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INITIATION, STABILITY AND LIMITS OF DETONATION FOR ADVANCED STABLE/AIR-BREATHING AND HYBRID PROPULSION ENGINE DESIGN

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13. ABSTRACT

During this period research was carried out on the influence of initial conditions on limits of detonability in hydrocarbon-air mixtures, with emphasis on the influence of detonation tube shape. Experimental results for circular cross-section tubes indicated that the detonation limit is a linear function of reciprocal tube diameter. For square cross-section tubes experimental results obtained seem to indicate that the limits of detonability are slightly wider than for circular, and neither hydraulic radius, tube area, or narrowest tube dimension determines limits of detonability. However, measurements in rectangular tubes with various cross sections seem to indicate that for rectangular cross section tubes there exists a very close correlation between the limits of detonability and the narrowest hydraulic diameter of the tube, as long as one side is not too narrow. Investigation of development was also carried out including study of the stability of propagation of spherical flames in CH_4, H_2, C_2H_4, and C_2H_2 with increasing oxygen content in the air, using soap bubble techniques for determining flame speed. In all systems investigated no indication of flame acceleration or transition to detonation was observed. Results indicated that external mechanisms were responsible for flame acceleration and transition to detonation in experiments of other researchers. Some of the experimental results have been reported at the de Chema conference in Feb 1972.

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	ROLE	WT	ROLE	WT	ROLE	WT
DETONATION						
LIMITS OF DETONABILITY						
INFLUENCE OF TUBE SHAPE ON STABILITY						
SPHERICAL EXPLOSIONS						

INFLUENCE OF THE SHAPE OF THE DETONATION TUBE

ON THE LIMITS OF DETONABILITY

Introduction

Limits of detonability are normally determined in detonation tubes of circular cross section. In these tubes one finds that the limit concentration of the mixture is proportional to the reciprocal tube diameter, except at tube diameters, which are close to the limiting tube diameter, below which no detonation exists, even in stoichiometric mixtures. For reliable determinations of limits of detonability two points are very important:

1. the test tube must be long enough. This means that the tubes must be so long, that further increase of the length of the tube does not influence the limit of detonability. (It may, however, reduce the uncertainty of the limit concentration, which should go to zero for infinite tube length.)

2. The detonation must be ignited by another detonation, so that it starts as an overdriven detonation and reaches its stability limit from "above". Otherwise one normally obtains limits which are narrower.

A simple minded explanation of the limits of detonability is based on the observation that close to the limit nearly always single headed spin appears, the frequency of which is essentially determined by the tube diameter and the sound velocity in the burned gases. It is driven by energy addition to the vibration which due to Raleighs statement takes place in the right phase of the vibration. If the chemical reaction becomes to slow, to fit that condition (details of the processes do not alter that result) than the detonation fails. This explanation allows to describe the experimental findings in circular tubes if one takes into account, that the wall generated expansion waves are stronger in narrow than in wide tubes, so that they compensate for the slightly higher temperature in the burned gas of limit detonations in tubes of small diameter and the C (limit) $\sim d^{-1}$ relation is obeyed quite well.

For rectangular tubes two spin modes are observed near the limits of detonability. The one fits to the long side, the other one, with higher frequency to the short side of the rectangular cross section. The above mentioned argument could lead to the conclusion, that the lowest (or the higher) of both frequencies determines the limit of detonability. If that is so the length of one of the two sides of a rectangular tube should be nearly the same as the diameter of a circular tube at the limit of detonability.

