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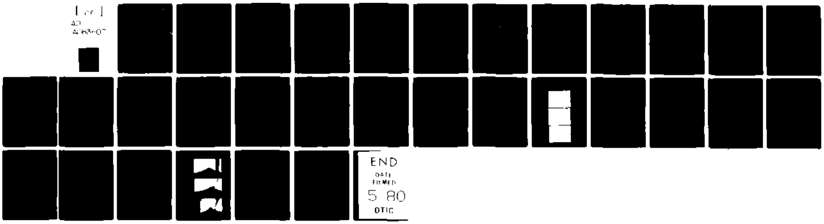

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INFLUENCE OF VARIOUS PARAMETERS ON INITIATION, STABILITY, AND LIMITS OF DETONATIONS

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ACCELERATION OF SPHERICAL FLAMES

INFLUENCE OF ORIFICES IN THE FLAME PATH

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Experiments on the influence of orifices on flame acceleration have been carried out with different hydrocarbon air mixtures in plexiglass ring metal tubes. Quantitative data could be obtained by pressure pickups and smear camera photographs.

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Part I

INFLUENCE OF ORIFICES ON THE INITIATION OF DETONATIONS IN SHORT TUBES

INTRODUCTION

It is well-known that obstacles in the path of a flame can influence the propagation of the "flame front" drastically. These effects have been investigated in some detail, starting from Dixon, Laffitte[3] et al. In the experiments of Shelkin[1] a spiral was inserted into a tube which could give rise to a kind of process, which looked very similar to a detonation, the propagation speed, however, was below the Chapman-Jouguet value. The influence of bended wires as obstacles on the initiation of detonations has been investigated by Baumann[2] et al. These obstacles can reduce induction time and induction length for the onset of detonations strongly. These authors found also that induction time and length for the onset of a detonation is reduced, when the unburned gas has a certain degree of turbulence prior to flame ignition. Induction distance and time do correlate with the Reynoldsnumber of the unburned gas flow. If the effect of obstacles is put into this correlation, it corresponds to Reynoldsnumbers (based on tube diameter) which are very high ($>$ 100 000). The mode of action of these obstacles can be attributed to the generation of additional turbulence when this term turbulence is taken in a very general sense.

Above, the word flame front has been put in quotation marks because under the influence of obstacles the flame front needs no longer to be a continuously conected surface which separates burned and unburned gas at one well defined continuously moving site. Many different types of burning may arise behind the main flame front, thus increasing the rate of energy release in the system. This can formally be described as an increase of the effective burning velocity relative to the unburned gas. The main flame burning in a rapidly moving gas stream may, in an extreme case, just act as a moving match.

Very efficient turbulence production is observed in jets (or behind corresponding obstacles). The fluctuation velocities can reach more than 20% of the maximum flow speed. Therefore, even at moderate driving pressures fluctuation velocities of 50 m/s or higher can be achieved.

In early experiments Wheeler put several plates with circular orifices in his flame tube. He observed flame speeds - in a laboratory coordinate system - of more than 400 m/s for CH_4-air mixtures. The combustion process never accelerated into a detonation.

In our experiments with spherical flames reported earlier, there was also no transition to detonation in mixtures with air and up to three consecutive grids, even for C_2H_4-air or C_2H_2-air mixtures. If the air was slightly enriched with oxygen, however, the situation could change dramatically. In a plot of the flame acceleration across the grid as a function of the Reynoldsnumber for low Reynoldsnumbers the "oxygen enriched air" experiments followed the "normal air" experiments. At a certain oxygen content, however, they did not follow the "normal air" curves but α suddenly jumped up, a detonation started, practically immediately behind the grid.

In the period until July 1978 the influence of orifices on flame propagation has been investigated for "normal air" mixtures. It was of interest to see, when (at what O_2 concentration)this effect appearing in systems with spherical grids starts behind orifices, how orifices do influence the initiation of detonation when oxygen enriched air is used.

EXPERIMENTAL

The investigations for the initiation of detonation were carried out in round brass tube of 40 mm inner diameter, which was closed at the ignition end (see figure 1). The ignition section had a length of 500 mm while the downstream section was 1000 mm long. Between the two sections different orifices, preferably roundshaped, could be mounted. Before each experiment the tube was filled with the mixture to be tested. The concentrations of the different components were determined by calibrated capillary flowmeters and the tube was flushed at least 10 times to make sure a homogeneous filling of the apparatus. The starting conditions were always ambient temperature and pressure. In most of the experiments ethylene has been used as fuel. A few experiments have been carried out with hydrogen and methane as well.

The mixture was ignited by a weak spark supplied from a spark plug at the end plate of the ignition section. The pressure-time-dependence could be observed in both parts of the tube by pressure gauges (Type Kistler) mounted in the tube walls. The signals were monitored on an oscilloscope.

For velocity measurements three ionization probes were fixed in the downstream section of the tube. The distance between them was 450 mm, and the position of the first probe was 50 mm behind the orifice. The traces of these ionization probes were also recorded on an oscilloscope. Thus the (mean) velocity between the positions of the probes could be obtained easily.

In some experiments a downstream tube with 80 mm diameter was used because the previous experiments did show that the maximum pressure downstream the orifice is obtained, when the diameter of the downstream tube is about two times that of the driver section.

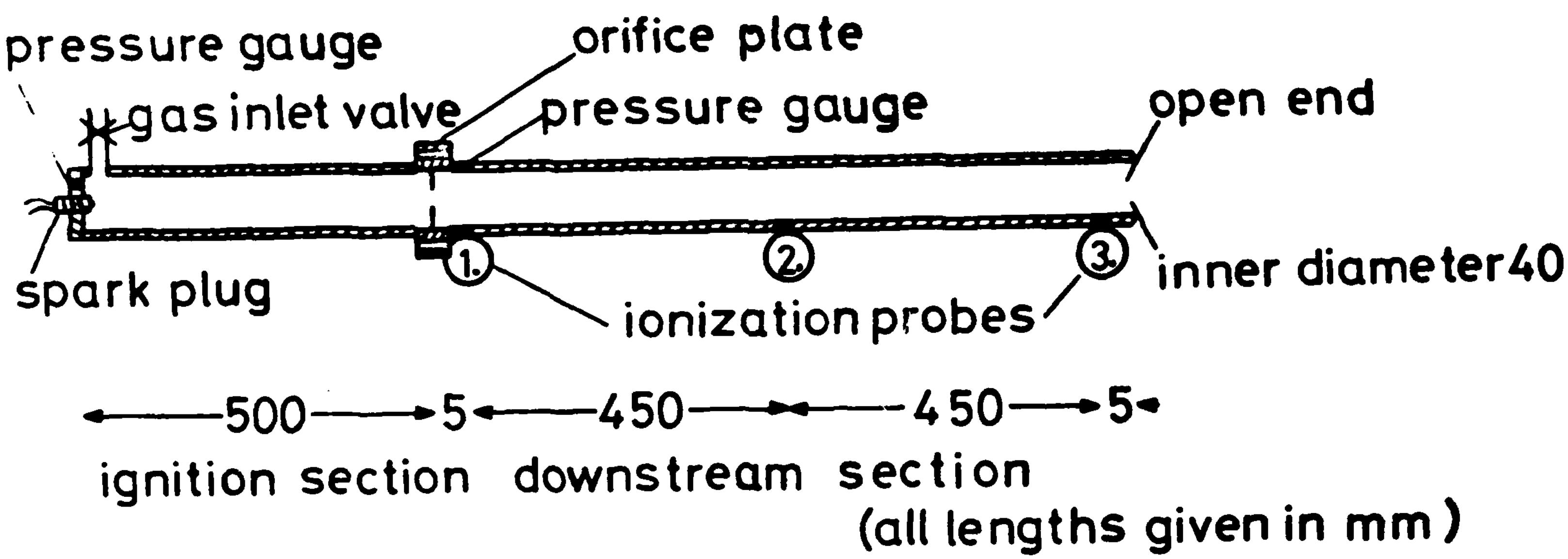

Fig.1 Experimental setup

EXPERIMENTAL RESULTS

The Influence of the Flame Velocity

In the spherical-grid-experiments various fuels have been used in order to have an independent variable for the Reynolds-number and in order to check the influence of the laminar flame speed.

