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

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20. Abstract

The influence of a sequence of orifices on the propagation of flames in tubes has been investigated by measuring stationary flame speeds and pressure profiles. Flame propagation speeds of more than 600 m/s, confirming Wheeler's results, could be measured. Maximum pressures reached values markedly above the isochoric explosion pressure. The mechanism is discussed.

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Abstract

The influence of a sequence of orifices on the propagation of flames in tubes has been investigated by measuring stationary flame speeds and pressure profiles. Flame propagation speeds of more than 600 m/s, confirming Wheeler's results, could be measured. Maximum pressures reached values markedly above the isochoric explosion pressure. The mechanism is discussed.

INTRODUCTION

In experiments reported previously we investigated the influence of a single orifice on the acceleration of a flame. These experiments have been performed with CH_4-air, C_2H_4-air, C_3H_8-air, H_2-air, COS-air and C_2H_2-air mixtures as well as in mixtures of C_2H_4 with oxygen enriched air. The diameter of the flame tubes ranged from 4 cm up tp 50 cm.

The maximum overpressure obtained depends on the ratio of orifice area to the area of the tube cross section (F_o/F_g). Towards smaller orifices there are two values possible. For small tube diameters the maximum overpressure has a maximum around $F_o/F_g \sim 0.25$ which is shifted towards small F_o/F_g values and much higher pressure values for tube diameters above a value which is typical for the mixture.

First systematic experiments on the acceleration of flames by orifices have been performed by Wheeler et al. in tubes with 5 and 30 cm diameter. He also performed experiments with sequences of orifices. For CH_4-air mixtures Wheeler reported flame propagation velocities for 12 orifices , 5 cm apart from each other, up to 420 m/s.

For a more detailed investigation of that effect of a sequence of orifices on the flame propagation velocity and especially on the pressure-time distribution, experiments have been performed in tubes of 4 cm diameter with up to 26 orifices. The combustion process could be followed by smear camera pictures and by pressure measurements at several positions along the tube.

EXPERIMENTAL SET UP

A scheme of the experimental apparatus is shown in Fig. 1.

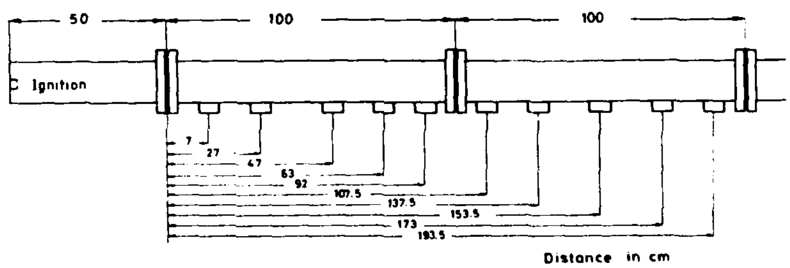

Fig. 1: Experimental Set Up.

A plexiglass tube of 4 cm inner diameter was closed at one end. There, one spark plug was mounted. 50 cm away from the spark plug there was the first orifice plate. The following orifice plates were fixed to two brass rods along the tube wall. The following orifice plates were available: plates with central circular holes of 0.7, 1, 1.5, 2, 2.6 and 3 cm diameter as well as plates with excentric orifices of 1.5 cm diameter. Distances between the orifice plates could be chosen as 2.5, 5, 10 and 20 cm. The part of the tube, which contained the orifice plates, was covered such that the smear camera could only observe a slit along the tube of 1 cm height.

The arrows in Fig. 1 indicate the positions where pressure gauges could be mounted. Up to 4 Kistler pressure pick-ups could be used simultaneously.

The stoichiometric or near stoichiometric CH_4-air mixtures were prepared via capillary flow meters. At least ten times the volume of the tube of mixture passed through the tube before the spark plug was fired.

EXPERIMENTAL RESULTS

A smear camera picture shows the progress of combustion in a tube with 21 orifice plates with 2 cm orifice diameter mounted 5 cm apart from each other in Fig. 2, on the left side of the figure processes in the 50 cm long ignition section are visible. (time axis downward!) Towards the right side the combustion process in the orifice section of the tube becomes visible. The first orifice (number 0) can easily be recognized. On the right side the propagation of the flame in a free tube section, downstream of the orifice section (behind orifice number 21) can be observed. The dark lines on the photographs outside of the orifice section are distance marks.

