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Measurement of the ignition velocity of flowing gas-air mixtures.

by Werner Unger.

After the great importance of a correct combustion for the operation of combustion engines was recognized, the combustion phenomena of air-gas mixtures were thoroughly investigated. Two methods were mainly applied to ignition combustion measurements of gas mixtures:

1. The dynamic method for laminar and recently also for turbulent flow conditions of the fresh gas.

2. The static method, in which the propagation velocity of the flame is observed in a gas mixture at rest.

Several scientists investigated the possible errors of the dynamic method. They showed that as long as the flow remains laminar the width and material of the burner as well as the flow velocity of the fresh gas do not affect the normal ignition velocity. Dynamic and static methods should give the same results, because for the combustion process it is immaterial whether the flame area is stationary in the chamber and the gas moves, or vice versa. This presupposes that in the combustion in the tube the flame takes exactly the shape of a plane perpendicular to the centre line of the tube. This condition cannot be realised, with the result that the two methods give very different figures. In the static method these differences could be explained with the theory that turbulent flows in the flame accelerate the combustion.

G. Damköhler (1) investigated the effect of turbulence on the ignition velocity of a gas mixture. The tests were based on the Bunsen burner method. In the picture of a Bunsen flame subject to laminar or turbulent flow Damköhler distinguishes an outer and an inner boundary surface of the cone. The inner and outer boundary surfaces are defined as the geometrical location of ~~fastest~~ and slowest combustion. In the investigation of a propane-butane-oxygen mixture the maximum ignition velocity for the inner cone ~~of the Bunsen flame was found to~~ be about 3 m/sec for laminar flow, and about 300% higher at Reynolds' numbers around 17,000. The ignition velocities which obtain in the outer boundary surface of the cone are of the same order for laminar and turbulent flow.

In 1937 W. Nussolt suggested the following work, which should clarify the laws on the variations of the ignition velocity of a coal gas-air mixture with the turbulence of the fresh gas flow.

(1) G. Damköhler: The effect of turbulence on flame velocity in gas mixtures. Jb. 1939 d. dt. Luftfahrtforschg Bd II (Triebwerk) p. 3.

Test method.

I used a test method working on the following principle:

An air-gas mixture of known composition and known mean flow velocity is imagined as flowing through a tube of given diameter. After leaving the tube the gas escapes into the atmosphere. The mixture is ignited in the tube by an electric spark. Two flame fronts appear. One of them moves towards the fresh gas flow, the other in the same direction as the fresh gas flow. The second flame, which burns in the flow direction, moves steadily towards the end of the tube. Its velocity relative to the tube is composed of the following quantities:

1. Fresh gas velocity.
2. The expansion velocity of the exhaust gases.
3. The combustion velocity of the mixture.

As the expansion velocity of the exhaust gases is a difficult quantity to determine, the second flame front was not referred to in the measurement of the ignition velocity, but only the flame front moving towards the fresh gas flow. Its velocity relative to the tube wall is composed of fresh gas velocity and flame velocity only. These are both quantities to be determined experimentally.

Test equipment.

In designing the test equipment for the described method the following conditions had to be met:

1. Velocity and composition of the air-gas mixture must be known and constant.
2. The fresh gas velocity must be variable within wide limits.

The scheme of the test equipment is shown in Fig. 1.

Combustion air and coal gas flowed separately through two gas meters and pressure equalizers into the mixing chamber and out into the atmosphere through the test tube. The tests covered three tubes of 20, 30 and 40 mm. bore; the first was arranged horizontally and vertically, the other two vertically. Smooth, seamless drawn precision steel tube was used throughout.

The ionisation method was used to measure the flame velocity in the tube. The propagation velocity of the flame in the tube was recorded by two ionisation gaps introduced in the tube, a two-way cathode oscillograph and a moving camera. The ionisation gaps divide the test tube in the following sections:

1. The equalization distance between mixing chamber and first measuring plug, at least 150 diameters in length.
2. The measuring distances, limited by two measuring plugs.
3. The initial distance, between measuring point and ignition plug.
4. The final distance between sparking plug and tube end.