For the same reason the influence of orifices was investigated for various fuels. The experimental set up was described above (see also Scientific Report from 1978). Fuels used - always stoichiometric mixtures in air - are, CH_4, C_2H_2, C_2H_4, CS_2 and H_2. The orifices were varied until the one was found which caused the highest downstream pressure. This required a large number of experiments which shall not be given here in detail.

Fig. 2 show the maximum overpressures achieved for the different fuels, plotted as a function of the laminar burning velocity Λ of the corresponding fuel-air mixture.

In a first approximation these results can be described by a straight line with a slope

$$\frac{dp}{d\Lambda} \approx 0.035 \text{ bar sec cm}^{-1}$$

This straight line is a striclty experimental result and the absolute value $\frac{dp}{d\Lambda}$ may well depend on the size of the experimental equipment, as will be shown later in this report.

A theoretical interpretation is not easy because there are many effects which play a role. An increase in Λ means an increase in the mean flame propagation speed in the driver section, higher pressure, higher speed of the jet, higher fluctuation velocity caused by the jet and therefore higher turbulent flame speed $\Lambda_{turb.}$

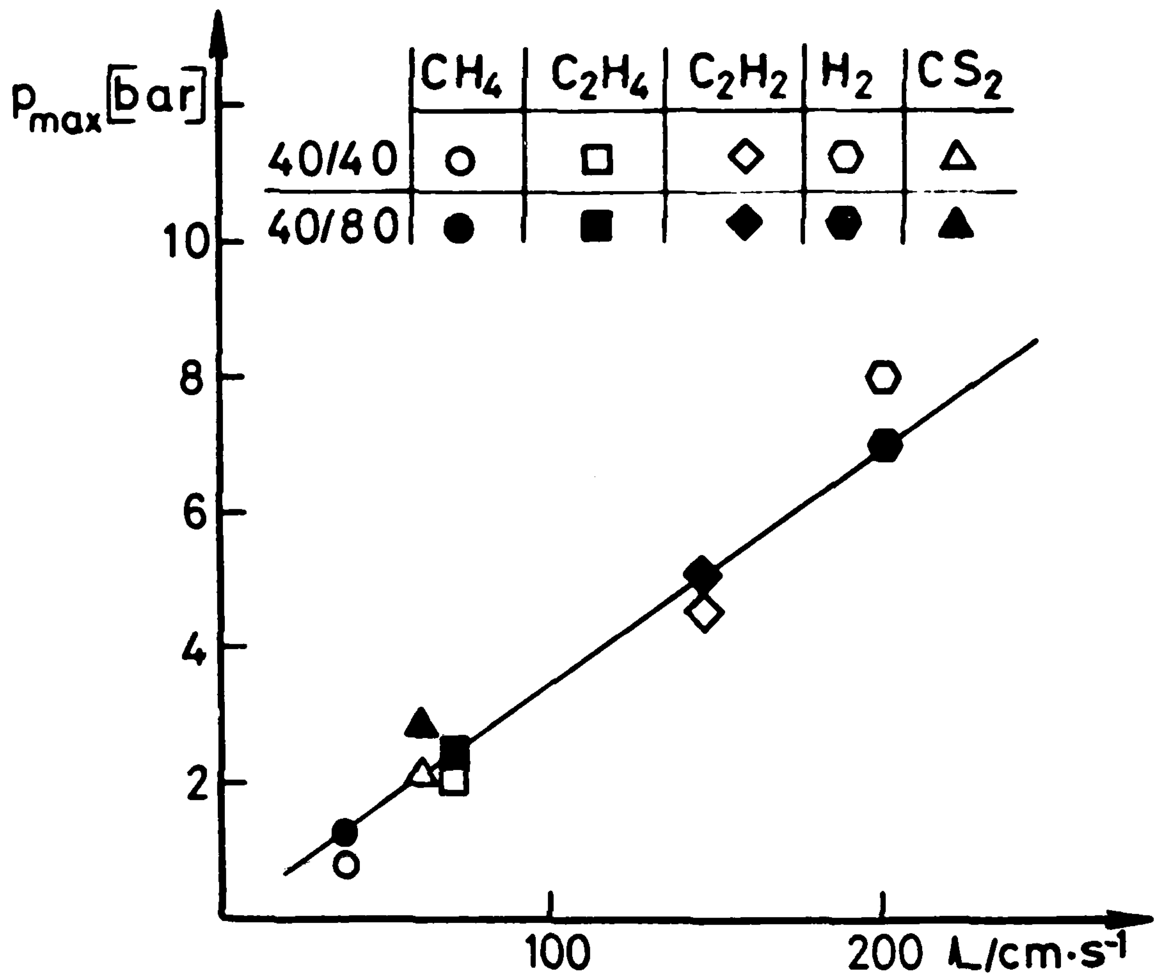

Fig. 2 Maximum overpressure for various fuels as a function of the laminar flame speed of the mixture

This is one quantity, which determines the maximum pressure downstream. In an unconfined downstream system, one would expect a nonlinear increase of P_{Max} with Λ with absolute pressures being lower than the ones measured here. Due to the confinement however, pressure release is practically one-dimensional while the flame propagates, at least for a short but important period forward and backward.

The Influence of the Oxygen Content of the Mixture

Experiments with various oxygen concentration in the "air" have been performed with C_2H_4 and CH_4 as a fuel.

For each orifice the amount of nitrogen in the mixture was changed within a certain regime. Fuel and oxygen were always present in stoichiometric compositions. The whole tube was too short (ratio length to diameter L/d = 37.5) to give an acceleration to detonation without an orifice mounted inside. In the tube with no obstacle the ethylene-micture with the lowest nitrogen content of 37.5% N_2 gave a velocity of about 220 m/s at the open end of the tube. The overpressure recorded in this case was approximately 1.8 bar. (Measurements with lower concentrations of nitrogen could not be made, because the electrical noise of the ignition disturbed the signals of the ionization probes).

When orifices were placed inside the tube the mean velocity achieved in the ignition section was even smaller. Values for the determined mean velocity $\bar{v}_{i.s.}$ for different orifice diameters are plotted in figure 3 as a function of the nitrogen concentration.

For orifice diameters from 10 to 40 mm the mean velocities in the driver section scatter to some extent. We therefore do not make a distinction between these orifices. The curve for the smaller orifices (6 mm diameter) lies definitely lower than the points for the other orifices, correspondingly the pressures in the driver section are higher. In the same figure the laminar burning velocities for stoichiometric ethylene-oxygen-nitrogen-mixtures are plotted as a dashed line. The real value of Λ is 1/50 of the number shown in fig. 3. To a first approximation the dependence of the mean velocity in the driver section and that of on the nitrogen content in the fuel is the same, the lines run parallel at least approximately.