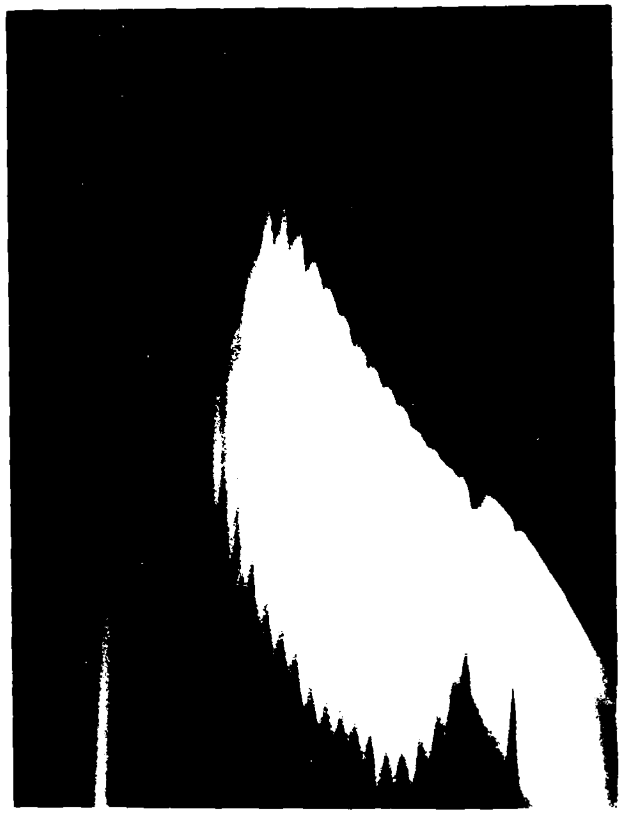

Fig. 2: Smear Camera Picture for 21 Orifices with 2 cm diameter and 5 cm distance. Flame propagation from left to right.

The process proceeds as follows: After a flame is ignited, it propagates in the driver section towards the first orifice plate. This part of the process cannot be seen in Fig. 2. The upper bound of the figure corresponds to the time when the flame passes through orifice plate number 4 (in the following abbreviated as OP 4). From here on the luminosity of the process becomes clearly visible between the orifice plates. One can also realize at what time combustion seems to start in the following chamber. These points can be connected by a curve. The slope of this curve gives a speed for the propagation of the process as a whole. In Fig. 2 this speed reaches a value of 440 m/s at around OP 15.

Downstream of OP 21, in the free tube, the propagation speed is about 350 m/s, it decreases further downstream.

This photograph gives the impression that the flame does not pass completely smoothly through the different orifices. It looks more as if combustion starts again around the middle of the chamber between the orifices. Behind the last orifice the situation is very similar to that behind a single orifice: one can observe a certain distance X between orifice and reignition position. This distance X increases when the orifice diameter is reduced, in agreement with what has been observed behind single orifices.

This photograph also shows the flow of the luminous burned gas. While at the beginning of the process unburned gas is blown through the orifice section, one can easily see that later on burned gas is driven backward into the ignition section; the gas flow changes its direction. This will become more obvious in some of the following photographs.

Pressure-time curves, taken at different positions along the tube (conditions as in Fig. 2), are shown in Fig. 3. The number give the number of the orifice plate upstream of which pressure (P) was registered. After the first orifice (signal 2) P increases quite slowly. This pressure increase proceeds further after the combustion process has reached the following chambers. In the following chambers the maximum value of P increases further and the rate of pressure increase becomes much faster. The signals in Fig.3

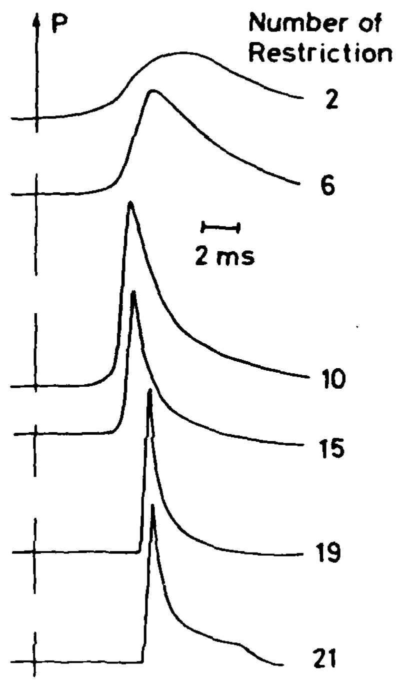

Fig. 3: Pressure Signals as a function of time. Conditions as in Fig. 2. Signals at OP 15 and OP 19 are taken with reduced (1/2) sensitivity.

are mounted in real time (within the limits of reproducibility of the experiments).

After this description of the process in general, some quantitative data shall be given for different experimental conditions.

Experimental Results for Orifices with 0.7 cm Diameter

For orifice with 0.7 cm diameter the flame extinguishes after two to four orifice plates (distance 2.5 and 5 cm). An example for 5 cm distance between the plates is shown in Fig. 4. The flame propagation speed for this process is about 18 m/s and therefore higher than in an empty tube.

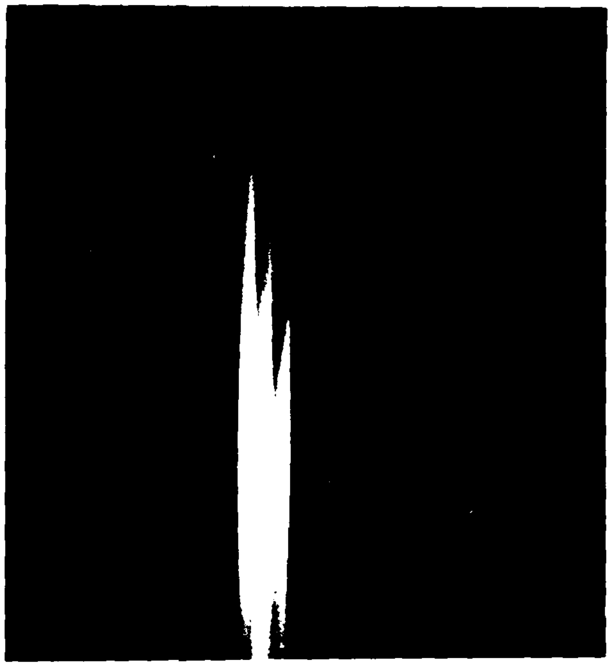

Fig. 4: A smear Camera Picture of failing flame. Orifice diameter 0.7 cm; distance 5 cm.

