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FLAME PROPAGATION IN THE PRESENCE OF REPEATED OBSTACLES: INFLUENCE OF GAS REACTIVITY AND DEGREE OF CONFINEMENT

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Summary

Flame propagation has been studied for gas mixtures of different reactivity in an obstacle environment made up of a bottom plate with regularly spaced sticks mounted on it. Flame propagation was studied in both three-dimensional and two-dimensional geometry (second plate mounted on top of the sticks). Because of a positive feedback mechanism between flame and flow field a continuously accelerating flame front is observed in both geometries. In two-dimensional geometry flame acceleration is larger than in three-dimensional geometry. The reactivity of the gas mixture has no effect on the results: the relation between flame velocity at a certain radius and the laminar flame velocity is the same for all gases in each obstacle environment.

Introduction

Analysis of damage caused by unconfined vapour cloud explosions that occurred in the last 40 years [1—4] shows that strong blast waves must have been generated. This means that if deflagrative explosions are assumed high flame velocities must have occurred.

There is general agreement that changes in the flow field ahead of the flame can cause the flame to accelerate [5]. The changes in the flow field ahead of the flame are determined among others by obstacles that are present in the flow field. Because of the flow around the obstacle a vortex is generated behind the obstacle, and along the obstacle there will be a flow velocity gradient. When the flame reaches the obstacle the flame is stretched, resulting in an increase in the amount of gas being consumed. The increased rate of combustion, evidenced by an increased flame velocity, will increase the flow velocity ahead of the flame, which will cause a more intense vortex and a larger flow velocity gradient near the next obstacle. This in turn will cause another flame acceleration when the flame reaches the next obstacle.

The maximum flow velocity that will be reached as a result of this positive feedback mechanism will depend largely on the number of obstacles (i.e. how long the mechanism will be effective), the distance between the obstacles (the flow field regains its original properties some distance behind the obstacle),

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the size of the obstacles (which determines the distortion of the flow field), the reactivity of the gas, and the degree of confinement (geometry of the flow field).

Moen ([6] and [7]) investigated a number of the above-mentioned parameters. He studied the influence of different spiral-shaped obstacles on flame propagation between two parallel plates. By varying the thickness of the spiral and the number of windings the influence of obstacle size and spacing were investigated. The tests were performed using stoichiometric methane—air mixtures. Leyer [8] has also performed tests to study flame propagation over obstacles placed between two parallel plates or on a single flat plate. The gas mixtures (gas—oxygen and gas—nitrogen—oxygen) were confined around the obstacles using a soap bubble. In [6—8] the reactivity of the gas and the degree of confinement were not varied. Therefore tests were performed using a set-up comparable with that used by Moen [6] in which these two parameters were investigated. The results of these tests are described in this paper. This research was part of a large experimental programme, set up to analyse what conditions are most effective in accelerating flames in unconfined vapour cloud explosions.

Experimental set-up and test programme

The experimental set-up in which flame propagation was studied consists of two square wooden plates (60 cm X 60 cm) that are mounted 9 cm apart, using wooden spacers at the corners. On the lower (bottom) plate wooden sticks (diameter 1 cm, height 9 cm) were mounted in rows 2 cm apart (see Fig. 1 and Fig. 2d). Other tests were performed with the same set-up after removing the top plate to study the influence of confinement (see Fig. 2c). Finally tests were performed with just one plate (Fig. 2a) and two parallel plates 9 cm apart (Fig. 2b) without the obstacles.

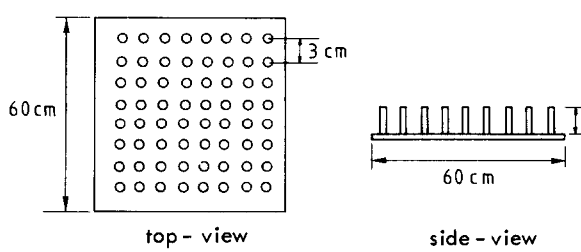

Fig. 1. Schematic diagram of repeated obstacles in single plate—sticks configuration; not to scale. The diameter of the sticks is 1 cm.

Ignition of the gas mixture was effected by means of a capacitive spark (gross energy 3.6 J) over the centre of the lower plate. Experiments were performed in an explosion vessel (capacity 1 m^3; see Fig. 3). The plates were mounted in the centre of the vessel; the distance between ignition source and vessel walls

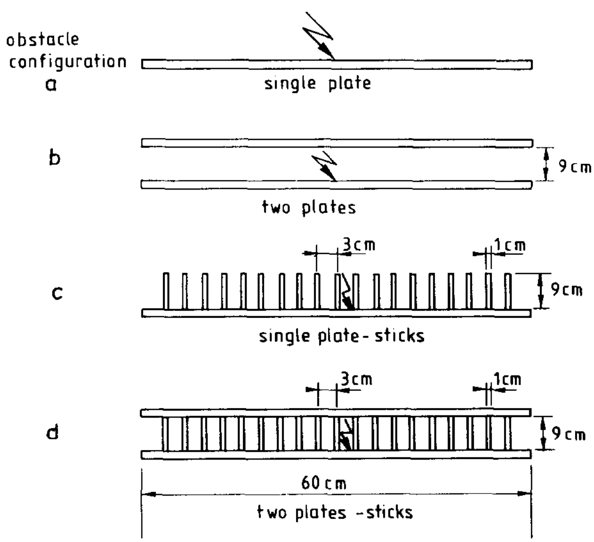

Fig. 2. Schematic drawings of the obstacle configurations.