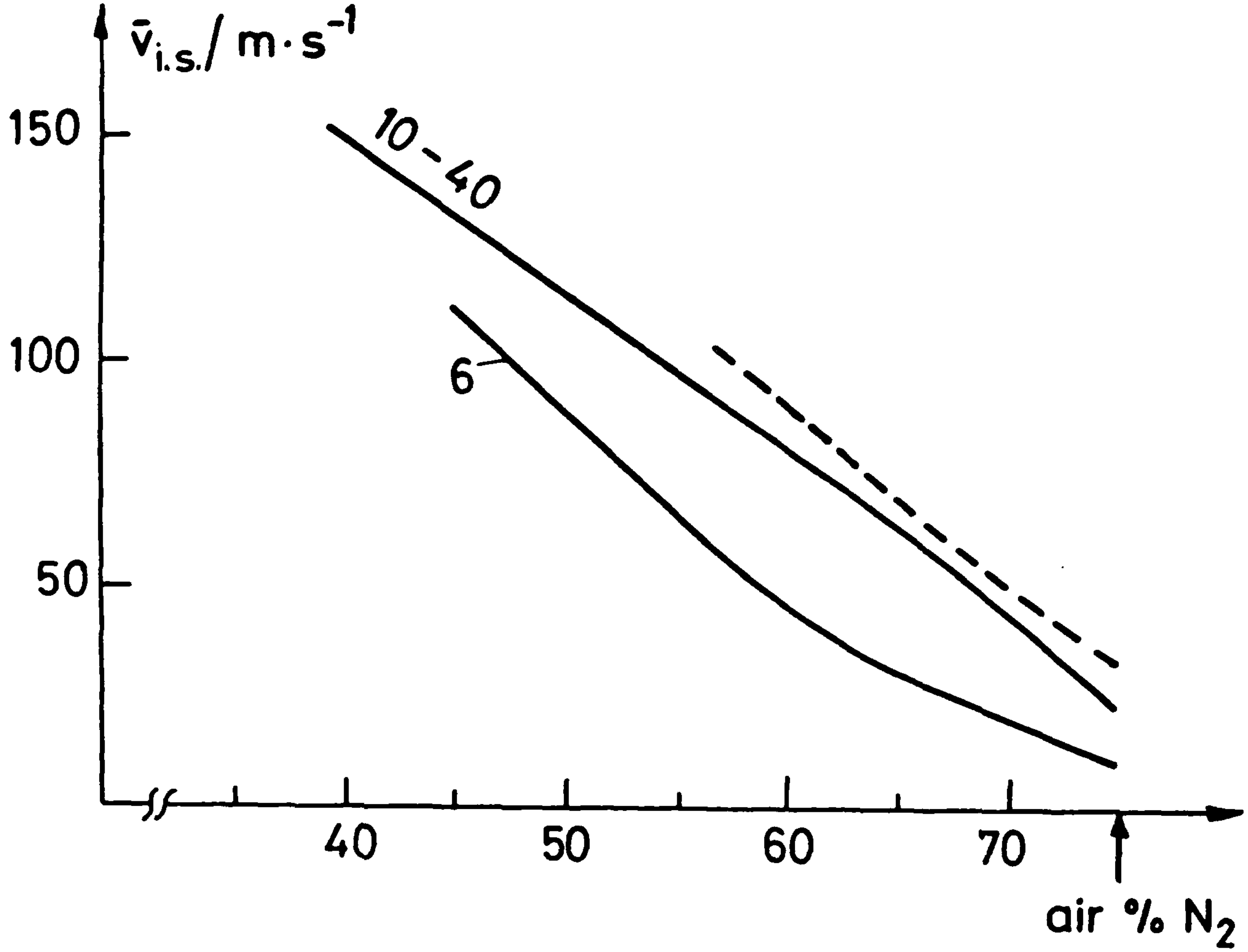

Fig. 3 Mean velocities in the driver section as a function of the N_2 content in the "air"; parameter: orifice diameters

The ratio between $\bar{v}_{i.s.}$ and Λ of about 40 - 50 does not seem unreasonable and is in agreement with earlier photographic measurements of $\bar{v}_{i.s.}$. The expansion ratio is close to 8 so that already for a laminar flame a factor of about 16 to 20 is expected. Photographs do show, that the flame is accelerated by wall turbulence towards the orifice.

The maximum overpressures, registered close to the orifice on the downstream side for stoichiometric C_2H_4-O_2-N_2 mixtures are shown in Fig. 4. Starting from air the maximum pressure increases, slowly at first and than stronger towards lower nitrogen content. With 40% N_2 there is definitely a detonation starting very close to the orifice. In the N_2 concentration range from air to 65% N_2 the increase of pressure again correlates with the laminar flame speed of the mixtures and for $\frac{dP}{d\Lambda}$ a value very similar to that for air mixtures is obtained.

How the process proceeds becomes more obvious if one compares fig. 4 with fig. 5. Fig. 5 shows the mean flame speeds measured between the ionization gauges 1 and 2 (V_{12} full line) and 2 and 3 (V_{23} dashed line), in the first and second 50 cm of the tube. These tow sections are filled with mixtures in somewhat different turbulence state. Close to the orifice the turbulence is essentially that generated by the orifice flow, and because about 80% of the unburned gas from the driver section are blown through the orifice unburned, about the same amount is blown out of the open end of the driver section so that the turbulence close to the open end is influenced strongly by wall turbulence.

Fig. 5 shows the two mean velocities v_{12} and v_{23} have the same value at a given N_2 concentration. Towards higher N_2 concentrations v_{23} becomes smaller than v_{12}, the flames decelerate with increasing distance ~~from the~~ orifice - as mentioned above, the tube is to short for the development of a detonation solely by wall turbulence.