Experimental Results for Orifices with 1.0 cm Diameter

Fig. 5 shows the maximum pressures obtained at the indicated orifice plates. (Abscissa gives the orifice number.) For 2.5 cm distance between the orifice plates pressure decreases with increasing distance from the first orifice. For distances of 5 and 10 cm the curves show a maximum around OP 12. The fluctuation of the experimental values between different experiments is rather large for these conditions.

Besides the peak pressure another quantity, which is useful for the characterisation of the pressure-time signals,

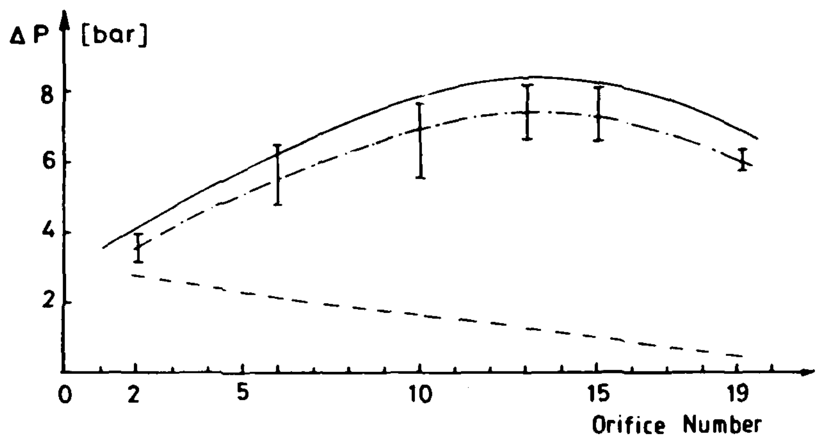

Fig. 5: Maximum Pressures for Orifices with 1 cm Diameter.
(——— 10 cm distance; —·—·— 5 cm distance; ---- 2.5 cm distance). The bars give the mean errors.

is the half value time $t_{1/2}$ (see Fig. 3). For the experiments with 1 cm diameter orifices, these $t_{1/2}$ values between OP 2 and OP 12 are nearly equal. They decrease slightly towards larger orifice numbers.

Für 2.5 cm distance between the orifices the flame extinguishes after about 3 orifices. The pressure curve in Fig.5 shows the discharge of the gas from the tube.

For 5 cm distance between the orifices, flame speeds up to 95 m/s could be observed and maximum pressures close to 8 bar. After OP 15 to OP 20 the flame fails as can be seen in Fig. 6.

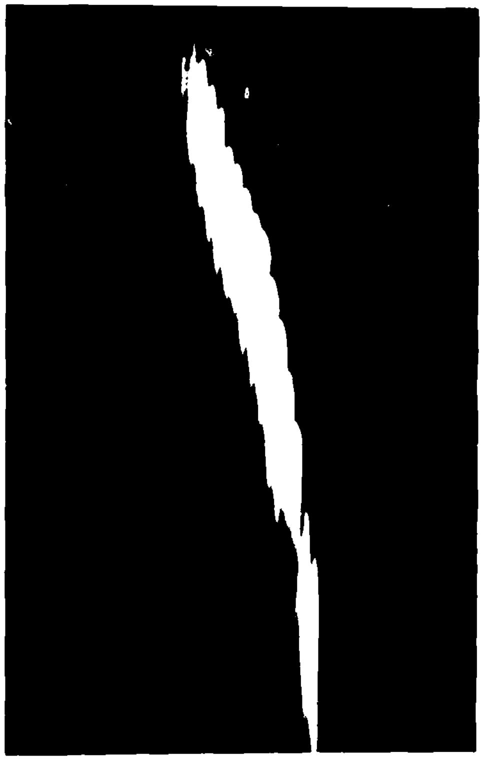

Fig. 6: A Smear Camera Picture of Failing Flame. Orifice diameter 1 cm, distance 5 cm.

For 10 cm distance the scatter between consecutive measurements becomes even larger than for the 5 cm diameter experiments. The smear camera pictures are similar to those with a single orifice plate. Ignition seems to start some distance X downstream of the orifice and the reaction seems to propagate in both directions, backward and forward. The luminosity reaches the orifice plate before luminosity starts to become visible within the following chamber. The mean flame propagation speed is around 80 m/s and the flames fail usually around OP 15.

Experimental Results for Orifices with 1.5 cm Diameter

For this orifice diameter experiments have been performed for central orifices and for those with orifices drilled excentrically into the plate. Two consecutive orifices were mounted such that the centers of the orifices were 180^{o} apart from each other but all in one plane. One could not look through this mounting of the plates.

The flames passed through all orifice plates and did not fail as for the 1 cm diameter orifice plates. Apparently the stability limit for this system with CH_4-air lies at orifice plates with orifice diameters between 1.5 and 1 cm.

The appearance of the flame is similar to that to be described for the 2 cm diameter orifice plates.

The maximum pressure (Fig. 7) is reached after OP 7 to OP 9 and remains nearly constant towards the end. For comparison the maximum pressures for orifices drilled centrally into the plates are also shown. The rise of maximum pressure is slower and the maximum of the curve reaches 8 bar instead of 10 bar for central orifices.