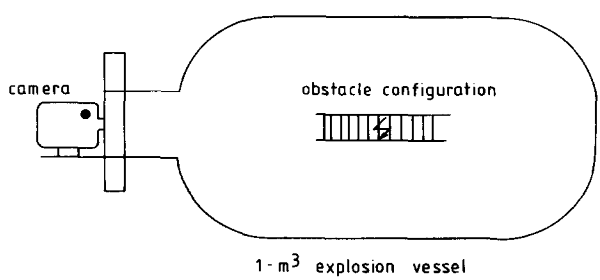

Fig. 3. Experimental set-up.

was 0.5 m or more. Flame propagation was filmed using a high-speed camera (max. 500 frames per second) through a window in the vessel wall. The camera looked at the set-up from the side, which causes a parallax error. In some tests the set-up was filmed from the top to investigate whether spherical or cylindrical symmetry was maintained. The explosion vessel was filled with the gas—air mixture. The mixture was prepared using an electronic flow meter and thoroughly mixed using a circulation pump. The composition of the mixture was checked before each test using a gas chromatograph.

As the tests were performed in a closed vessel no blast measurements were possible, but the pressure—time history of the explosion in the vessel was measured using two piezoelectric pressure transducers. In order to study the influence of the gas reactivity four different gases were investigated that had been classified in different classes of relative reactivity based on previous tests ([9] and [10]): 10% methane—air (low reactivity, laminar flame velocity 2.1 m/s), 4% propane—air (average reactivity, laminar flame velocity 2.6 m/s), 8% ethene—air (average reactivity, laminar flame velocity 5.0 m/s) and 10% acetylene—air (high reactivity, laminar flame velocity 13.5 m/s). The laminar flame velocities mentioned were measured in the same explosion vessel.

Description of flame propagation

The way in which the flame will accelerate in these plate—stick configurations will be very similar to the process described in [6] and [7]. The flame initially propagates laminar. Because of the volume increase of the gas on combustion, the unburned gas will flow ahead of the flame front. The flow velocity V just ahead of the flame front is equal to $V = (\rho_u/\rho_b - 1)\, S$, where S is burning velocity, and ρ_u and ρ_b are densities of unburned and burned gas respectively. In an undisturbed flow field the burning velocity S will be equal to the laminar burning velocity S_L.

The presence of the obstacles will generate disturbances in the flow field. Between the sticks the flow will show a velocity gradient (see Fig. 4). Not only the sticks but also the two plates will cause a velocity gradient. When the flame enters this flow field, the flame will be stretched, causing an increase in flame surface area. The average flame front velocity V_f is:

$$V_f = \frac{\rho_u}{\rho_b} S = \frac{\rho_u}{\rho_b} \frac{A_f}{A_0} S_L ,$$

where A_f is the disturbed flame surface area and A_0 is the flame surface area without the disturbance. An increase in flame surface area caused by a flow

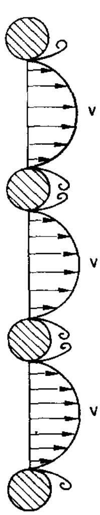

Fig. 4. Flow field generated by a flame front near a row of sticks.

velocity gradient thus causes an increase in the flame front velocity.

Downstream of the sticks the distortions of the flow field will decay and hence the flame front velocity will decay. However, if behind the sticks a second row of sticks is positioned at such a distance that the flame front velocity has not decayed significantly, then the flow velocity gradient between the sticks in the second row will be larger due to the higher flow velocity of the incoming flow. This will cause a further increase in flame front velocity when the flame reaches the second row. This positive feedback mechanism will remain effective as long as the obstacles are repeated and will cause the flame to accelerate.

Behind the sticks initially discrete vortices will be formed that will become turbulent when combustion progresses and the flame accelerates. The Reynolds number based on the stick diameter and the flow velocity ahead of the flame is large enough to ensure transition to turbulence (at a flame front velocity of 5 m/s, a stick diameter of 0.01 m and a kinematic viscosity of 15.7 $\times 10^{-6}$ m^2/s the Reynolds number is about 3000). A shear layer forms the separation between the turbulent region behind the sticks and the main flow where the flow velocity gradient is. A flame entering a turbulent region increases in surface area like a flame entering a flow velocity gradient. The flame becomes folded and wrinkled which causes a flame velocity increase. An increase in turbulence intensity will cause the small-scale turbulence to play an important role by enhancing the transport of heat and mass in the flame, which also increases the flame front velocity.

So two mechanisms are important in flame propagation: turbulence and flow velocity gradients. Both cause a continuous flame acceleration when the separation between the rows of sticks is small enough. Moen [7] has shown that both mechanisms are not equally important at the same place and time. In experiments on his scale the flow velocity gradient will determine the flame propagation for relatively small flame front velocities and distances of less than about 60 cm. For larger flame front velocities and distances turbulence is the governing mechanism, which is caused by a broadening of the turbulent region behind the sticks at higher flow velocities. As in these experiments the maximum flame travel over the plate is 30 cm, the flow velocity gradient can be expected to determine the flame front behaviour. It has been found [7] that flame front accelerations are larger when flow velocity gradients are important than when turbulence is the determining factor in the flame propagation.

In the tests without the top plate (see Fig. 2c) a situation is created that is more "unconfined". In this situation the flow field is three-dimensional, as opposed to the two-dimensional flow field when the two plates are used. The consequence is that in the three-dimensional geometry for the same initial flow velocity, the flow velocity in one direction will decay faster as a function of distance than in the two-dimensional situation. In this situation smaller flow velocity gradients will occur near the sticks, and only one gradient near the bottom plate. This will cause a smaller increase in flame surface area and therefore smaller flame acceleration.

A different approach to the single plate—sticks configuration is also possible. It has been shown ([6] and [11]) that results of investigations of flame propagation in the presence of obstacles can be correlated using the "blockage ratio": the quotient of the surface area blocked by obstacles and the total surface area. If the blockage ratio is calculated for the single plate—sticks configuration it is found to be a sharply decreasing function of the flame radius, whereas for the two plates—sticks configurations it is a slowly varying function of distance. As the flame acceleration over an obstacle will be smaller for smaller blockage ratios, the increase in flame front velocity will be smaller in the single plate—sticks configuration than in the two plates—sticks configuration.