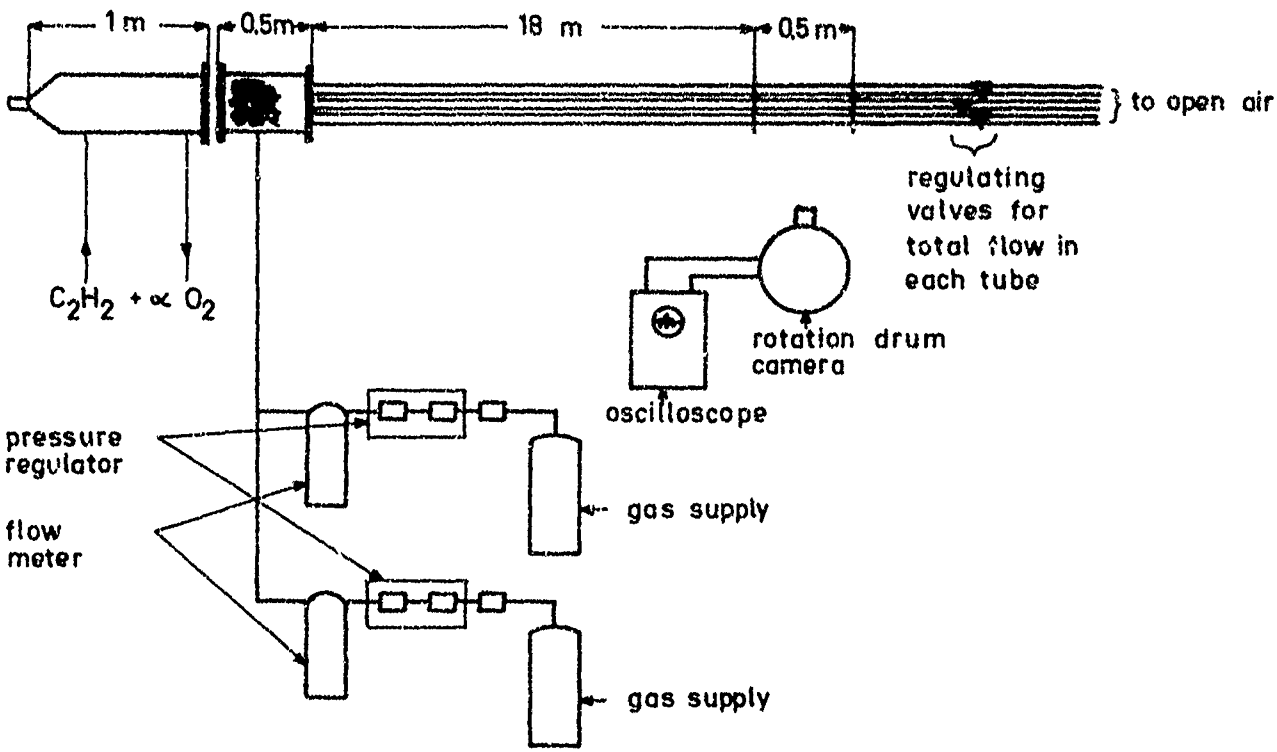

Fig. 1 Experimental set up for Measurements of the Influence of Tube Shape on the Limits of Detonability

Experimental Arrangement

The influence of the shape of the detonation tube on the limits of detonability has been investigated in an apparatus described below:

Three tubes are mounted parallel. The flow resistance of the tubes are made equal by proper choice of an end piece of each tube which is two meters apart from the windows. The whole length of the tubes is 20 meters. Windows are made from plexiglass, 40 cm long, and mounted flush into the tubes. For the experiments the windows of the various tubes are arranged one above the other with 1 cm distance inbetween. Each tube is signed by two Tesa strips with characteristic distance so that the picture of each tube can easily be recognized on the film.

The ignition section consists of a 1.5 meter long tube of 9 cm diameter and a spark gap at the closed end. The tube is filled over a distance of 80 cm with a wire entanglement in order to improve the establishment of the initiating detonation. (Mostly an adjusted C_2H_2-O_2 mixture) It is connected with another tube of the same diameter (with a thin diaphragm between both). In the end plate of this section the detonation tubes are mounted.

This section and the detonation tubes are filled simultaneously with the same mixture (clean CH_4-O_2). Mixture compositions are measured by capillary flow meters connected to the gas supply by two successive constant pressure valves. An additional valve is mounted at the steel tank. Calibration of the flow meters is done with precision gas meters.

Variation of the gas composition should have a negligible influence on the results because the experiments are performed, such that detonations in one or two tubes fail, while the third tube still shows stable detonation. Taking a mixture in some distance from the limit, the three detonations arrive at the same time at the windows. Coming closer to the limits of detonability, detonations start to fail and the arrival of the combustion processes at the windows does not take place at the same time anymore. The absolute values of the detoration limits are therefore not as precise as the relative data.

