DISCUSSION

(pps. 141 - 151)

E. Schmidt. Unger's tests were carried out in clearly defined conditions. He utilised the well known condition of the fully developed turbulence in the tube, to explain the importance of turbulence on the flame velocity.

I shall report on tests made in Brunswick on the propagation of flames in an elongated bomb fitted with observation windows. Fig. 1 shows the bomb, which measures 1 m. length and 24 x 24 mm^2 clear cross-section, with 4 windows on the opposite sides, allowing ~~the~~ combustion to be observed both in its own light and with Toepler's Schlieren method.

From the many tests, here are three photos by my co-worker H. Steinicke on propane-air mixtures in the light of the combustion at 1 atm. with an air ratio $\lambda = 0.8$ (Fig. 2 and 3) and $\lambda = 1$ (Fig. 4). The windows are photographed on a film, which moves at constant speed perpendicularly to the longitudinal axis of the bomb. A flame progressing in the bomb produces an inclined light track, the gradient of which relative to the direction of motion of the film gives the measure of the flame velocity. Fig. 2 shows the combustion in the bomb open on one side, with ignition at the open end. This is the simplest case of combustion; the burnt gas can flow off freely, whilst the unburnt portion is not subject to a noticeable pressure increase and remains at rest, apart from certain oscillations, to which I shall refer later. The illustration shows two similar tests on the same film. The bottom edge of the film corresponds to the open end of the bomb, where the ignition is effected; the top edge to the closed end. The dark horizontal stripes correspond to the 3 bars between the bomb windows. The additional narrow breaks in the flame tracks served to differentiate the tests. The flame begins to flow in the bomb at the bottom left, with a low very constant speed of 0.55 m/sec. Its light trace is rather undulated by oscillations which, as shown by their frequency, correspond to the basic oscillation of the gas column oscillating as an open ended pipe (~~bomb length = $\frac{1}{4}$~~ wavelength). As the flame proceeds, the frequency of this basic oscillation goes up, because the bomb gets filled in a growing measure by hot gas, in which the sound velocity is higher. Near the bomb centre the amplitude of the oscillations increases steeply, whilst the flame velocity rises to about 5 m/sec. for the following reasons: Eddies are released on the walls of the tube by the oscillating motion of the gas column; the gas mass is rendered turbulent and the effective flame surface is enlarged. Towards the closed end the flame velocity decreases again, because here the amplitude of the oscillation diminishes and with it the excited turbulence.

The combustion is entirely different with the ignition at the closed end of the bomb. Fig. 3 shows a photo likewise taken with a propane-air mixture with $\lambda = 0.8$. The mean flame velocity is considerably higher, because the expansion of the burnt gas pushes forward the unburnt portion. The Reynolds numbers in this case are far above the critical value, with the result that vigorous turbulence appears after a short time. The observed flame velocity is therefore steeply increased by turbulence above the value corresponding to stationary or laminar gas flow; it contains moreover the very high speed of the gas motion. The striking step of the light track at the end of the first window could not be explained with certainty. The fan-like light traces, originating from the main flame front, are subsequently burning groups of eddies of the boundary layer, which were not immediately burnt, because they lay on the cold wall of the bomb, were loosened by the eddying and ignited by mixing with the hot combustion gases. Their backward motion is a result of the cooling of hot combustion gases, which sucks back the burnt gas in the tube.

Fig. 4 shows the combustion in a sealed bomb, with 3 similar tests on the same film. The flame velocity has its maximum at the start and drops steeply at the combustion end. Initially the displacement velocity is very high, and so is the Reynolds number which characterizes the turbulence; towards the far end of the bomb they both decline steadily to zero. At the combustion onset the waves of the light track are due to periodic vortex release, their frequency is much lower than the natural frequency of the bomb content and its order of magnitude well coincides with the vortex frequency observed in the tube entrance flow.

In the course of very many tests with various mixture ratios, the mean flame velocities were measured in the 1 m. test bomb, and divided into: normal combustion velocity, such as occurs in the mixture at rest with a plane flame front, increase due to displacement and increase due to turbulence.

Fig. 5 a to c show the results for a propane-air mixture of 1 atm. initial pressure in terms of mixture strength. Fig. 5 a and b apply to the bomb open at one end, with ignition at open or closed end; Fig. 5 c to the sealed bomb. In the comparison of the graphs, note that in Fig. 5 b the velocity scale is reduced to 1/10, to allow the clear representation of the high flame velocities. The curves show the great influence of turbulence and displacement on the flame velocity; tests in different conditions however can only be compared cum grano salis. In the combustion chamber of an engine the combustion proceeds as in a sealed bomb; the only difference is that after admission the mixture is in a highly turbulent state even before the ignition, with the result that the flame velocity is initially boosted by turbulence.