Without the sticks (Fig. 2a) the situation is different: no obstacles are present, so there will be no large flow velocity gradients. Only just above the plate a small velocity gradient will cause a small increase in flame front velocity.

When two plates are used (Fig. 2b), higher flame velocities will be encountered, because a flow velocity gradient will occur also near the second plate. Besides, the flow field ahead of the flame will be more intense because of the two-dimensionality of the flow field. However, no high flame velocities are to be expected because there are no more elements in the flow field to cause distortions.

Experimental results and discussion

In Figs. 5—8 examples are given of photographic recordings of flame propagation over the four different obstacle configurations. Comparison of the figures shows that flame acceleration occurs for the single plate—sticks configuration (Fig. 7), but above all for the two plates—sticks configuration (Fig. 8). In Fig. 8 it can be seen from the shape of the flame front that with an increase in the flame front velocity there is also an increase in the velocity gradient.

In Figs. 9—12 the results of the tests are given. For each gas mixture the relationship between flame front velocity (measured just above the ground plate) and flame radius is given for all four obstacle configurations.

A framing camera has been used to record flame propagation. To calculate the flame front velocity (data points in Figs. 9—12), the distances covered by the flame between two successive frames must be determined. Therefore the accuracy of the measured flame front velocities is limited. In order to increase the accuracy (up to ± 1 m/s), the values were averaged over several frames if the flame front velocities were low. For higher flame front velocities the distance covered between frames is larger and averaging is not needed anymore. From the figures it is clear that for all gas mixtures the highest flame front velocities are found for the two plates—sticks configuration. The flame front velocity increases exponentially. For the single plate—sticks configuration the flame acceleration is less drastic. Without sticks there is hardly

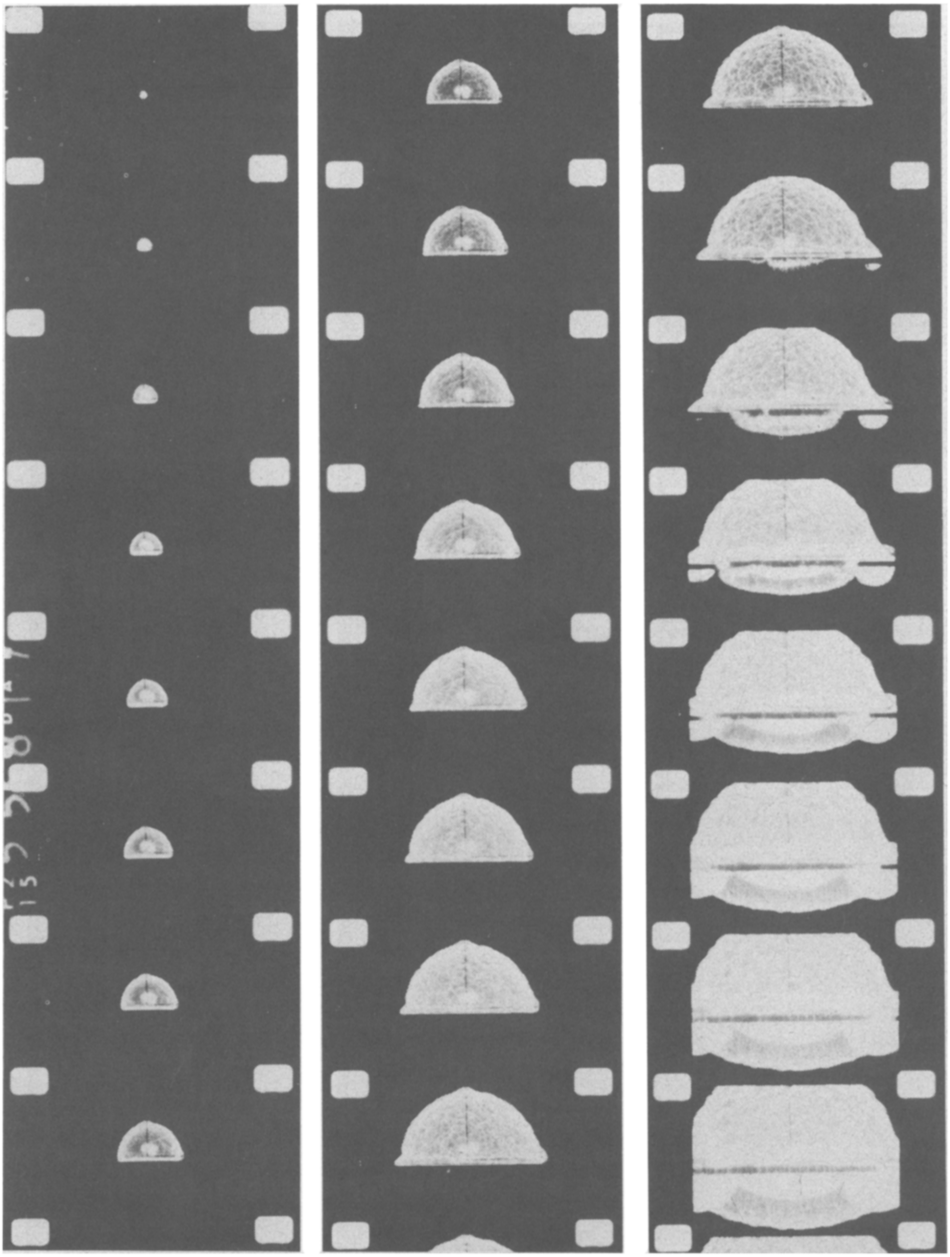

Fig. 5. Example of flame propagation over a single plate (8% ethene—air).

any flame acceleration except for a slight increase in flame front velocity for acetylene and ethene. Between two plates the flame front velocity is invariably higher than near one plate.