Thorough prelimary tests dealt with the following points:

1. Design of measuring and sparking plugs, and their relative position in the tube.

2. Length of the initial, measuring and terminal tracts.

3. Effect of tube length on flame velocity.

Fig. 2 shows the design of measuring and sparking plug.

A 0.5 mm. steel wire was cemented in a steatite tube 1.5 mm. outside bore, the latter being strengthened by a copper tube. Through two diagonal holes in the tube wall the ionisation gaps were introduced inside the tube. To be constantly certain that the ionisation current flows between the insulated electrodes only at the approach of the flame, the distance a of the two electrodes was always smaller than b, that between measuring electrode and tube wall.

This arrangement produces a section reduction of 7% in the 20 mm. tube, 5% in the 30 mm. and 3% in the 40 mm. ones. With turbulent velocities the disturbing effect of the flow caused by the steatite tubes on the ignition velocity is smaller than in the case of laminar velocities. For those reasons a second arrangement was used at speeds of the fresh gas below the critical speed. The measuring electrode consisted of a 1 mm.NCT-3 steel wire, cemented in a small sinteral corundum tube 3 mm. outer diameter, flush with the inner tube wall. The tapered steel wire tip protruded 3 mm. inside the tube, and the tube wall was the earth. Comparative tests with the two measuring plugs at fresh gas speeds of 2.3 and 4.9 m/sec. in the 20 mm. tube and 2.0 and 3.6 m/sec. in the 40 mm. tube showed no difference in the measured ignition velocity and no difference in the speed of the ionisation flow.

The most convenient length for the initial tract (ignition plug to first ionisation gap) was found to be 10 diameters. The ionisation gaps were 200 mm. apart.

In the evaluation of the tests the flame velocity inside the initial and the measuring tract was computed from the oscillograph diagram, and a mean value was obtained. The flame velocity variations were within the limits of accuracy and did not indicate any increase or decrease of the flame velocity with the tube length.

Test results.

The composition of the coal gas was determined in a series of Orsat analyses. It varied within the following limits:

CO_2	3.6 - 4%
C_mH_n....................	1.6 - 1.9%
O_2	0.3%
CO	16.2 - 19.5%
H_2	50.2 - 53.8%
CH_4	18.8 - 20.5%
N_2	4.7 - 5%

The stoichiometric mixture contained on the average 21% gas. In a series of tests the air quantity was kept constant and the mixture composition was varied by addition of various gas quantities. The fresh gas velocity - computed from volume measurement and tube diameter - did not remain constant; it grew with the gas content. It went up by 13.6% when the gas content rose from 16 to 26%. This fresh gas velocity variation was obtained by extrapolating the results of several groups of tests.

Fig. 3 shows the ignition velocities obtained in a 20 mm. horizontal tube, plotted against the % mixture strength for fresh gas velocities between 0.54 to 4.9 m/sec.

There are two groups of curves of different character. Below 2.2 m/sec. fresh gas velocity the curve zeniths decline less steeply than above 2.2 m/sec. This points to a reduction of the ignition limits as the fresh gas velocity increases. The maximum ignition velocity for a given gas speed obtains at a mixture strength of 21% coal gas, i.e. in the proximity of the stoichiometric mixture. The slight displacement of the peak of the various curves is due to a variation of the gas strength, as the tests were not always made on the same day.

Test results on 20, 30 and 40 mm. tubes in a vertical position show the same characteristics. For this reason they are collected in Fig. 4a, which shows the ignition velocity in terms of fresh gas speed for a mixture strength of 21% gas. The ignition velocity rises with the increase of fresh gas velocity and tube diameter; it reaches 10 m/sec. for a 40 mm. diameter and 5.6 m/sec. gas velocity. Fig. 4b shows the linear variations of the ignition velocity as a function of the tube diameter, for various basic velocities.