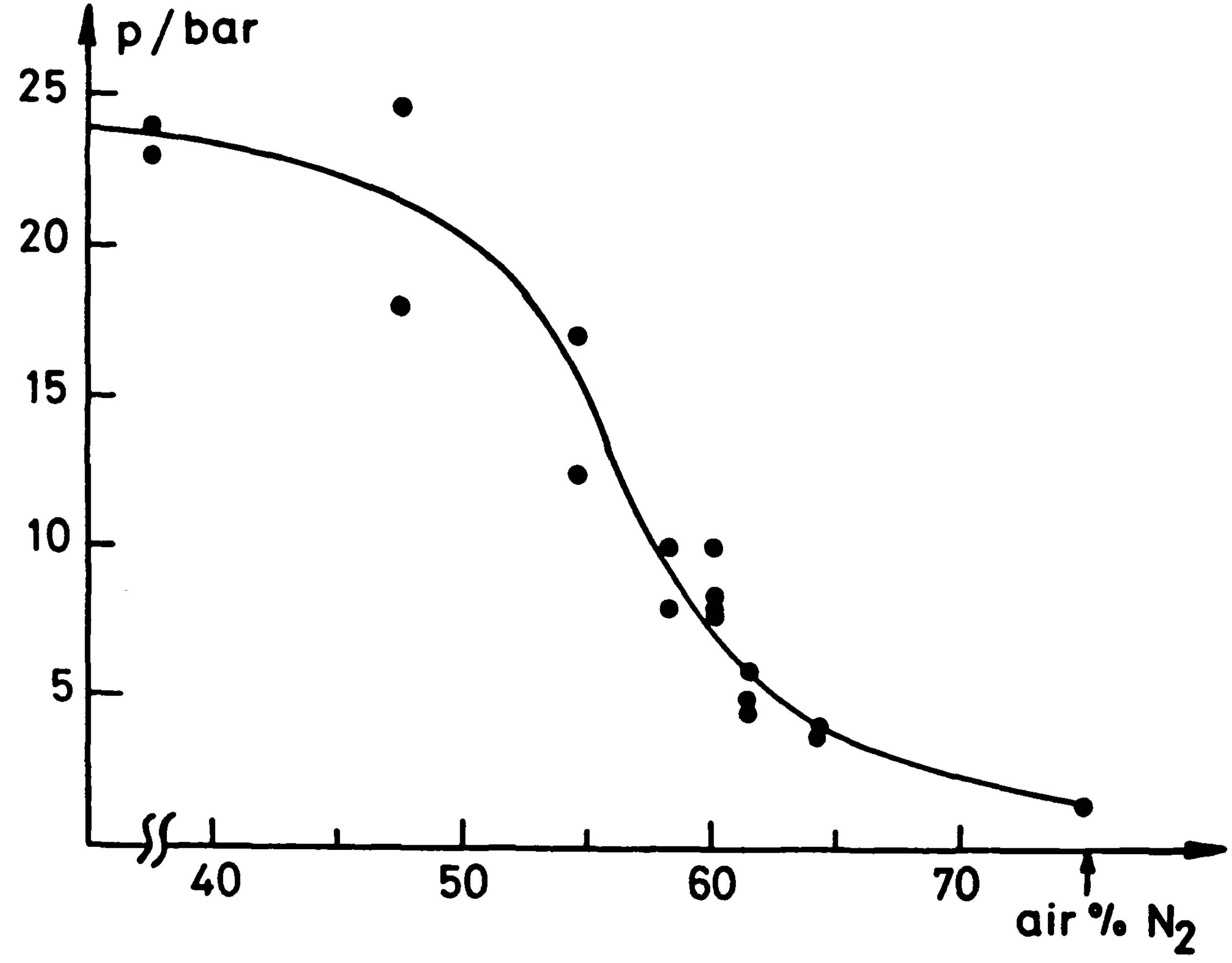

Fig. 4 Maximum overpressure for $C_2H_4-O_2-N_2$ mixtures

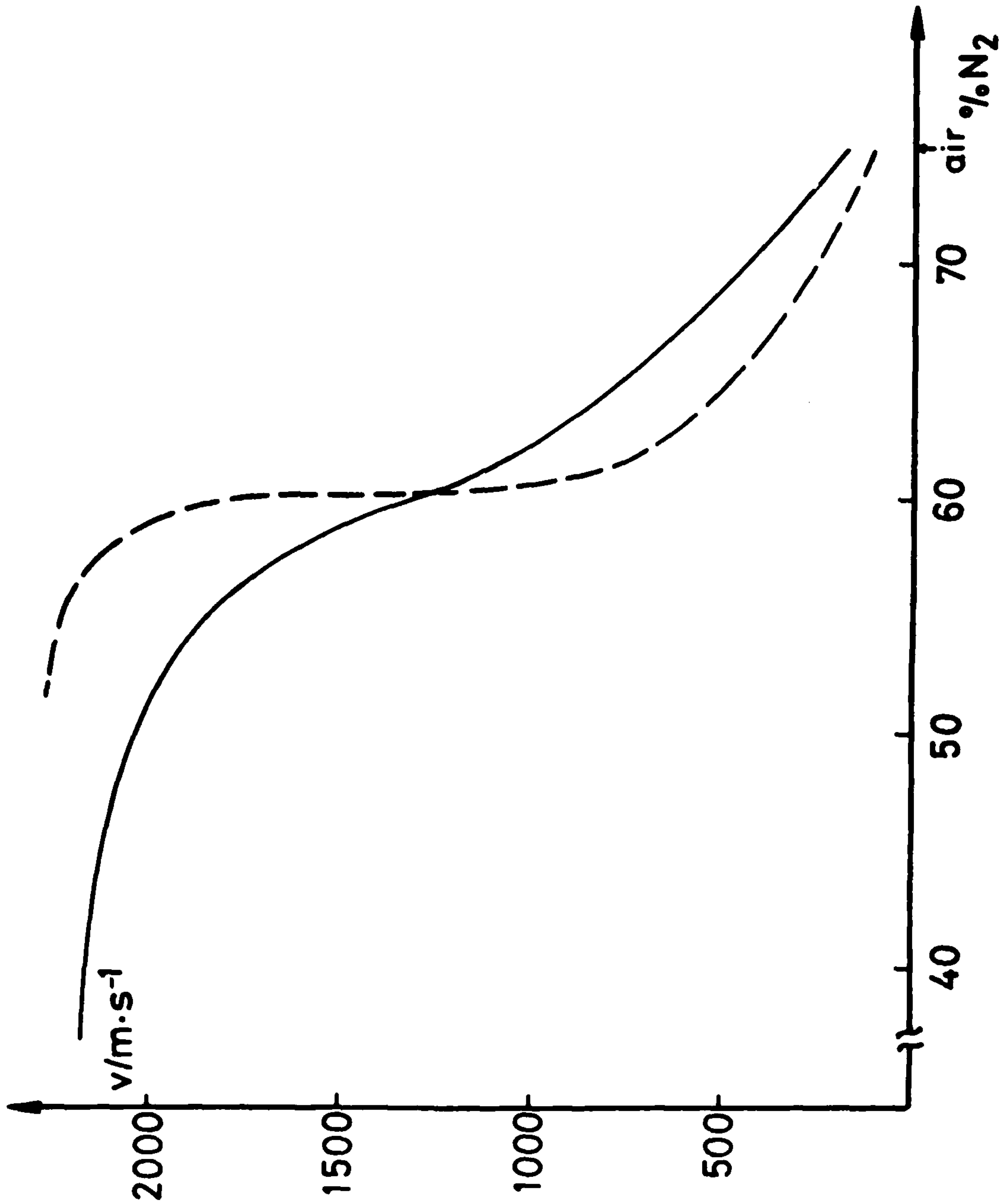

Fig.5 Mean flame velocities in the downstream section

Towards lower N_2 concentrations the flame apparently accelerates downstream of the orifice and develops into a detonation under the influence of the flow conditions generated by the orifice. Apparently the N_2 concentration, at which the two mean velocity curves cross, indicates the limit for transition to detonation. For the experimental condition described the laminar flame speed of the mixture would be Λ = 1.8 m/sec and therefore well within the line of fig. 2.

A comparison of fig. 4 and 5 shows the pressure measured alone can easily lead to a incorrect picture. At mixtures with a N_2 content around 40% the detonation starts apparently close to the orifice with some larger fluctuations towards higher N_2 concentrations. At about 55% N_2 transition takes place at or close to the end of the first section of the downstream tube and therefore the pressure at the orifice does not reach the detonation pressure value anymore.

Similar experiments have been performed for orifice diameters of 6 and 10 mmm. The values for $\frac{dP}{dc_{N_2}}$ and for the $\frac{dP}{d\Lambda}$ are very similar for the "no detonation" side of the curves. They therefore fit also into curve 2. A slight variation appears for the transition to detonation characterized by the point where $v_{12} = v_{23}$ with orifice diameter.

Orifice diameter	6 mm	10 mm	20 mm
c_{N_2}	53%	56%	60 %

Table I: N_2 concentration c_{N_2} at the limit for Onset of detonation for various orifice diameters

Experiments with Methane

The same experiments as for C_2H_4 have been performed for $CH_4 - O_2 - N_2$ mixtures with a 10 mm orifice. Fig.6 shows the mean velocity in the driver section as a function of the N_2 concentration. The absolute value of Λ = 40 cm/sec and $d\Lambda/dC_{N_2}$ $\approx$ 5.67 cm sec^{-1} % N_2 are smaller than for C_2H_4 and the curve has a shape similar to that for the 6 mm orifice used for the C_2H_4 experiments.

The generated behaviour of the $CH_4 - O_2 - N_2$ mixtures is similar to that of the $C_2H_4 - O_2 - N_2$ mixtures and shall not be presented in detail here. The $\frac{dP}{d\Lambda}^2$ and the transition to detonation takes place for a N_2 concentration of 39%.