When comparing the gas mixtures the flame front velocities are found to

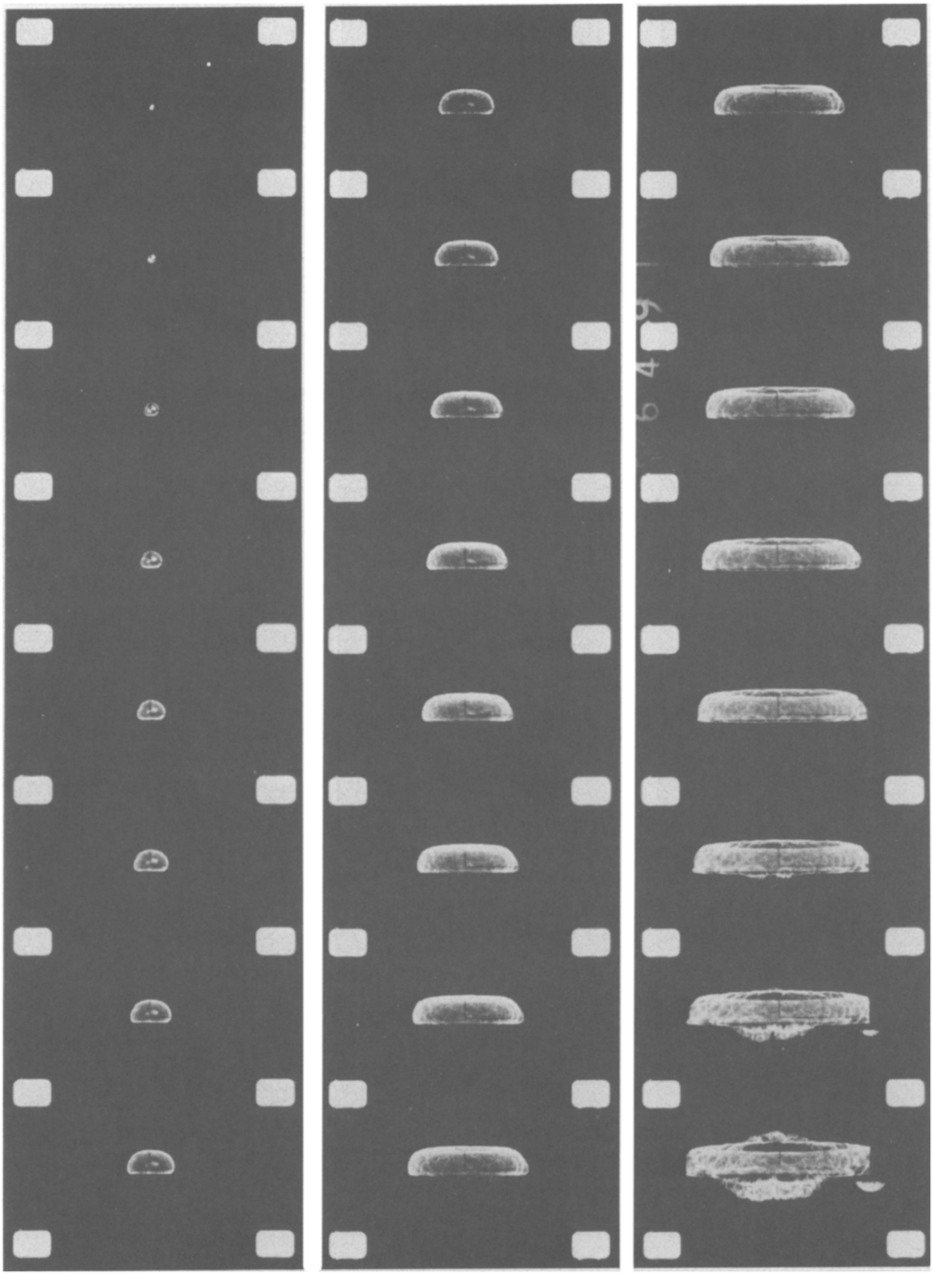

Fig. 6. Example of flame propagation between two plates (8% ethene—air).

increase from methane, through propane and ethene, to acetylene, i.e. in order of relative reactivity.

In the two plates—sticks configuration there are two stages in flame propagation: as the mixture is ignited near the lower plate, the flame initially