The bottom part of Fig. 4a also shows the test results for a 20 mm. horizontal tube. At low gas speeds, the ignition velocity is rather higher for horizontal motion of the flame than for vertical motion. On the other hand for fresh gas speeds over 3.5 m/sec. the ignition velocity is lower for the horizontal tube than for the vertical one. The ignition velocity variations are due to gravity effects, producing an asymmetric distortion of the flame with the horizontal motion of the flame front. We shall discuss this again later.

To compare the tests with different tube diameters and to explain the question as to whether the ignition velocity depends directly on the turbulence of the fresh gas flow, the ignition velocity was plotted against the Reynolds number for a mixture strength of 21% gas in a vertical tube.

The curve shows the steep ascent of the ignition velocity with the Reynolds number, more marked below than above the critical Reynolds number, proving that the ignition velocity is affected by the variation of the flow characteristic in the tube. This graph shows further that the ignition velocity is not controlled by the Reynolds number, but by the tube diameter and the gas velocity. Otherwise the results for all diameters should coincide. Test results show however that the ignition velocity drops as the tube diameters grow larger. The limiting case would be an infinitely large tube, i.e. an infinitely large gas mass with a plane as combustion surface. The flame would then move at normal ignition velocity towards the fresh gas.

By plotting the ignition velocity against the gas velocity on a logarithmic scale it can be seen that the ignition velocity varies as a power function.

Two equations could be determined for the vertical flow in the tube.

For laminar fresh gas velocity the test results for all tube diameters can be given by the equation

$$z = (32.5 \cdot d + 2.375)\, v^{0.489}$$

and for turbulent gas velocity by:

$$z = (42.1 \cdot d + 1.963)\, v^{0.595}$$

where z is the ignition velocity, d the tube diameter and v the fresh gas speed. The exponent of the fresh gas speed grows from 0.489 to 0.585, i.e. by 21%, when the critical Reynolds number is exceeded towards the region of turbulent flow.

From these two formulae, which apply above and below the point of transition from laminar to turbulent flow, it appears that a variation of the character of the flow involves a change of the combustion process in the tube.

The above-mentioned measurements are obtained from tests in which the flame struck back in the gas flow. This always happened in tests under 5.5 m/sec. fresh gas speed in a horizontal tube and under 9 m/sec. in a 20 mm. bore vertical tube. If this velocity limit was exceeded, an unstable region was reached in which the flame partly struck back, partly was involved in the gas flow or even swung to and fro on a 10 cm. stretch. Only at basic speeds exceeding 10 m/sec. did the gas flow carry continuously the flame towards the open end of the tube. At these high fresh gas speeds the tests gave no clear or well reproducible results. For the same basic speed the values obtained for the ignition velocity varied by as much as 100%. Owing to these considerable variations, no absolute effect of mixture strength on ignition velocity could be found.

These variations can only be due to the flame itself. With a stable and continuously recurring flame front the flame velocity cannot possible vary by 100%, which is however quite easy in the case of an unstable flame front.

It might be supposed that the turbulence existing in the fresh gas at high Reynolds numbers is the origin of an unstable flame front. Tests on 30 and 40 mm. tubes showed however that measured values could be obtained with little scattering even at Reynolds numbers corresponding to a basic velocity of over 10 m/sec in 20 mm. tubes.

The unstable flame front is not produced by the fresh gas turbulence, but is due to the dynamics of the flame front propagation.

Which type of flow occurs in the combustion in a tube? The following ideas have merely a qualitative value.

We have a gas mixture at rest in a cylindrical tube and we ignite it at the open tube end. (Fig.6). An arched flame front symmetrical to the tube axis takes shape; it moves in the tube at a speed z, that is higher than the normal ignition velocity of the fresh gas z_n. The latter occurs in the centre of the tube, where the combustion surface is perpendicular to the axis of the tube. Because the effective flame velocity z is greater than the normal ignition velocity z_n, an additional velocity v_{zu} must come forward to maintain the stability of the flame front and compensate the difference of the two velocities. At another point on the combustion surface the resulting ignition velocity z_r is higher than the normal ignition velocity z_n but lower than the propagation velocity of the flame. The difference is compensated by an additional velocity, which in this case is smaller than that in the centre of the tube. There is a point at which flame velocity and resulting ignition velocity have the same value, i.e. no fresh gas flow occurs. Still nearer the edge the resulting ignition velocity exceeds the flame velocity $z_r > z$, whereby the additional fresh gas flow becomes negative, i.e. fresh gas flows towards the combustion surface.