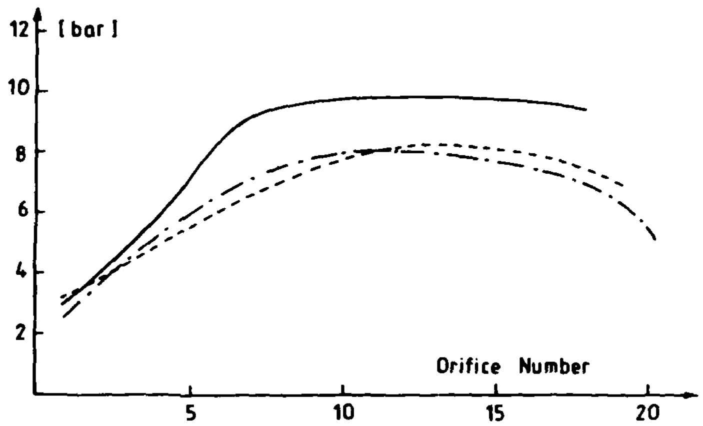

Fig. 7: Maximum Pressures for Orifices with 1.5 cm Diameter.
(——— 1.5 cm diameter, central orifices, 10 cm distance;
—·—· 1.5 cm diameter, excentric orifices, 10 cm distance;
- - - - 1 cm diameter, 10 cm distance)

Experimental Results for Orifices with 2 cm Diameter

The maximum pressures obtained for orifices of 2 cm diameter are shown in Fig. 8. For small distance between the orifices, the pressure increases rather slowly along the tube and no stationary state is reached after OP 20. The two other curves seem to indicate that after about 15 orifices the combustion process reaches a stationary state. In both cases the maximum pressures reached are definitely higher than the isochoric explosion-pressure of stoichiometric CH_4-air mixtures starting

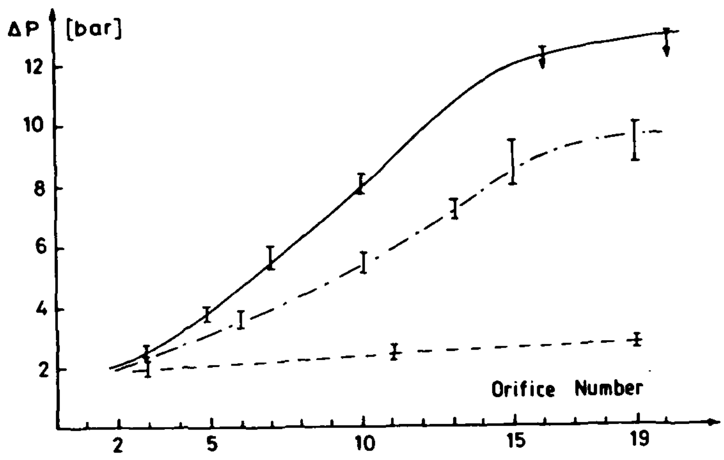

Fig. 8: Maximum Pressure for 2 cm Diameter Orifices with Distances of
——— 10 cm; —·—· 5 cm ; — — — 2 cm.

from NTP. At the pressure gauges between OP 15 and 20 the maximum pressure values of different experiments show rather large fluctuations and the pressure values within one experiment show also more scatter than usual.

The values of P for the solid line (10 cm distance) give the highest values obtained in 8 experiments.

The pressure rise to maximum pressure at OP 12 and later takes place within 0.1 to 0.2 milliseconds. This is close to the time resolution of the pressure gauges and corresponds to the time for sound propagation within the chamber.

The half values $t_{1/2}$ of the pressure signals are shown in

Fig. 9. These $t_{1/2}$ values decrease with increasing number of the orifice. They are, as to be expected, highest for orifice distances of 10 cm, where the gas volume between the orifices is largest.

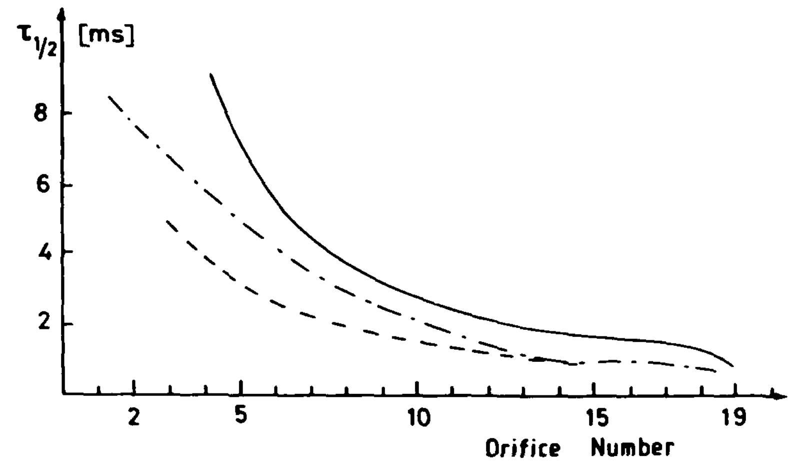

Fig. 9: Half Values $t_{1/2}$ of the Pressure Signals at Different Orifices. Conditions as in Fig. 8.

A smear camera photograph of a combustion process for 2 cm orifice diameter and 5 cm distance is shown in Fig. 10. The three wider dark lines are distance marks and the first orifice plate (OP O) is in the middle of the middle one. Towards the right side one can see how the process accelerates, one can recognize the flow of the burned gas and the luminosity gives an indication of the total pressure and temperature.