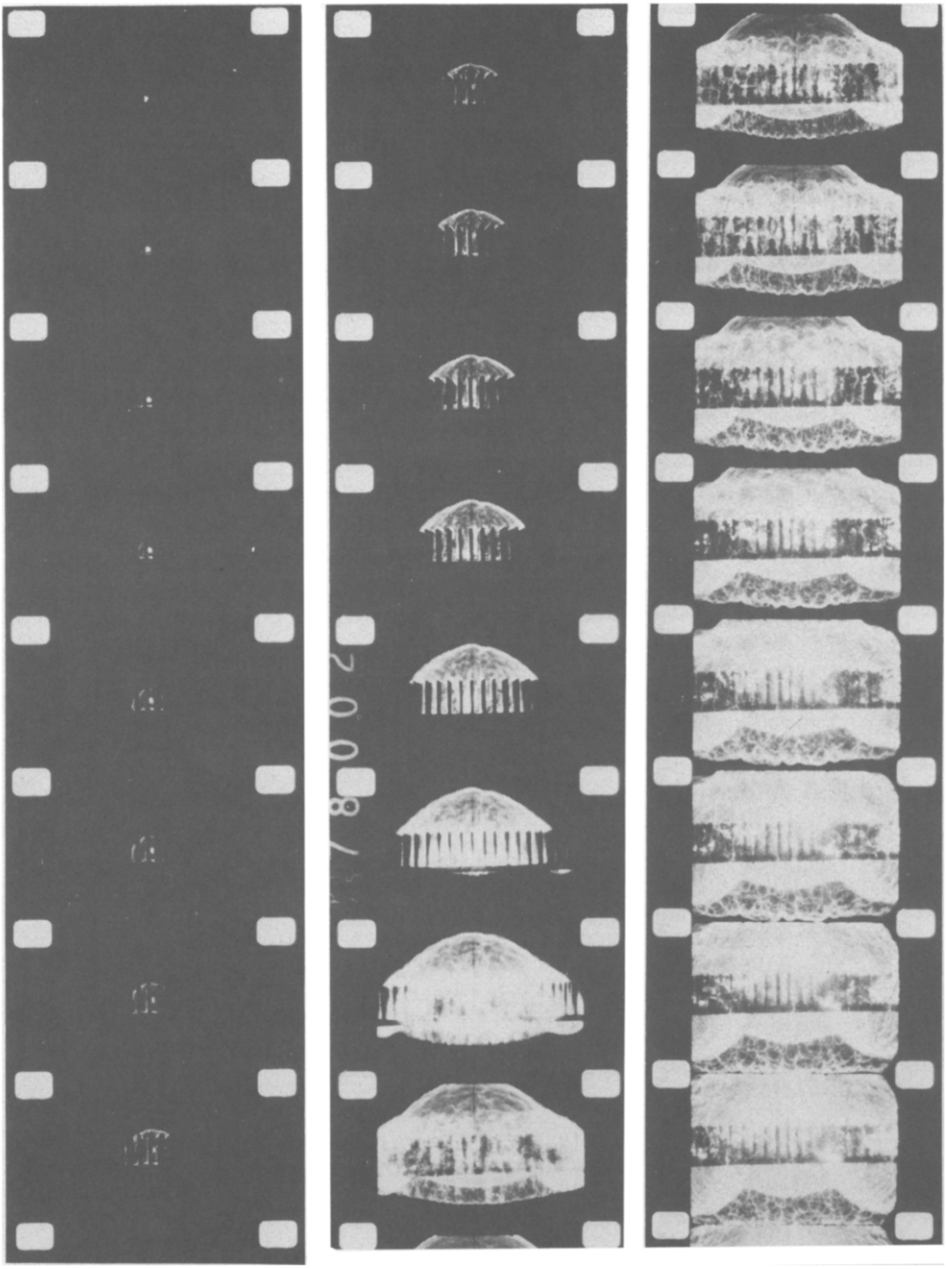

Fig. 7. Example of flame propagation over a single plate with sticks (8% ethene—air).

propagates hemispherically. When the flame hits the top plate at 9 cm, the surface area is decreased and the flame decelerates, which can be distinguished in Figs. 9—11. Next, the flame attains a cylindrical shape and accelerates. The same mechanism should occur in the two plates configuration, but because

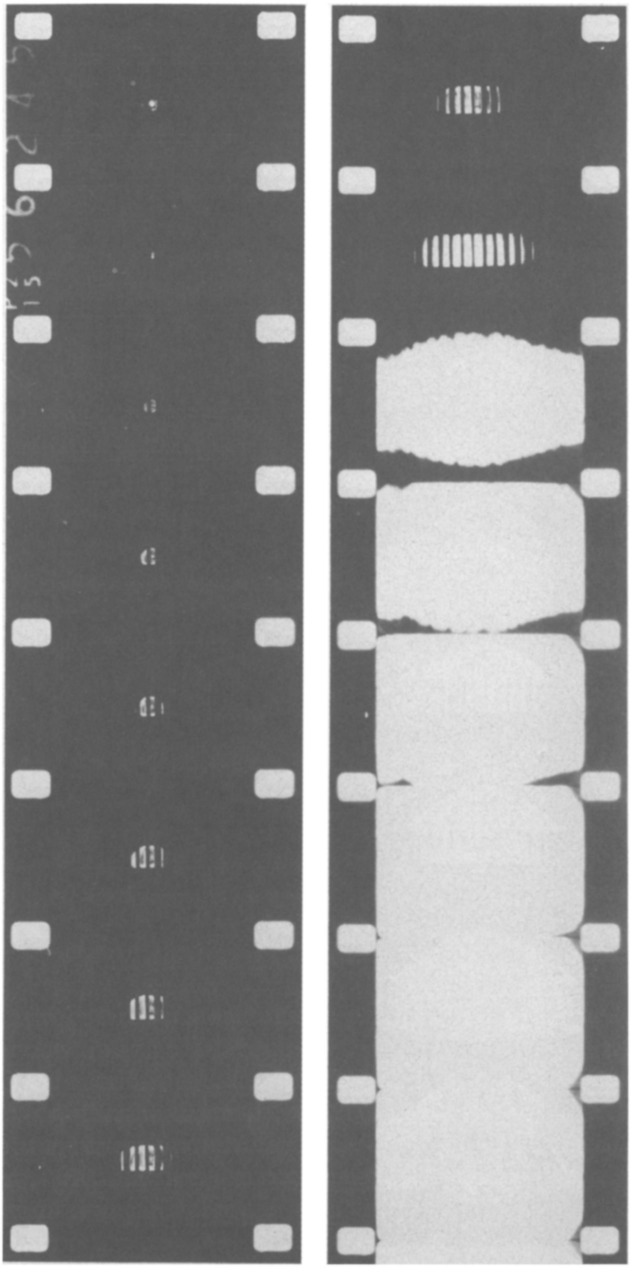

Fig. 8. Example of flame propagation between two plates with sticks (8% ethene—air).

there is hardly any flame acceleration it is hardly or not at all to be seen in the figures.