In the past, measurements of limits of detonablility have been performed with an apparatus in which the detonation tubes reached about 15 cm into the initiation section. This has been done in order to delay the influence of the reflected detonation. With the rectangular tubes used, it was found, however, that under these conditions the tube is deformed in the inition section so that unreliable results have been obtained. Therefore the connection of the detonation tubes with the initiating section have been changed and the tubes were mounted flush into the end plate. For tubes with circular cross section this did not influence the limits of detonability much; the same may be assumed for tubes of other shape.

The rectangular and the square cross section brass tubes (1 mm wall) in addition are supported by steel bars on the long side over the whole tube length. This is necessary because otherwise at places where apparently detonations start, the tubes are deformed or destroyed. At the place where the windows are mounted all tubes are supported against deformation by steel constructions. The pressure in the tubes filled with gas mixture has been atmospheric pressure in all cases. No correction for variations of the atmospheric pressure has been applied. Temperature of the mixture was 20 $^{o}C \pm 1$ in all experiments. After each experiment the tubes were cleaned and dried by blowing dry nitrogen through for a while. Every day the leak rate and the cross section of tubes were checked.

Experimental Results

For the experiments the following tubes have been used:

Circular cross section

Diameter	(cm)	2.0 (A)	1.8 (B)	0.8 (C)
Area	(cm^2)	3.15	2.54	0.5
Hydraulic radius	(cm)	1.0	0.9	0.4
Hydraulic diameter	(cm)	2.0	1.8	0.8

Square cross section

Side length	(cm)	1.8 (D)	1.6 (E)
Area	(cm^2)	3.24	2.55
Hydraulic radius	(cm)	1.02	0.902
Hydraulic diameter	(cm)	2.04	1.804

Rectangular cross section

Long side	(cm)	3.8 (F)	1.6 (G)
Short side	(cm)	0.8	0.8
Area	(cm^2)	3.04	1.28
Hydraulic radius	(cm)	0.985	0.64
Hydraulic diameter	(cm)	1.97	1.28