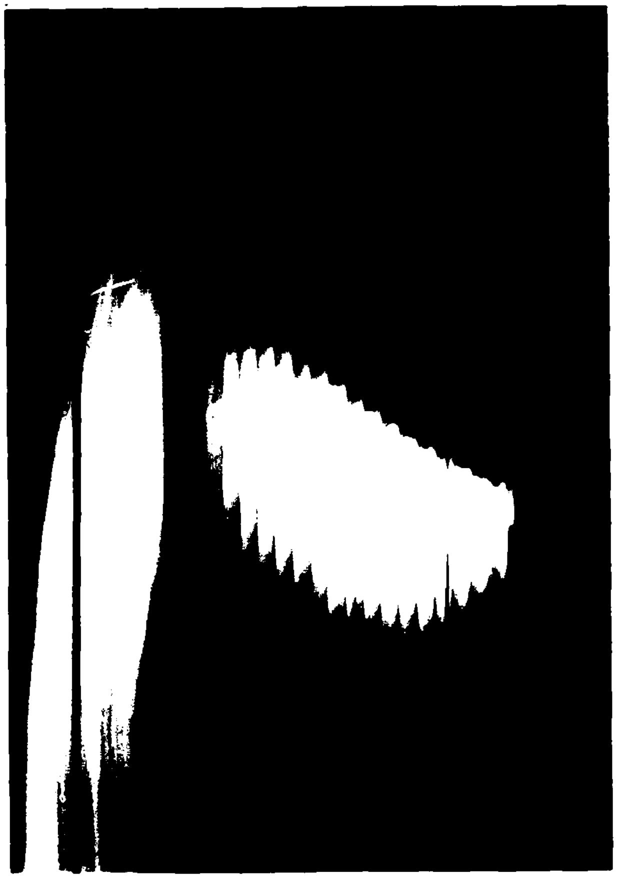

Fig. 10: Smear Camera Photograph for 2 cm Orifice Diameter and 5 cm Diameter

The particle path has the shape of an S in the middle of the orifice section. At first the particles are shifted forward, after some time their velocity goes to zero, turns around such that the flow is directed towards the ignition section and only later the gas starts to flow out of the tube. Even though this picture gives more details than Fig. 2, the combustion process within the chamber cannot be clearly recognized and the combustion in the following chamber seems to start before that in the first chamber is finished.

From the slope of the curve connecting the various pictures in the different chambers one can see that the propagation speed of the process towards the end exceeds 500 m/s. In general the speeds for the last 5 to 8 orifices are around 450 m/s and nearly stationary.

In an experiment with 10 instead of 21 orifice plates this speed was about 270 m/s. This is close to the value which one can observe at the 10th orifice if 21 orifice plates are mounted.

Experiments with 2.5 cm distance between the orifices show similar phenomena as Fig. 10. (see also Fig.14) Flame speeds between the last orifices were around 370 to 410 m/s.

The situation for 10 cm orifice distance is shown in Fig. 11.

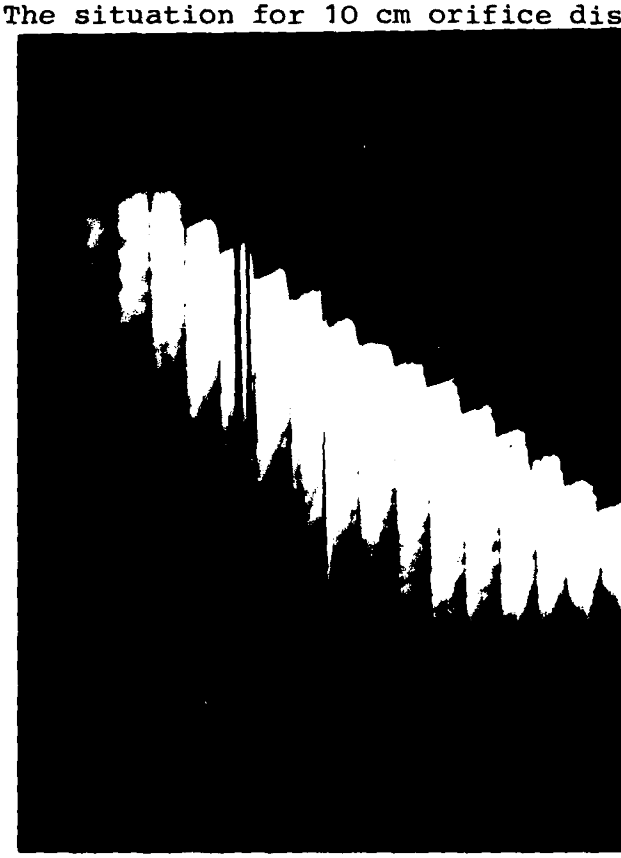

Fig. 11: Smear Camera Photograph for 2 cm Orifice Diameter and 10 cm Distance.

The process is nearly stationary, the speed is lower than for 5 cm distance between the orifices. One can see the particle path and, in addition, a system of "lines" appears which are directed towards the ignition section and also lines coming back from there. This phenomena will become more obvious in the following photographs. It is a system of pressure waves which are generated by the combustion process and reflected form the orifice plates.

If the orifice plates are mounted at distances much larger than 10 cm, say 20 cm, the processes behind the orifice become very similar.to that for a single orifice. The total acceleration of the flames from one orifice to the next one remains small. The propagation speed observed was about 150 m/s. This is less than that observed from the light trace on the film within a single chamber.