In order to make a comparison between the results of these experiments and the data from [6] it is necessary to know the pitch (the distance between

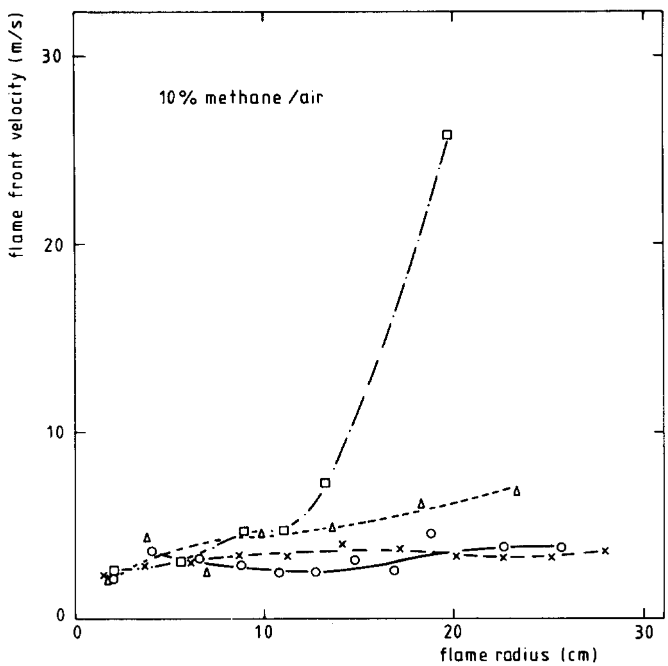

Fig. 9. Relationship between flame front velocity and flame radius for different obstacle configurations; gas mixture = 10% methane in air; ○ = obstacle configuration a; × = obstacle configuration b; △ = obstacle configuration c; □ = obstacle configuration d.

two successive obstacles measured from centre to centre) and the blockage ratio of the two plates—sticks configuration. As no "constant density forest" was used in these experiments, average values had to be determined by looking in different directions and at different radii. The blockage ratio was determined to be about 0.31 and the pitch 3 cm. In [6] data are published concerning the maximum flame speed of stoichiometric methane—air flames observed in a 30.5 cm radius chamber as a function of the blockage ratio for five different obstacle configurations. Interpolation of these data results in a maximum flame front velocity of 35 m/s at a blockage ratio of 0.31 and a pitch of 2.92 cm (experimental conditions comparable to those used in this study). Extrapolation of the test results of the two plates—sticks configuration performed with stoichiometric methane—air mixtures yields a maximum flame front velocity of about 100 m/s at a 30 cm radius.

The difference is most probably due to quenching effects present in the experiments described in [6]. For a blockage ratio of 0.5 the distance between the plates in these experiments amounted to about three times the quenching distance and a comparison has been made by interpolating between this point and a data point for a blockage ratio of 0.25.

Moen [7] has derived a simple model for flame propagation over repeated obstacles between two plates as a function of blockage ratio and pitch. This

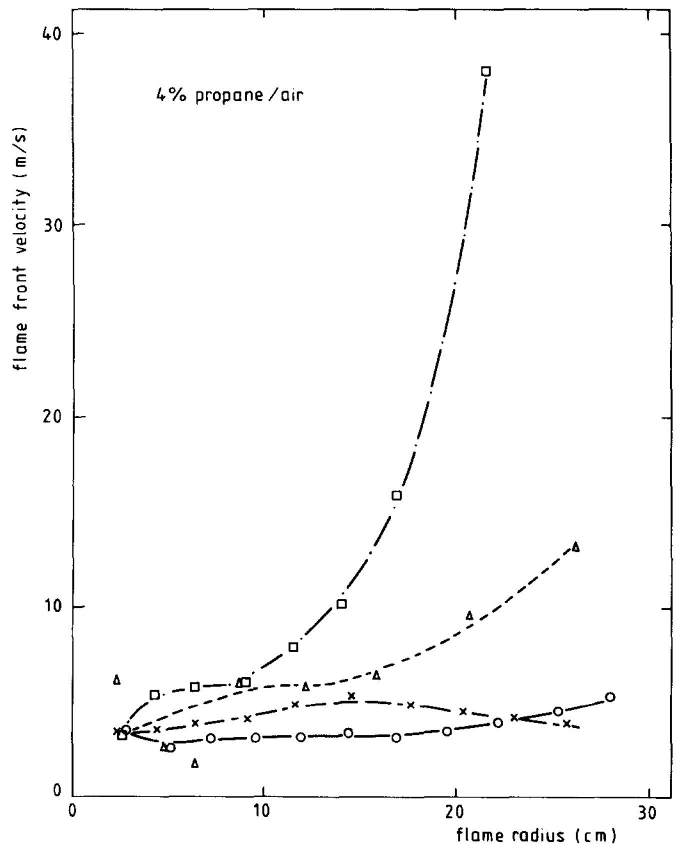

Fig. 10. As Fig. 9 for 4% propane in air.

model is valid when turbulence governs the flame propagation. Here a similar model will be presented to describe the flame propagation when the flow velocity gradient determines the flame propagation in both the two plates–sticks configuration and the single plate–sticks configuration.

If the increase in flame surface area after passage of a row of sticks depends only on the flow velocity ahead of this row, and is proportional to this velocity, then the relative reactivity of the gas mixture (sensitivity for flame acceleration) will not be important. Thus it can be expected that if the measured flame front velocities are divided by the laminar flame front velocity V_L of each gas, one relationship for each obstacle configuration between V_f/V_L and radius will be found. Figures 13 and 14 show that this is indeed the case for both the two plates–sticks and the single plate–sticks configuration.

As long as the flame acceleration is determined by the flow velocity gradient a relationship between flame front velocity V_f and flame radius r