In this test method the fresh gas flows with an imposed speed towards the combustion surface, which in turn moves relatively to the tube wall towards the fresh gas end. How can such a flame front take shape? Let us consider first the flame in the centre of the tube, where it is perpendicular to the axis of the tube. The normal ignition velocity z_n prevails here. The fresh gas moves towards the flame at the maximum local speed v_{max}. An additional fresh gas flow of the order

$$v_{zu} = z_F - Z_n \div (-v_{max})$$

must appear, in order that the flame can move at velocity z_F against the fresh gas flow.

At a point x_1, the resulting ignition velocity is $z_r = \frac{zn}{\cos\alpha}$.

If $z_r < z_F$, an additional speed of the order

$$v_{zu1} = z_F - z_r \div (-v)$$

appears (v is the speed of the fresh gas at the point in question).

As $z_r > z_n$ and $v < v_{max}$, it is $v_{zu1} < v_{zu}$.

v_{zu} diminishes with the further progress to the flame surface towards the tube edge. It reaches its zero value where $z_r - z_F = (-v)$ and it becomes negative when $z_r - z_F > (-v)$.

The additional speeds that occur in the flowing mixture are therefore similar to those in the mixture at rest.

Photographs were taken to obtain a picture of the flame conditions. Fig. 7 shows photos of the flame front, for horizontal (a and b) and vertical (c and d) flame motion. Photo a refers to a laminar fresh gas flow at 0.75 m/sec. and 20% gas in the mixture. Photo b shows the flame at 2.5 m/sec. (turbulent flow) and 20.8% gas.

The flame in the laminar flow maintained its form, in contrast to the flame front in turbulent flow which presents a fissured surface.

The two flames have however something in common: they are both bent forward and are non-symmetrical to the axis of the tube.

The flame with vertical motion is symmetrical. If the flow in the tube is laminar (Fig. 7c), the flame surface is continuous. With turbulent flow however (Fig. 7d) the flame front is fissured, though symmetrical. In the case of horizontal motion the flame distortion can only be due to the effect of gravity; the test equipment was the same in both cases except that the tube position was moved through 90°.

To compare the ignition velocity of a mixture determined by this new method with the normal ignition velocity of the dynamic method, a series of tests with the Bunsen burner was undertaken. The test arrangement was similar to those customary for dynamic measurements.

The maximum ignition velocity obtained with the Bunsen burner was 0.7 m/sec. for a mixture with 21.7% gas. As might be expected, the normal ignition velocity is a fraction of that measured in the tube. The measurements on the Bunsen burner and in tubes might coincide if a plane flame front, perpendicular to the tube axis, should obtain in the tube. We have seen however that in the tube the flame front is always arched. The shape and size of the flame surface are determined by additional flows, produced by that flame, combustion and velocity distribution in the tube.

The above represents an attempt experimentally to determine the effect of the flow turbulence on the ignition velocity of a gas mixture.

It proved that the ignition velocity is not directly dependent on the Reynolds number, this being the measure of flow turbulence; rather we find an exponential function of the gas speed and a direct function of the tube diameter. The maximum ignition velocity was found to be 10.5 m/sec., i.e. of an order comparable to that of a slow running gas engine.

Fig. 1 - Test equipment.

Fig. 2 - Diagram.

Fig. 3 - Ignition velocity and mixture strength in a 20 mm. horizontal tube.

Fig. 4a - Ignition velocity and fresh gas speed.

Fig. 4b - Ignition velocity in terms of tube diameter.

Fig. 5 - Ignition velocity in terms of Reynolds number.

Fig. 6 - Flow conditions near the flame.

Fig. 7 - Flame in horizontal and vertical tube.