Experimental Results for 2.6 cm Orifice Diameter

For these conditions only a few pictures have been taken for 5 and 7.5 cm orifice distance. The pictures look similar to those for orifices with 2 cm diameter. The velocity downstream of the last orifice plate was about 500 m/s and slightly higher than that between the last 5 orifice plates.

Experimental Results for 3 cm Orifice Diameter

The distribution of maximum pressure (Fig. 12) for orifices with 3 cm diameter is for the different distances between the orifices similar to that for 2 cm orifice diameter. The

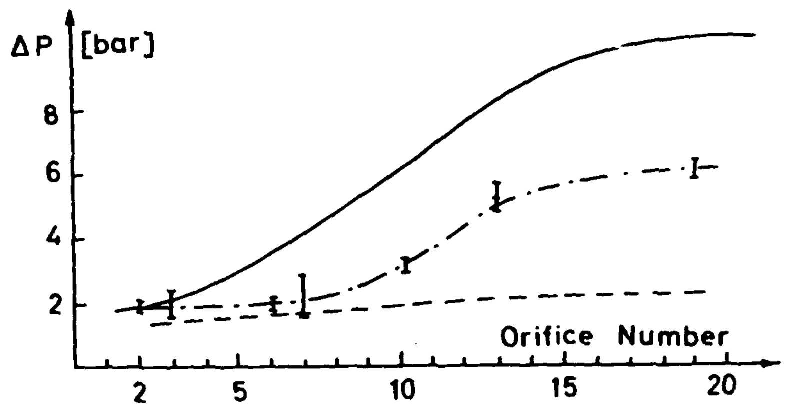

Fig. 12: Maximum Pressure for 3 cm Diameter Orifices with Distance of —— 10 cm; —·—·— 5 cm; – – – – 2.5 cm.

pressure values are slightly lower than for 2 cm diameter orifices, the reproducibility is better. After the last orifice flame propagation velocities up to 770 m/s have been observed.

For 3 cm diameter orifices (the ratio $F_o/F_g = 0.56$), the system is relatively open. Therefore, pressure waves, which are generated within the tube, can spread more easily than with 2 cm orifices. This becomes obvious in Fig. 13 which shows the first 18 chambers, each 10 cm long. During the acceleration phase some faint lines can be observed which are directed towards the ignition section. In a later phase, when the total pressure becomes higher (also higher than the Laval-Pressure!),

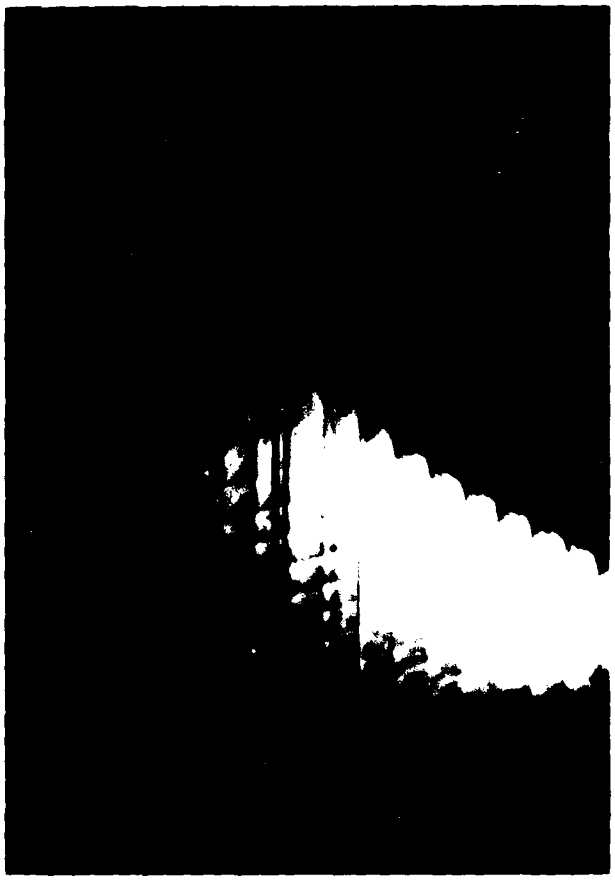

Fig. 13: Smear Camera Photograph for Orifices with 3 cm Diameter, 10 cm apart. System with 21 orifices.

this system of lines becomes more obvious. They seem to start in a chamber under consideration A and are directed towards the ignition section. After having left the chamber A, they correspond to nearly constant velocity. With increasing flame propagation speed they come closer together. Whether they start as a pressure wave resulting from the reflection of a pressure puls coming into chamber A before ignition starts cannot be recognized on the photograph. Some parts of the photograph can be interpreted that way. These backward running pressure waves must pass through the orifices where they seem to be partly reflected. This might generate the lines in Fig. 13 which are nearly parallel to the flame front. Under proper condition these two sets of waves form a grid on the photograph as to be seen in Fig. 13 where the particle path can also be observed. Maybe there is an additional synchronizing effect. In the gases downstream of the last orifice a structure can be observed, which looks like the horizontal lines in spinning detonations. The progress of chemical reaction cannot be clearly realized from these photographs, it seems, however, obvious that it is not simply the propagation of a closed flame front in forward direction.

The flame propagation velocity is similar to the apparent slope of the liminosity within the chambers. Around OP 15 to 18 it is practically constant and about 610 m/s. This combination of orifices with 3 cm diameter,which were mounted 10 cm apart,generated the highest flame propagation speed which we observed in these experiments.