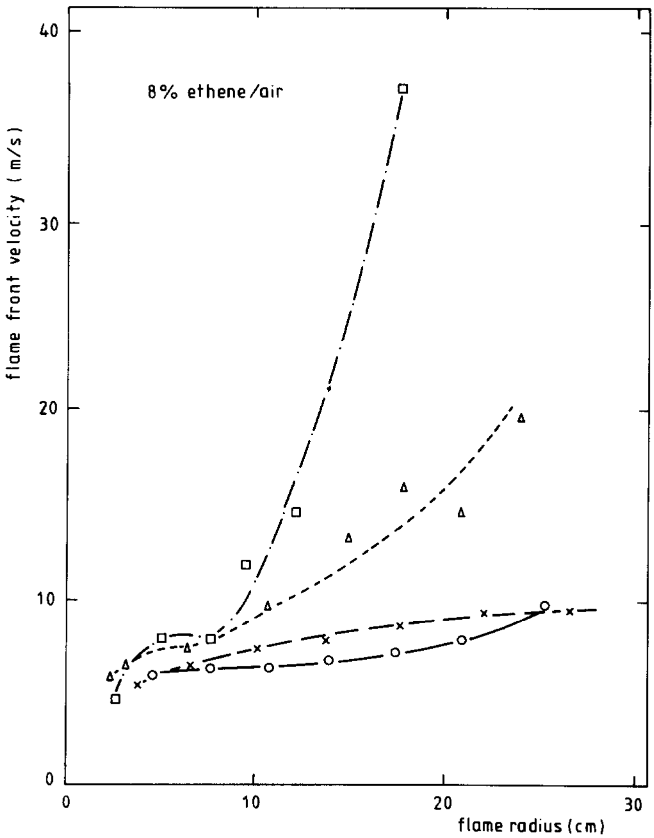

Fig. 11. As Fig. 9 for 8% ethene in air.

can be found. The flame front velocity after the first obstacle V_{f1} is:

$$V_{f1} = V_{f0}\left(1 + \frac{\Delta A}{A}\right),$$

where V_{f0} is the flame front velocity ahead of obstacle 1, and $\Delta A/A$ is the relative increase in flame surface area upon passage of the obstacle.

The flame front velocity after the second obstacle V_{f2} is:

$$V_{f2} = V_{f1}\left(1 + \frac{\Delta A}{A}\right) = V_{f0}\left(1 + \frac{\Delta A}{A}\right)^2 .$$

In general the flame front velocity V_{fn} after the nth obstacle is:

$$V_{fn} = V_{f0}\left(1 + \frac{\Delta A}{A}\right)^n .$$

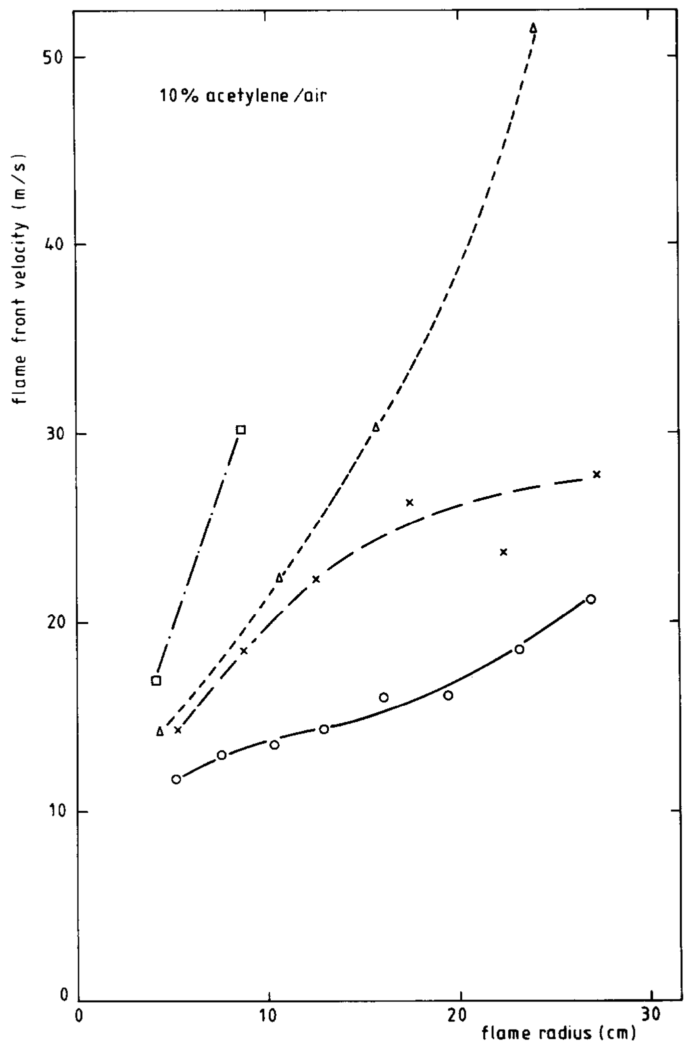

Fig. 12. As Fig. 9 for 10% acetylene in air.

As $n = r/p$ with p = pitch this equation can be rewritten as:

$$V_f(r) = V_{f0}\left(1 + \frac{\Delta A}{A}\right)^{r/p} .$$

From the experiments it is found that there is an initial phase in the flame propagation. If the flame front velocity at the end of the initial phase is αV_L and the flame radius at the end of this phase is r_0, then the dimensionless

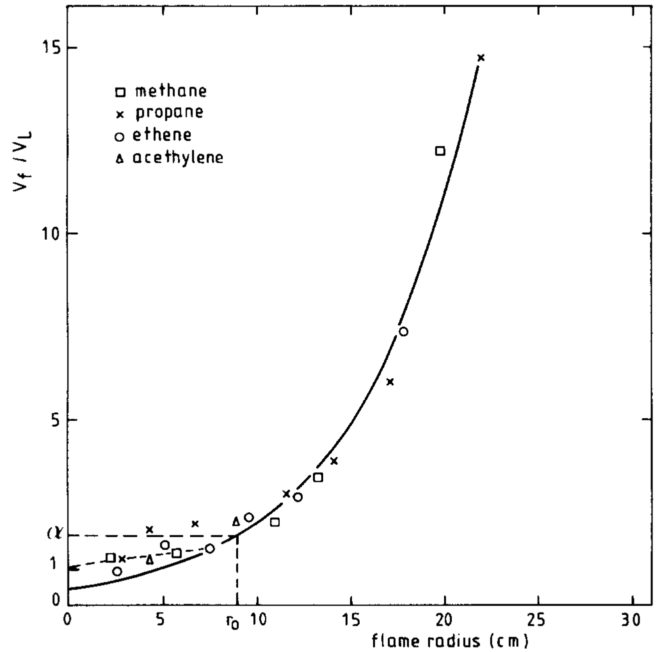

Fig. 13. Relationship between dimensionless flame front velocity V_f/V_L and flame radius for two plates—sticks configuration. The drawn line represents eqn. (1a).