CONCLUSION

These experiments with O_2 enriched air do show, that in a partly confined situation an orifice can help to reduce the transition time and -distance into a detonation. Up to a certain enrichment with O_2 the maximum pressures attainable in the system used can be obtained from a simple relation between maximum overpressure and laminar flame speed of the mixture. The breakdown of this relation takes place at N_2 concentrations which are higher than in spherical systems. In order to obtain detonation close to the orifice a much lower N_2 ($<$40%) concentration has to be used. This case however can be considered as a situation where a detonation could start outside of an orifice in an outside completely unconfined system. It is to be expected that the critical N_2 concentration for such a process will depend to a certain extent on the size of the system in a sense that for a larger system the critical N_2 concentration becomes higher.

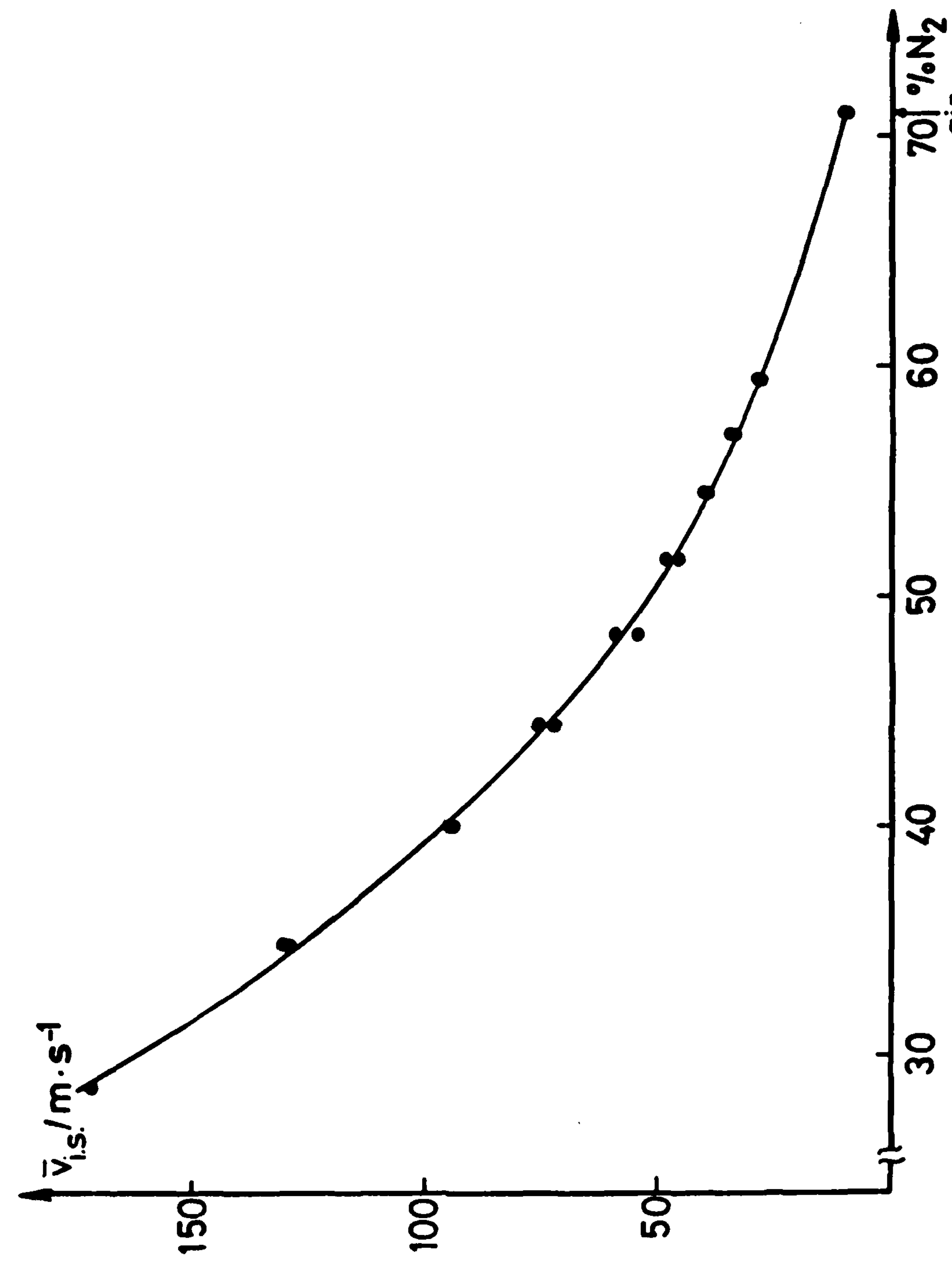

Fig. 6 Mean velocity in driver section for $CH_4 - O_2 - N_2$ mixtures

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Part II

FLAME ACCELERATION BY OBSTACLES

In the previous report the influence of orifices on the acceleration of C_2H_4-air flames in 40 mm diameter tubes has been reported for various downstream sections. In addition first results about experiments in larger tubes have been described. In this report more details about experiments with systems with larger dimensions can be given.

Scaling of the Driver Section

For the 40 mm tubes various orifice shapes have been tested and there was no distinct difference, except for very flat slits,between these orifices. It was therefore decided to use for the larger scale experiments only orifices with circular cross section.

Measurements of pressure in the driver section show that pressure increases and very often approaches a constant value until the flame reaches the orifice. In some cases, however, it continues to increase, in others it passes through a maximum and drops. (See Fig. II.1)

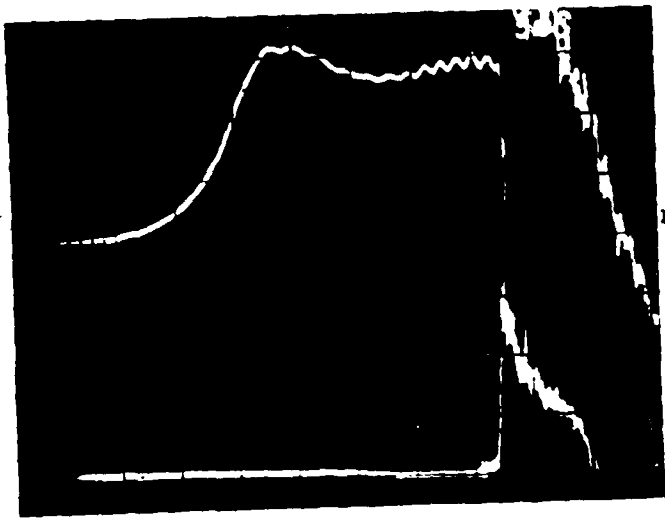
The continuous increase usually happens for very small orifices, for small values of the ratio of open to total area F_o/F_g, maximum appears for large F/F_o values; there are, however, exceptions.

In order to be able to compare measurements in tubes of different diameters, it is necessary to have comparable conditions. As reported last year, the pressure in the driving section in combination with F/F_o seems to be an important parameter.

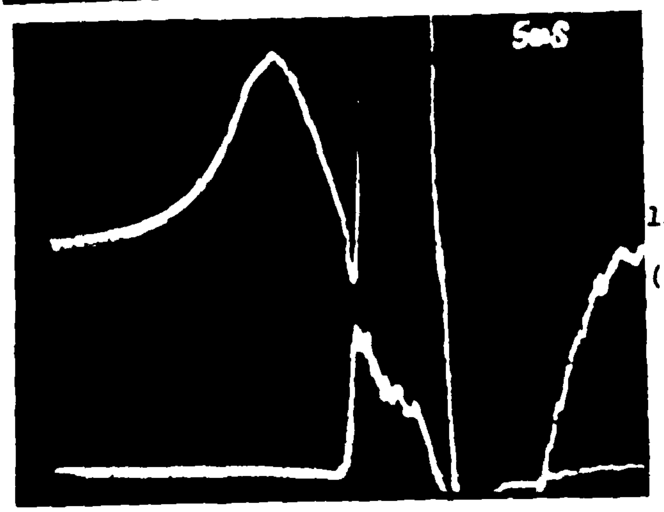
Pressure records and smear film camera pictures indicate that, after ignition, the flame burns and accelerates. This is more pronounced in experiments with large orifices than in those with small ones. When the flame comes close to the

Fig. II.1 Typical Pressure Records in driver section for 80/80 tubes (upper curves). The lower curves are pressure records in the downstream section (different amplification)

small orifice
(6 mm)



medium orifice
(20 mm)



large orifice
(40 mm)

orifice, its propagation is apparently influenced by the flow through the orifice.