For an orifice distance of 2.5 cm (see Fig. 14) pressure rise is small and the maximum flame speed behind the last orifice is about 250 m/s. No stationary state is reached around the last orifice. The flow lines bent backwards rather late which might indicate that part of the combustion process takes a rather long time under these conditions.

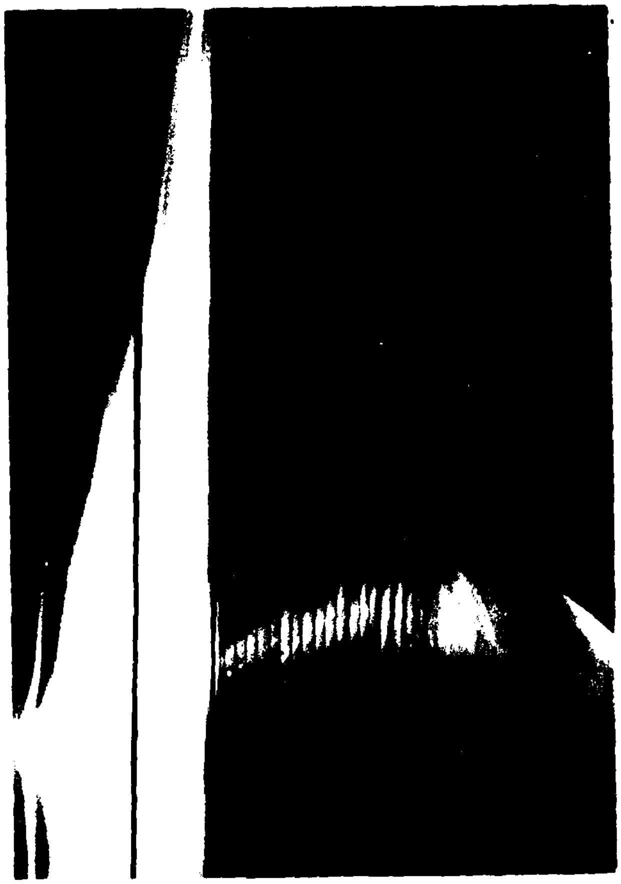

Fig. 14: Smear Camera Photograph for Orifices with 3 cm Diameter, 2.5 cm apart. System with 21 Orifices.

DISCUSSION

A somewhat more detailed analysis of the processes described is shown in Fig. 15. The upper part of Fig. 15 shows the "flame path" obtained from smear camera pictures. The flame speed v_F is taken from that curve. It increases from 100 m/s at OP 4 to 420 m/s at OP 20 where it becomes practically constant. In the pressure diagram the solid line connects the maximum values. The two other lines give the pressure distribution at the time when OP 19 shows the maximum pressure. The pressure drop from

OP 19 to OP 20 is very steep as can be seen from Fig. 3. Towards lower orifice numbers the mean pressure gradient at that moment is about 8 bar per meter. Gas flows from OP 19 into two directions, with supersonic flow towards OP 20, where the pressure ratio is larger than the Laval ratio and subsonically into the burned gas side.

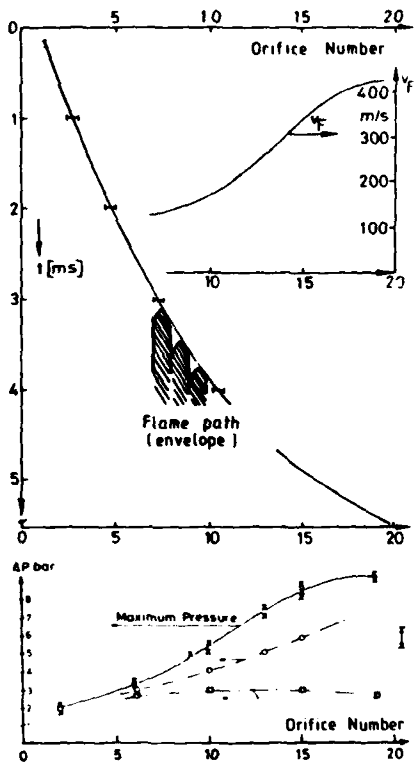

Fig. 15: Flame path along the orifice section of the tube and flame speed v_F for an experiment with 2 cm orifice diameter and 5cm distance.
The lower part of the figure gives: ——— maximum pressure —o— · —o— Pressure along the tube at the time where maximum pressure is reached at OP 19. □— · · — · · : Pressure 1 ms later. I Pressure downstream of OP 21.

One millisecond later pressure distribution is given by the lowest curve in Fig. 15: the gas starts to flow out of the tube.

A comparison of the increase of pressure for orifices of 1.5, 2 and 3 cm diameter (see Fig. 16) (all 5 cm apart) shows that the maximum pressure is reached for 1.5 cm orifices after OP 7 and, therefore, faster than for the 2 and 3 cm diameter orifices. The pressure maximum, however, is highest for the 2 cm diameter orifice (while the flame speed is highest for 3 cm orifices).

For higher orifice numbers the maximum pressure increases only slowly, the rise time in the pressure-time signals, however, becomes very short. The pressure rise in the following chamber will therefore increase faster until flow into the chamber and combustion cooperate to increase pressure, at least for a short time. As soon as the Laval pressure ratio towards the following chamber is reached the flow into that chamber is choked and P can rise even faster.