My co-worker, U. Neubert, took Schlieren photos of the same bomb, by the light of a quadruple spark gap; each of the four sparks discharging simultaneously illuminated one of the windows. By means of Schlieren templates instantaneous photos were taken on four films moving at constant speed. High-capacity condensors allowed up to 100 quadruple sparks and as many exposures. The time interval between exposures corresponds to their spacing on the film.

Owing to the peculiarity of the spark system, the exposure time at the beginning and end of a series is larger than in the middle. This variable speed is no drawback, as it allows us to have the most interesting part of the process in the region of closer sequence.

Fig. 6 shows these exposures taken on a bomb open at one end, ignition at the open end, with a $\lambda = 0.8$ propane air mixture at atmospheric pressure. The strip at the right shows exposures of the first window, at the left are exposures of the second window. The two strips do not refer to the same ignition, but the tests are so uniform that the left strip can be considered as the continuation of the right one. For each strip the time interval between two subsequent frames is marked on the left, and the flame velocity calculated from it and from the flame progress on the right. The ignition occurs at top right in the right hand strip. The flame moves from right to left, and the flame front shows peculiar swellings due to single large groups of eddies. These rather slow movements are the result of the ignition always occurring at one point and not simultaneously over the whole cross-section. As the flame progresses, the swellings converge to a uniform flame front, although they reappear in the second window, presumably excited by protruding edges of the glass plates. The exact flame velocities are of the order of 1 m/sec. and show periodic variations due to superimposed oscillations of the gas column, as in Fig. 2. Apart from these oscillations the flame velocity is nearly constant.

Fig. 7 shows exposures taken on the same mixture in the same open bomb, but for the ignition at the sealed end; at the right of the frames is marked their interval in milliseconds. The flame velocity is much greater, because the burnt gas displaces the unburnt and pushes it forward. This flow of the unburnt gas attains such high speeds that the motion becomes turbulent. It is therefore clear why from the third frame of the second window turbulence sets in, which advances gradually from the wall to the middle of the tube. It is even possible to estimate the size of the groups of eddies. In the third window the head of the flame front too has become turbulent, the flame velocity rises and in the first exposures of the fourth window it reaches very high figures of the order of 100 m/sec. In the evaluation of the flam velocity it should be noted: if a rather long gas column is already burnt out, the hot gases collect on the wall as a result of cooling, and the burnt gases behind the flame front move again backwards.

As you see, the flame propagation in tubes is a very intricate problem. Flame velocity measurements made with different methods which do not allow us to follow the details of the process cannot be compared.

Busomann. According to Unger, turbulence occurs almost exactly at the critical Reynolds number, i.e. 2.400. Considerable precautionary measures were necessary in the determination of the critical Reynolds number. But Unger not only introduces air in the tube, he also mixes it with gas. Has he used special devices, such as baffles, to avoid disturbances?

Unger. In my case not always the same gas velocity corresponds to a Reynolds number of 2,400, because air pressure and temperature vary. Thus on different days I found different velocities for the same Reynolds number. A logarithmic plotting of the ignition velocity against the gas speed gave two clear lines, which intersect at a speed corresponding to Reynolds number 2,400.

The two gases were mixed in a mixing chamber, which produced a considerable disturbance of the flow. A flash-back safety device consisting of a series of fine mesh wire nets behind the mixing chamber provided a good rectification of the flow.

The initial distance between non-return grid and test gap was at least 150 diameters,up to 300 d. for small tubes; initial tracts of 80 d. did not give well reproducible results.

Damköhler. We too found that the initial distance must measure at least 150 d. In my earlier tests with the Bunsen burner method, I found the change to turbulence at 2,300 exactly. This was easy to ascertain because the laminar Bunsen flame burns silently and the turbulent one hisses. Unger has shown us a graph on which the flame velocity was plotted against the mixture strength; from this he concluded that the turbulence affects the ignition limit. This is possible but not absolutely certain, because the test points have a certain scattering and it can well happen that the top curves too will drop to zero at the ignition limits. This proves conclusively that the top curves must have a stronger lateral inclination than the bottom ones. It is however still possible that there is a secondary turbulence effect on the ignition limits, causing the burnt gas to be whirled in the unburnt by turbulence; whereby the gas would have a different composition at the moment at which it burns. This manifests itself by affecting the ignition region.