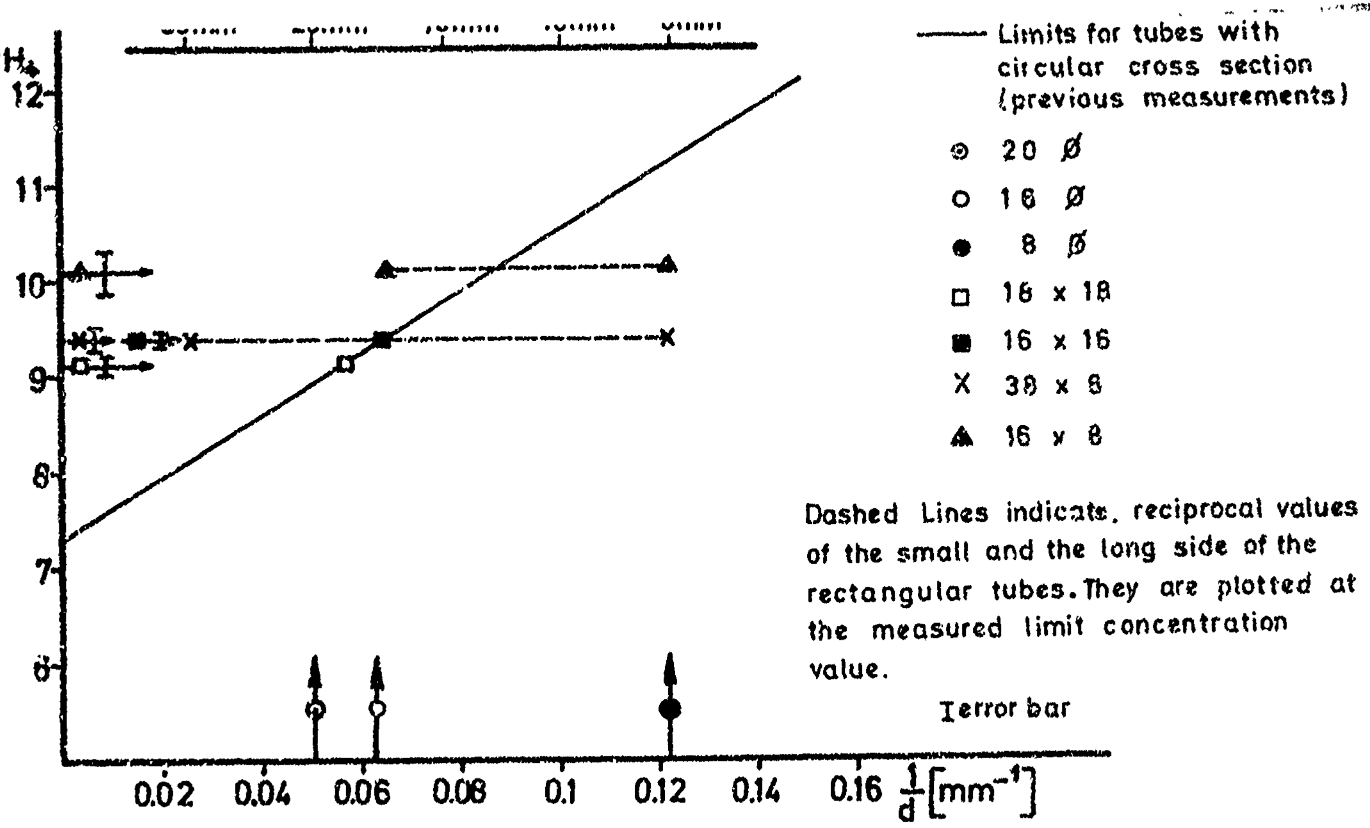

Fig. 2 Limits of Detonability for lean CH_4 - O_2 Mixtures for various Tube Shapes and Diameters

For tubes with circular cross section previous results could be confirmed within the limits of experimental error. The limit concentration is a linear function of the reciprocal tube diameter.

The two tubes with square cross section behave in a similar manner. For the tube with larger side length the limits of detonability are slightly wider than for the other one. The absolut values of the concentrations at the limit seems to fall on the line for tubes with circular cross section in the C(limit), 1/d plott if the side length is taken as d. The hydraul'. diameters of the square cross section on tubes are a little larger than the side length. They do not fit as well in the C(limit) - d^{-1} plott as the side length. In case of tube D the limits are definitely narrower than for tube A while the hydraulic diameter is larger. The differences are, however, small.

A different situation arises for the rectangular tubes. Here neither the long side nor the short side nor the hydraulic radius fit into the line C(limit) - d^{-1}. The limits of detonability for the 3.8 x 0.8 rectangular tube are definitely narrower than those for the tubes A, D and E. They roughly correspond to those for 1.6 cm square tubes while the limits for the 1.6 x 0.8 rectangular tube are still narrower.

If the smallest distance in the tube would determine the limits both rectangular tubes should nearly coincide with the 0.8 cm diameter circular tube. Apparently the 1.6 cm long side widens the limits about 1 % while the 3.8 cm side widens them about 1.8 % compared to the limit for infinite tube diameter, which in the present case is about 4 % away.

The hydraulic diameters for these tubes do not fall on the C(limit) - d^{-1} line either. However, the line connecting the hydraulic radii at the limits for the rectangular tubes seems to be parallel to the C(limit)-d^{-1} line for the circular cross section tubes. Roughly one can say that an estimate of the limits of detonability based on the hydraulic diameters gives a reasonable value which in the case under discussion here fits better than 1 %. It is obvious, however, that this is not a good description of the real process. Apparently a correct stability analysis has to take into consideration the details of the interaction process between chemical reaction and flow inside and behind the reaction front. To a certain degree, however, the correlation with the hydraulic diameter seems to be a reasonable approximation as long as one side is not to narrow. It is to be expected, that there exists a condition, that the small side of the rectangle hasto be larger than a lower limit d_1 , which, however, is definitely smaller than the limiting diameter for tubes with circular cross section. For very large tubes (in each dimension) the shape of the tube should have nearly no influence on the limit of detonability for infinite tube diameter. That would require, that, if one wants to keep the linear relation at the limits of detonability for C(limit), d^{-1} there exist limit lines which depend on the shape of the cross section of the tube. This influence is, however, not very pronounced, even a ratio of the sides of a rectangular tube close to 5:1 gives only a deviation, based on the hydraulic radius of less than one percent. On that basis it can be understood, why attempts for a quantitative description of the limits of detonability and the influence of tube diameter, pressure, temperature and other parameters on these limits have not been very successfull in that rough models could be improved and put on a quantitative basis.