The only property of the driver sections which can easily be varied is the length of the system. After some tests with driver sections of various length, it was decided to use those tubes which are shown in Fig. II-2.

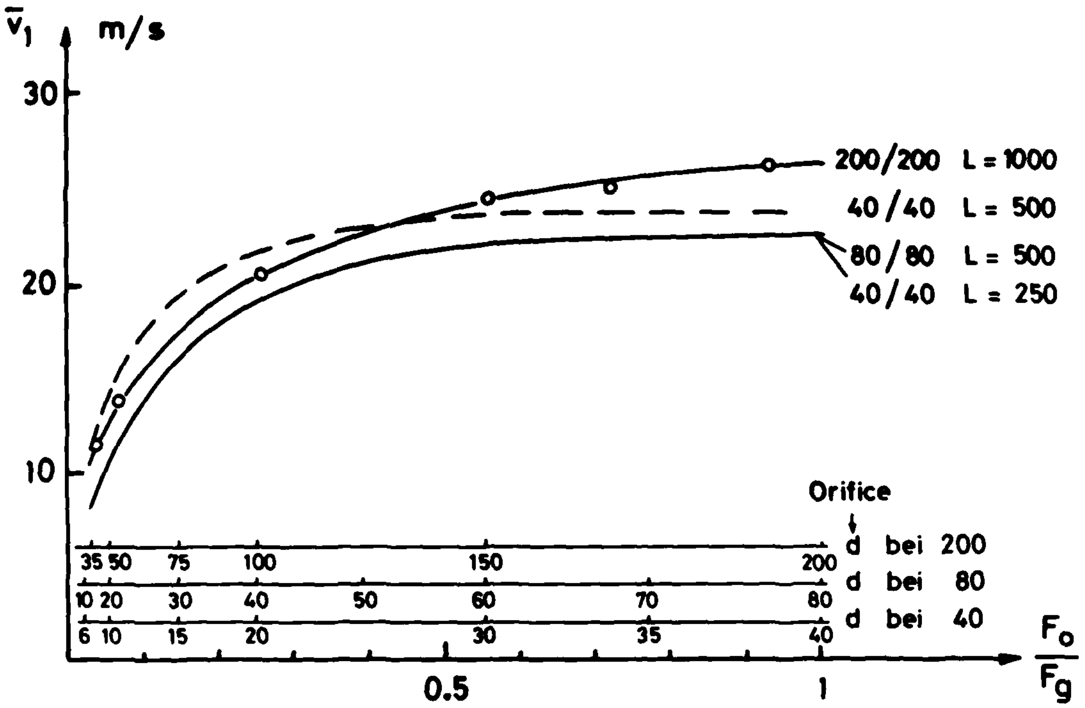


Fig. II. 2 Mean velocity of flames in driver section

For the 80 mm diameter, the length used was 500 mm, for the 200 mm diameter tube it was 1000 mm so that the diameter to length ratio was approximately constant. The volumes of the driver section used are given in the table below.

Table I   Tubes

Diameter mm	40	80	200	40
Length mm	250	500	1000	500
Volume liter	0.314	2.5	31.5	0.63

The mean velocities, taken from pressure records, in the driver section are shown in Fig. II-2 as a function of F_o/F_g and in addition as a function of the real orifice diameter for the corresponding tube diameter. For all tube diameters these curves show a similar shape, the velocity is low for small F_o/F_g values, and it becomes larger for increasing F_o/F_g. The curves look sufficiently similar for the various driver tubes to allow a comparison of the results. It should be noted that the time necessary for the flame to burn through the driver section for a given F_o/F_g increases with the length of the tube and the total volume of gas driven out of the driver section is for an expansion ratio $\rho_o/\rho_e \approx 8$ about 85%. Therefore, the volume of gas prepared by the jet increases with increasing tube diameter like the volume given in table I.

If one evaluates the flame speeds in the driver section from a smear camera picture, one realizes that the flame propagation speed increases when the flame approachs the orifice so that the flame speeds close to the orifice are always higher than the mean values.

As mentioned above, pressures have been measured in the driver section. The pressure records differ somewhat in shape. In order to simplify matters, the maximum pressure has been used as a characteristic quantity. These maximum pressures agree fairly well for the different tubes for a given F_o/F_g no matter what the shape of the pressure record looked like. They are shown in Fig. II-3.

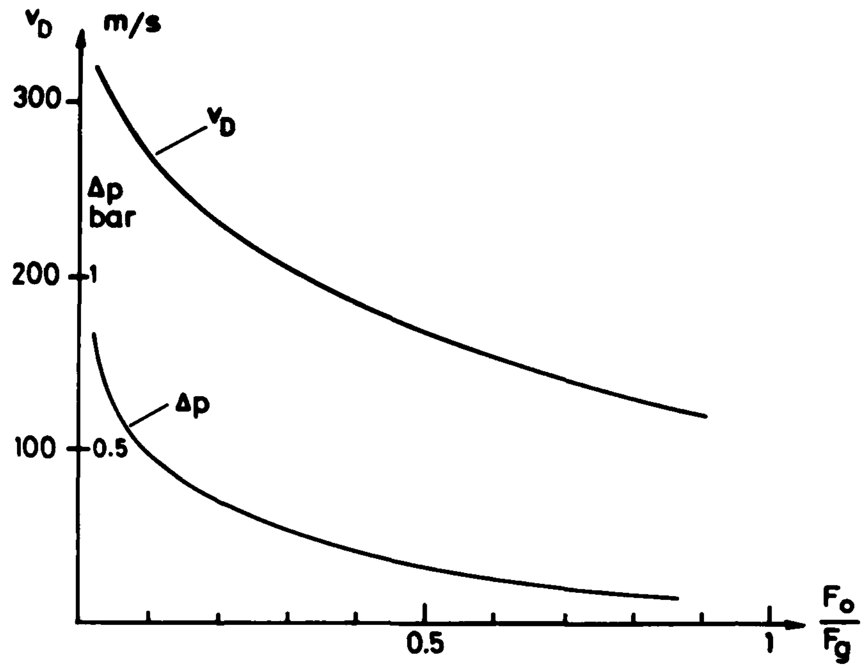


Fig. II. 3 Δp Maximum overpressure. Driver section for 40, 80 and 200 mm ⌀.
v_D Flow velocity througt orifice calculated from Δp

The overpressures Δp in the driver section increase with decreasing F_o/F_g as to be expected. For these pressures the flow speeds of the gas unburned through the orifice are also shown in Fig. II-3. These values have to be taken as upper bounds and they are definitely too high around $F_o/F_g = 1$ where about 30-40 m/s would be reasonable, the speed of the gas without obstacle. Towards small orifices, where the flow speed approaches sound speed, the values in the curve should be very close to the real values.

Observation in the Downstream Section

When the flame passes the orifice , burned gas starts to flow into the downstream section. Its velocity, at equal pressure, will be much higher than that of the unburned gas. After a short time interval (see Fig. 8 in report from last year) the pressure in the downstream section rises very rapidly to a maximum value and than decreases continuously. This pressure-time profile, taken at one place close to the orifice, is only one indication for the real process. Comparisons between the pressure-profiles obtained in tubes of different diameters have to be performed with great care.