Unger. In tests at gas speeds 2 to 5 m/sec. on mixtures with about 16% gas I always reached satisfactory ignitions. At speeds up to 18 m/sec., however, with the same mixture, combustion could no longer be obtained even with multiple ignition.

Lindner. The propagation direction of the flame is always given by the normal to the flame front; the propagation velocity must therefore be measured perpendicularly to the front. The photos show however that the flame front is partly oblique, owing to the unsymmetrical flow. If the propagation is measured in the direction of the tube axis, as was done here, the velocity appears greater than its true value. This point must be considered when evaluating the results. The mass conversion velocity, in H. Mache's meaning, is found correctly from the velocity along the tube axis, because here the combustion surface is exactly in front of the tube cross section. Comparable results on turbulence effect can however be obtained by starting from the effective velocity perpendicular to the front and not from the mass conversion velocity.

Schlieren photos of the flame front which I took in a bomb showed a growing subdivision of the front surface due to blister-like bulges, presumably caused by turbulence effects. The front is then composed of a great number of small spherical caps; the consequent surface enlargement increases the flame velocity in proportion. To what extent this is due to the surface expansion or to pure turbulence, i.e. mixing and exchange processes in the gas mass, cannot be determined by measurement because these processes take place in very narrow spaces.

E. Schmidt. In all Unger's tests we find considerable turbulence and therefore strongly fissured flame fronts. It is difficult to talk of a single flame front and of a normal propagation velocity, as in the Bunsen burner. The importance of the tests remains however the same, because in most practical cases the interest lies in this flame propagation accelerated by turbulence.

Damköhler. As could be expected it was found that this flame velocity increase does not only depend on the Reynolds number. Turbulence cannot be characterized by one quantity, but by at least two, e.g. Prandtl exchange number and mixture path (?). It might be fluctuating velocities and mixture path, but there are always two quantities. We could also put it this way: one should differentiate between coarse and fine turbulence bulges. Both can have, even over large distances, translation capacities of equal value, i.e. the same exchange number; but in their structure they are different: one turbulence is coarse with a large mixture path and small velocity fluctuations, the other is fine with a small mixture path and great velocity fluctuations.

E. Schmidt. Work goes on in various quarters and with different methods on the combustion problems. On one hand physical-chemists try to explain the processes with theories and to frame them into a complete theoretical system; on the other the engine designer, whom the characteristics of the combustion process prevent from fully utilizing the constructional possibilities to increase the output of his engines, tries to find his ~~own solutions.~~ Naturally he clings to the concrete single task and cannot select the test conditions as freely as the scientist, who is only concerned with general theories. Both are necessary and must mutually complete each other; it is the purpose of our committee to establish connections and bridge gaps. It is just in the field of combustion that we are confronted with much unmapped territory. From the standpoint of production, it is lucky that the pioneers of the combustion engine did not know how little they knew; otherwise they would have lacked the boldness and candour of ignorance, which produced the combustion engine as well as the steam engine ahead of all theory. That should however not keep us from following the phenomena to their origins and trying to explain them with the scientific basic laws. Only thus is it possible to attain the best in practice. Many more tests are needed. In my opinion however we should be more careful in interpreting test results, rather than build up far reaching conclusions and suppositions on limited information. This meeting swayed on the side of physical chemistry. I should ask the engine designer not to tire in the common pursuance of the problems of combustion, even if the road to cover is still long, until the physical chemist can really stretch out his hand to him.

Fig. 1 - Test bomb with windows.

Fig. 2 - Combustion of a propane-air mixture of $\lambda = 0.8$ in the bomb open on one side, with ignition at the open end.

Fig. 3 - Combustion of a propane-air mixture of $\lambda = 0.8$ in the bomb open on one side, ignition at the closed end.

Fig. 4 - Combustion of a propane-air mixture of $\lambda = 1$ and 1 atm. initial pressure in the closed bomb.

Fig. 5a- Bomb open at one end. Ignition at open end.

Fig. 5b- Bomb open at one end. Ignition at closed end.

Fig. 5c- Sealed bomb.

Fig. 5 a - c - Distribution of the visible flame velocity.

Fig. 6 - Schlieren exposures of the flame front in bomb open at one end, ignition at the open end, with $\lambda = 0.8$ propane-air mixture.

Fig. 7 - Same as before, but for ignition at sealed end.