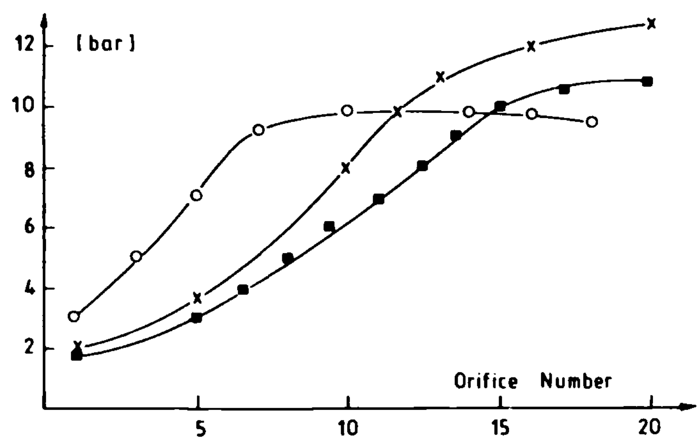

Fig. 16: A comparison of maximum pressure for orifices of 1.5, 2 and 3 cm diameter 5 cm apart.

If one takes chamber (i), then one can write the change of mass m_i in that chamber which is caused by the difference in mass flux from and to the neighbouring chamgers $J_{(i-1,i)}$ and $J_{(i,i+1)}$. Therefore

$$\frac{dm_i}{dt} = J_{(i-1,i)} - J_{(i,\ i+1)}$$

When the pressure in the chamber i-1 is sufficiently high ($P \gg 2$ bar) a jet will enter chamber i and the flow is approximately given by

$$J_{(i-1,i)} = F \ \frac{P_{i-1}}{c_{i-1}} \cdot 0.77 \qquad (\text{for } \gamma = 1.33)$$

Here F is the efficient orifice area, c_{i-1} the sound velocity in chamber i-1.

The flow into chamber i+1, in case that P_i is below P Laval, is approximated by

$$J_{(i,i+1)} \approx F \ \frac{\sqrt{P_i ; \Delta P}}{c_i} \cdot 1.63$$

Here $\Delta P = P_i - P_{i+1}$

As long as P_{i-1} is large compared to P_i the pressure increase in i is mainly determined by the flux $J_{(i-1,i)}$ into chamber i and

$$\frac{d\ P_i/P_{io}}{dt} = (\ P_i/P_{io})^{\frac{K-1}{K}} \cdot \alpha \qquad \text{with}$$

$$\alpha = P_{i-1}/P_{io} \ \frac{c_{io}^{\ 2}}{c_{i-1}} \cdot \frac{F}{V_i} \cdot f(\gamma)$$

P_{io} is the initial pressure in chamber i and V_i its volume.

The "time constant" α depends essentially on F/V_i, on P_{i-1} which changes with time. An estimate of α shows that for the experiments described here there was always enough time to increase pressure in the following chamber such that maximum overpressures above the isochoric explosion pressure can be attained. Its height depends on flow conditions and the time necessary for the heat release in chamber i.

The problem is similar to the venting of a container in which an explosion takes place. The time necessary for the chemical reaction can be estimated from some photographs. Its order of magnitude is comparable with the "time constant" of pressure rise in chamber i. If it is attributed to an effective flame speed relative to the unburned gas, their value would be very high indeed.

The photographs indicate that the mechanism for the propagation of the combustion process is rather complicated. Even for 3 cm diameter orifices it does not seem to be a closed flame front, which burns through the chamber. The reason for the very intensive combustion seem to be similar to those behind a single orifice.

1.) the extremely high turbulence caused by flow through orifices
2.) instability of the flame front near the orifice on the upstream side which causes instability of the flame (Taylor instability: $\nu \sim \sqrt{\lambda \cdot g \Delta \rho}$, ν = frequency, λ " wave length, g acceleration

before orifice, $\Delta\rho$ density difference between burned and unburned gas)

3.) high jet velocity which causes rapid entrainment and very rapid mixing of burned and unburned gas.

In experiments with one orifice, there was a reignition distance X. For the experiments described here, the distance between two orifice plates was either smaller or comparable with X. The conditions were such that no free jet could develop. A part of the jet is blocked by the next orifice and turned back into the chamber. Taking this into account, the observations can be understood at least qualitatively.

Around the first orifices the flow is already turbulent. The ignition in the next chamber takes place after the pressure in this and the following chambers has been increased already, at least slightly. The heat release rate increases, the Laval pressure ratio is reached and the process is self-supporting and accelerating.

For small orifices the flow velocity becomes so high that entrainment of unburned gas extinguishes the combustion process as for single orifices.

Orifice distances of 2.5 cm cause only slight pressure rises and flame speeds. The small distance increases the time constant α. The conditions for the flame spread, however, are rather unfavourable, the corresponding X is large compared to the orifice distance and cooling is very rapid.

In the experiments described here maximum pressure and maximum speed for 3 cm orifices coincide. For the 2 cm orifices the maximum speed is obtained at 5 cm distance, the maximum pressure for 10 cm orifice distances. This shows that the parameter F/V as well as the reaction time are important. It is comparatively simple with the model described and a properly chosen simple assumption about an effective flame speed to describe the experimental results. Some experiments about the flow through several orifices do show, however, that there seem to be special couplings between the flow in consecutive chambers which should be investigated first.

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