The maximum pressures obtained in the downstream section are shown as a function of F_o/F_g in Fig. II-4 for the tube diameters 40/40, 80/80 and 200/200.

These curves show distinct differences towards small orifices and come close to each other when F_o/F_g approaches one. The 40/40 and 80/80 curves exhibit pronounced maxima at $F_o/F_g = 0.3$ and $F_o/F_g = 0.2$. For the 200/200 curve the maximum must be at values below $F_o/F_g = 0.05$. This curve must have a maximum like the others because at some orifice diameter the flame will not be able to pass and entrainment will be so rapid that reignition can no longer take place. In order to get an impression of the real orifice sizes, an additional

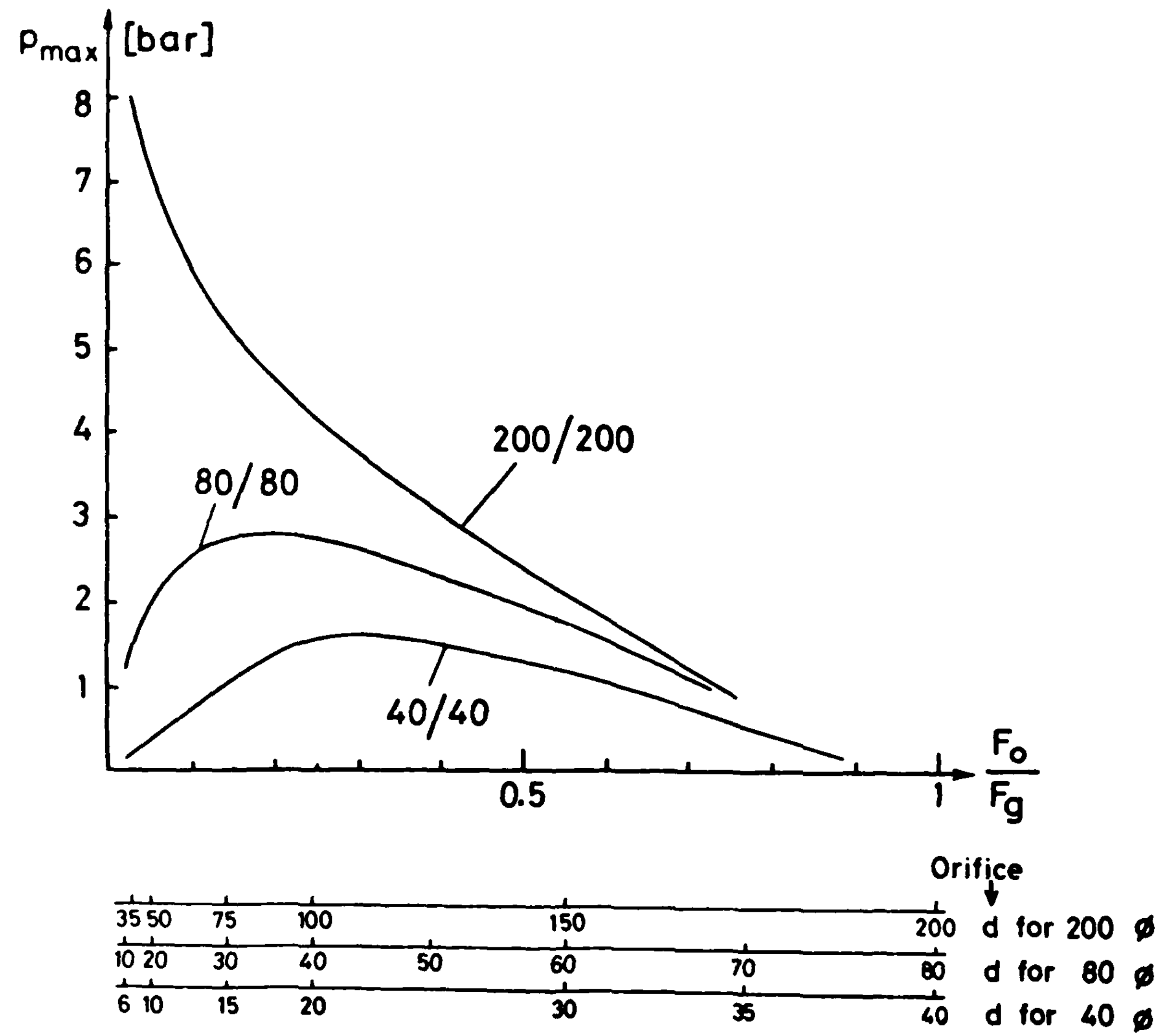


Fig. II. 4 Maximum overpressure in the downstream section as a function of F_o / F_g for various tubes. The dependence on the orifice diameters is also given scale is given below Fig. II-4 with the diameter of the orifices for the various tube diameters. It shows that the maximum pressures are obtained for orifice diameters around 20 - 30 mm.

The pressure records show that for small orifice diameter the pressure signal from the downstream explosion is hardly transmitted into the driver section, while for larger diameters one can very well recognize the explosion signal on the record of the pressure transducer in the driver section. This is important for the pressure release after the explosion. The rise time of the pressure signals is close to the time resolution of the transducers, in any case it seemed shorter than 1 ms.

Photographic Observations

Some observations of the flame spead downstream of the orifice have already been reported. If flame propagation through orifices is observed with a drum camera, one can realize that, at least for small orifices, there is a dark space and some distance downstream reignition takes place causing a flame to burn towards two directions, up- and downstream. Fastax camera pictures did show that in this case there seems to be one ignition kernel from which a flame propagates outwards. Smear camera pictures taken for the 200/200 tube, that means for larger size, did show a different situation however. (See Fig. 10 and 11 of the 1978 report) One observes a number of luminous traces which seem to merge and generate a rather rapid flame. For a 10 cm diameter orifice this reignition zone was about 50 cm long. These luminous traces belong to small burning gas volumes which become visible after they are ignited or when they are large enough. Apparently, these traces are carried along by the gas jet. The burning speed of these gas bubbles is not very high but the number is large so that the effective total energy release rate may be very high.

In order to see whether similar situations arise already for smaller orifices, smear camera pictures have been taken with high speed film in the 80/80 tubes with different orifices. For the 20 mm orifice, one can clearly realize these flame traces originating from the orifice side, mostly before the main reignition did take place at a distance X_i from the orifice. This looks somewhat different than on the fig. 10 and 11 in the 1978 report. Fig.II.5)