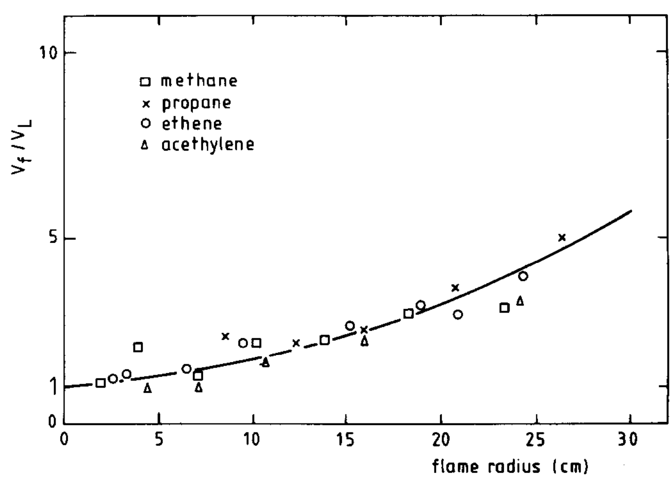

Fig. 14. Relationship between dimensionless flame front velocity V_f/V_L and flame radius for single plate—sticks configuration. The drawn line represents eqn. (1b).

flame front velocity $V_f(r)/V_L$ becomes:

$$\frac{V_f(r)}{V_L} = \alpha\left(1 + \frac{\Delta A}{A}\right)^{(r-r_0)/p} \tag{1}$$

The value of $\Delta A/A$ will be strongly dependent on the blockage ratio and also on the number of walls along which the gas flows. $\Delta A/A$ will probably also depend on the pitch p and certainly on the geometry of the flow. As $\Delta A/A$ depends on the blockage ratio and on the pitch of the obstacles its value will not be constant as pitch and blockage ratio are not constant over the plate. The assumption of the constancy of $\Delta A/A$ in the derivation of eqn. (1) therefore is a simplification. The value of $\Delta A/A$ in these experiments can be found by fitting the curve of eqn. (1) to the data in Figs. 13 and 14.

In the two plates—sticks configuration flame propagation is hemispherical initially. Some time after the flame reaches the top-plate, flame propagation is cylindrical. Therefore the flame radius at the end of the initial phase is taken to be r_0 = 9 cm (the distance between the two plates). From Fig. 13 it appears that the flame front velocity at this moment amounts to 1.85 V_L ($\alpha = 1.85$).

Using these data one derives:

$$\frac{V_f(r)}{V_L} = 1.85\,(1.62)^{33.3r-3} \tag{1a}$$

with $\Delta A/A$ = 0.62 and p = 0.03.

If $\Delta A/A$ is varied slightly the curve will still fit to the majority of the data points in Fig. 13. $\Delta A/A$ can be varied between 0.55 and 0.67. In the single plate—sticks configuration no initial phase is present. Therefore r_0 = 0 cm and α = 1. To fit the data of Fig. 14 one derives:

$$\frac{V_f(r)}{V_L} = (1.19)^{33.3r} \tag{1b}$$

with $\Delta A/A$ = 0.19 and p = 0.03. Here $\Delta A/A$ can be varied between 0.16 and 0.22.

The large difference in $\Delta A/A$ values reflects mainly the difference in geometry of the flow field, which causes a weaker coupling between the flow in the direction of the sticks and the flame front velocity. From the above it is clear that the relative reactivity of the gas mixture as such has no influence on flame propagation in this regime. Flame propagation is determined by flame surface area increase caused by flow field gradients. As soon as turbulence becomes important, it can be expected that the reactivity becomes significant also. In [12] it was found for different values of the Reynolds number that, at a given turbulence intensity, the quotient S_T/S_L (turbulent/laminar burning velocity) decreases when the laminar burning velocity increases. It is therefore to be expected that for higher flame front velocities there will be no longer one single relationship between dimensionless flame front velocity and flame radius for all gases. This should have to be verified experimentally at a larger scale.

As these experiments were performed in a closed vessel, there will be some pressure increase by the time the flame front reaches the edge of the plates. This pressure increase was about 2.5 to 5 kPa during the experiments.

The flame propagation over the obstacles also has its effect on the course of the explosion in the remainder of the mixture in the vessel. This effect is most clear for the two plates—sticks configuration which causes a very strong jet ignition of the mixture. The maximum rate of pressure rise in the vessel in that case is about twice the value found with ordinary spark ignition of the quiescent mixture.

Conclusions

Both in two- and three-dimensional geometries a continuous accelerating flame was observed in the presence of repeated obstacles. A positive feedback mechanism between the flame front and a disturbed flow field generated by the flame is responsible for this. The disturbances in the flow field mainly concern flow velocity gradients. Without repeated obstacles the flame front velocities reached are low, both in two-dimensional and three-dimensional geometry.

In the presence of obstacles flame front velocities attained in two-dimensional geometry are much higher than in three-dimensional geometry. Upon passage of an obstacle the flame surface area increases by about 60% in two-dimensional geometry and by about 20% in three-dimensional geometry. The difference is caused by the difference in coupling between flame front velocity and flow velocity in the direction of the obstacles.

The relative reactivity has no influence on the results of these experiments: it is possible to correlate the results for different gases using the laminar flame front velocity.

The presence of the wall of the vessel in these experiments could interfere with some of the results because of interaction of pressure waves returning from the wall to the centre and the flame front.

The results of the experiments cannot be scaled up as more insight is needed in the role of flame velocity gradients on a larger scale.

The experiments make clear that not only the presence of obstacles but also the degree of confinement plays an important role during at least the early phase of the explosion.

Acknowledgement

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