Some Experiments on the Propagation of Spherical Flames

Introduction

The soap bubble method is a well known method for determination of flame speeds Λ. If the expansion radio ρ_1/ρ_0 is known one obtains the flame speed by measuring the rate of propagation of the flame area

$$\Lambda = v \cdot \rho_1/\rho_0$$

In most of the experiments reported in the literature the spread of the flame on the film, (taken by a smear camera) is a straight line indicating constant values of . The flow situation for such a case is shown in Fig. 3. The gas ahead of the flame is shifted away from the center. The pressure increases from a very weak front shock towards the flame front. Behind the flame the gas is practically at rest. Flame velocities obtained by the soap bubble method are in good agreement with values obtained by other methods.

There are, however, indications, that the flame propagation does not take place as smoothly as one might expect from the fact that the measured flame velocities are all right.

Trosbin published schlieren pictures of flames which indicate cellular structure of the flame front. Measurements of flames in constant pressure bombs often give not only

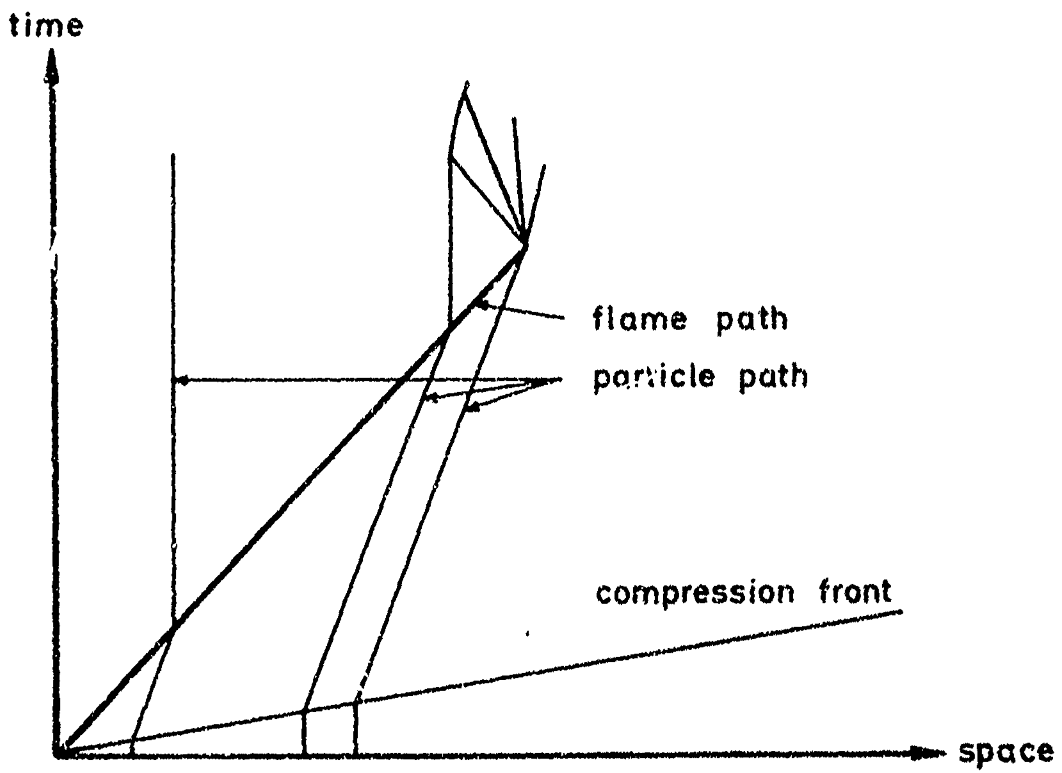

Fig. 3 World Line of Stationary Spherical Flame

wrong absolute values of Λ but also a wrong pressure dependence of the flame speed. Investigations of sound generated by flames also indicates a structure.

Kogarho reports that flames in propane oxygen mixtures, ignited by a spark can accellerate and show transition into detonation.

Istratov performed calculations on the stability of spherical flames. These calculations gave a critical Reynoldsnumber based on the radius for the stability of spherical flames. The value of this critical Reynoldsnumber, however, is far away from the one obtained by Troshins experiments.

The problem of stability of spherical flames is of fundamental importance for explosions of free gas clouds. The central question is: which mechanism leads to flame accelleration?

In tubes it is obvious: the unburned gas, flowing ahead of the flame can become turbulent and this can lead to progressive flame accelleration, generation of shock waves and so on, a well known process. The immediate generation of interacting shock waves normally takes place only in a later stage of the process.