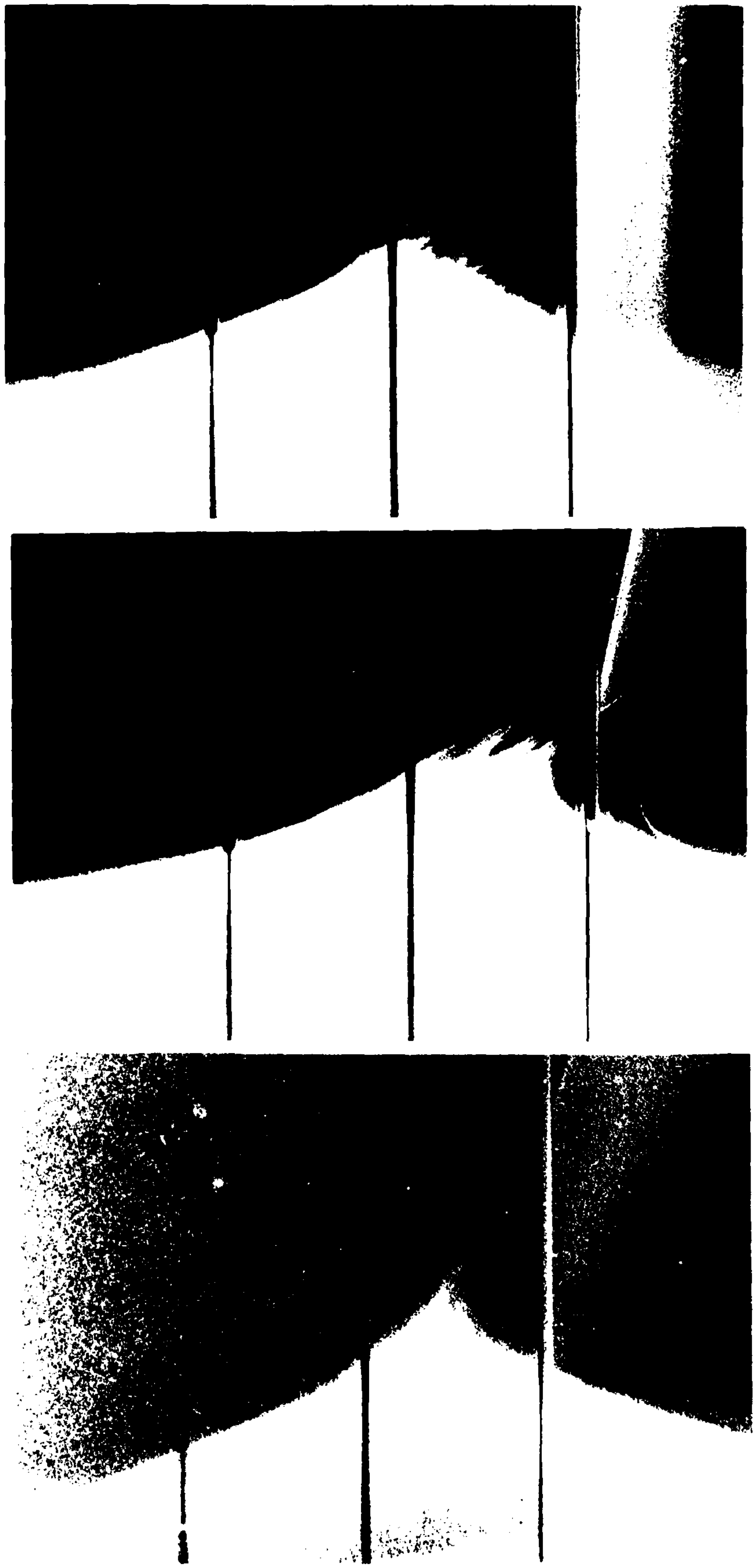
For the 60 mm orifice one can see at least on the film that a flame burns through the orifice and reaches a point from which a flame seems to spreed which documents itself by a high exposure of the film. It is followed by a pressure wave coming from the endwall of the driver section (after reflexion) with 870 m/s propagation speed.

These observations indicate that the phaenomena observed for the 200/200 system do also occur in smaller systems. There, however, they seem to be of minor importance because the volume which can be covered by these "ignition kernels" is much smaller. It may well be that for the same F_o/F_g value, if the linear dimensions of the systems are large enough such that the orifice diameter is also large, the flame, or parts of the flame, may just burn through the orifice, while in smaller systems the flame is first extinguished. In that case the quantity X_i becomes a more formal character.

Flame Speeds in the Explosion Section

From the photographic pictures just described, one can evaluated flame propagation speeds in the tube some distance downstream of the"reignition locus". There, the process is not stationary so that the data are average values. Some of these results are given in Fig. II- 6

<u>Fig. II.5</u> Smear camera pictures with reignition zone for orifices with 20, 40, and 60 mm diameter



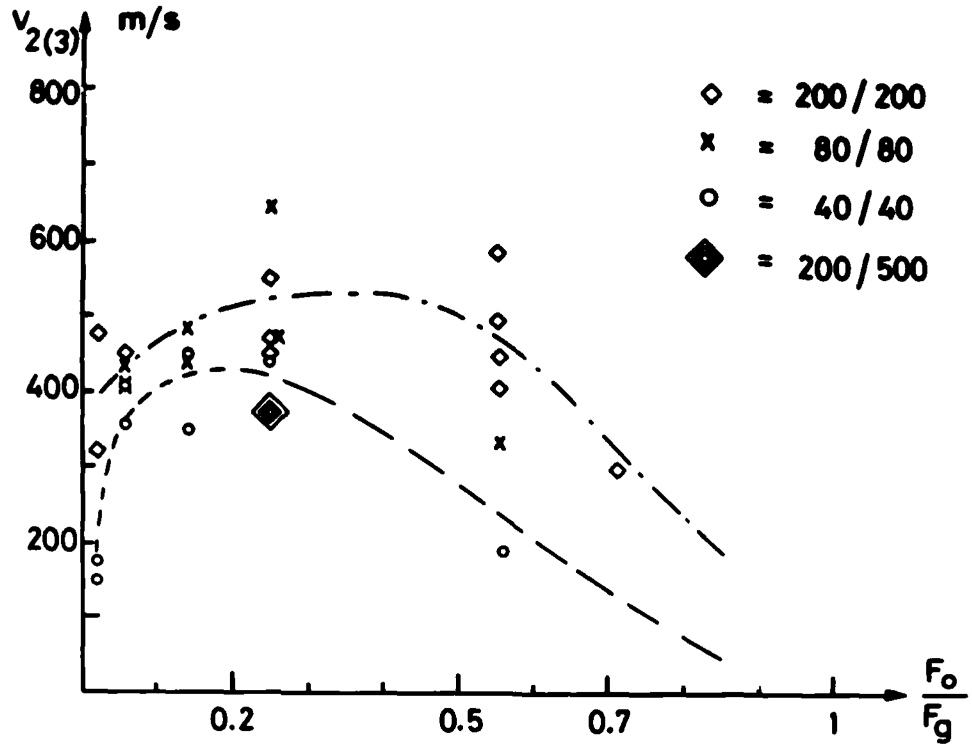


Fig. II. 6 Flame velocity in downstream section (m/sec)

as a function of F_o/F_g for different tube diameters. The scatter of these data is relatively large. Nevertheless, the general tendency is rather similar for the different tubes. For small F_o/F_g values the flame propagation rates increase, they pass through a maximum and then decrease again. The absolute values are somewhat larger for the bigger tubes than for the smaller ones. Maximum values of 500 to 600 m/s are registered corresponding to flame speeds relative to the unburned gas of up to about 60 m/s (assuming the flame propagates as a onedimensional flame in the tube).

For low F_o/F_g values that flame speed does not describe the complete situation. There, another flame propagate from the "ignition locus" backwards to the orifice so that for a short while the total heat release rate may become approximately two times that of the flame propagating downstream, in agreement with what one would expect from the maximum pressures measured for larger tubes.

DISCUSSION

The experiments about the influence of orifices on the propagation of flames in tubes do show that due to the high degree of turbulence generated by the jets downstream of the orifice very high local flame speeds can be achieved. The maximum pressures are obtained for orifice diameters of 2 - 3 cm. For the smaller tubes, the jets emerging from those orifices are not free jets and the influence of the wall on the "preparation" of the unburned gas in that section of the tube is somewhat hindered. In the 200 mm tubes the diameter is large enough such that a practically free jet can develop and the formation of vortices as well as the entrainment proceeds completely free. Further the effect of "multi spot reignition" also improves the situation for the generation of high pressures. The pressure values do not correspond, however, to a completely unconfined situation. They are higher because pressure release takes place effectively as a one dimensional process through the end of the tube. The flame speeds, however, may serve a hint, how high the effective flame speeds may rise within the highly turbulent flow field generated by the combustion driven jet.