Calculated final temperature and final density of unburnt residual gases. (Rothrock and Biermann).

Fig. 5 - Influence of intake temperature on permissible boost pressure.