There are indications that the disturbance of the flame front in bomb explosions and also in some soap bubble experiments are generated by reflected pressure waves. Especially in bomb explosions this could clearly be shown. The first step in air experiments therefore had to be to find an experimental arrangement to minimize that influence.

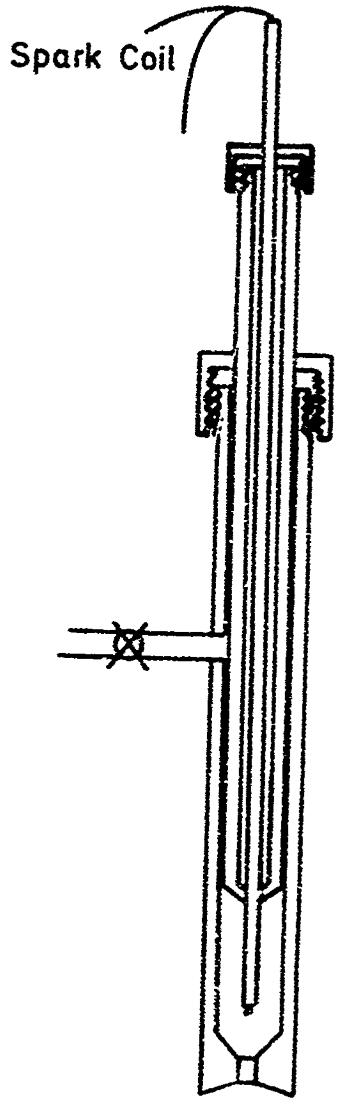

Fig. 4 Soup Bubble Generator

Experimental Arrangement

The gas mixture is prepared by capillary flow meters with pressure stabilized supply. Part of the continuous flow is extracted through a soap bubble generator via a special valve. If the bubble reaches the wanted diameter this valve is closed. The soap bubble generator (Fig. 4 consisted of a plexiglass tube (1.5 cm diameter) with a piston inside. This piston contained the electrodes. It was constructed such that it closed the flow inlet as well as the gas exit to the soap bubble. This bubble generator was mounted on a 1 cm stell bar. There were no solid walls around the bubble at distances below 1 m so that reflected waves needed at least 1/150 sec to come bake to the soap bubble. For flame speeds in the order of one meter per sec and about 10 cm bubble diameter this means that reflected sound waves do hardly come back as long as the bubble burns. The bubble generator itself was mounted by thin long metall tubes. Sound waves reflected at these tubes can come back to the flame. They are, however, highly attenuated. This had to be accepted because the ideal method, free gas bubbles ignited centrally by laser radiation would have been much to complicated in that phase if the investigation.

The smear camera is mounted about one meter away from the soap bubble. The soap bubble is projected into an image plane where a slit takes away most of the picture; only a small horicontal strip of the bubble is then projected on the film for measuring the flame spread.

Experimental Results

In order to check the reliability of the system flame velocities of CH_4-air and H_2-air mixtures have been measured and found to be in good agreement with literature data. Then the following systems have been investigated

CH_4 - α air

CH_4 - α air (with 50 % O_2)

CH_4 - α air (with 80 % O_2)

CH_4 - α O_2

H_2 - α air (with 50 % O_2)

H_2 - α O_2

$(CH_4 + H_2)$ + α O_2

C_2H_4 - air

C_2H_4 - O_2

C_2H_2 - air

C_2H_2 - (air with 50 % oxygen)

C_2H_2 - O_2

In all these systems which were investigated in soap bubbles of 7 cm diameter not the slightest indication of a flame accelleration could be observed. (Ignition by an engine spark)

The experiments continued with attempts to generate larger soap bubbles. For the methane, the (CH_4+H_2) and the C_2H_4 systems bubbles of 15 cm diameter could be generated. For C_2H_2 - air and for C_2H_2 - O_2 bubbles up to 12 cm could be formed.

The photographs of these flames (each mixture has been used 3 to 5 times at different days) also did not indicate any accelleration of the flames.

These results indicate that up to about 15 cm diameter of the gas ball there seems to be no internal mechanism which accellerates flames (even in mixtures with O_2) so that transition to detonation takes place. At least in that range of diameters of the bubble external mechanisms must have been active in the experiments of other authors.

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