Shock Waves (2005) 14(3): 193–203
DOI 10.1007/s00193-005-0264-7

ORIGINAL ARTICLE

**S. P. Medvedev · S. V. Khomik · H. Olivier ·
A. N. Polenov · A. M. Bartenev · B. E. Gelfand**

Hydrogen detonation and fast deflagration triggered by a turbulent jet of combustion products

Received: 9 December 2003 / Accepted: 16 December 2004 / Published online: 12 September 2005

Abstract Initiation of detonation by a turbulent jet of combustion products has been studied in a detonation tube of 141 mm inner diameter. Jet formation techniques based on either a perforated plate or bursting membrane subjected to the impact of a stable detonation wave were utilized. Critical conditions of detonation initiation in hydrogen–air and hydrogen–oxygen–nitrogen mixtures have been found to depend on both the mixture sensitivity and the geometrical parameters of the arrangement.

Keywords Jet initiation · Detonation · Perforated plate · Bursting membrane · Critical conditions

PACS 47.70.Fw; 82.33.Vx; 82.40.Fp

1 Introduction

The possibility of detonation initiation by a turbulent jet of combustion products was first demonstrated by Knystautas et al. [1] in the experiments with acetylene–oxygen mixture. The basic element of the setup consisted of a spherical combustion chamber equipped with a venting orifice. The outflow of combustion products through the orifice resulted in an initiation of a detonation wave in the surrounding volume, which was filled with the combustible mixture as well. It was shown that the initiation process could start in immediate proximity to the outlet in the zone of turbulent mixing between high-temperature combustion products and unburned fresh mixture. This phenomenon was referred to as direct initiation of detonation by a turbulent jet of combustion products.

Carnasciali et al. [2] extended the assortment of combustible mixtures and simultaneously modified the technique of producing the turbulent jet of combustion products. The combustion chamber was separated from the test section by hermetically sealed membrane designed for the rupture at maximum pressure of the explosion at constant volume. In comparison with Knystautas et al. [1], the advantage of this technique was the absence of the unburned component in the turbulent jet. Beside of this, the technique described enables to use different combinations of the explosive mixtures in the combustion chamber and in the test section. In the experiments of Carnasciali et al. [2] the composition of the combustible mixture and the diameter (shape) of the outlet were varied in a wide range. Similar experiments were performed by Bezmelnitsin et al. [3] and Bezmelnitsin [4]. The main outcome of the investigations of Carnasciali et al. [2], Bezmelnitsin et al. [3], and Bezmelnitsin [4] was the determination of the critical conditions of detonation initiation, namely, the composition of the combustible mixture and the diameter of the turbulent jet of combustion products at which detonation regimes occur. Some results on the effect of strength of initiation source on the critical conditions of jet initiation of detonation were reported by Krok [5], and Pfahl and Shepherd [6]. Additionally, special efforts were undertaken by Bezmelnitsin et al. [3] and Bezmelnitsin [4] to reveal the distinctive features of the jet initiation process under confined and unconfined conditions. In accordance with Bezmelnitsin et al. [3], the initiation processes can be divided in the following way: (1) direct initiation in the zone of turbulent mixing between combustion products and fresh mixture; (2) detonation initiation by localized explosions, which result from the interaction between the jet and shock waves reflected from the bounding walls. It should be noted that concentration limits of detonation initiation in Carnasciali et al. [2] and Bezmelnitsin et al. [3] were determined for sensitive oxygen-enriched mixtures. However, the

---

This paper was based on work that was presented at the 19th International Colloquium on the Dynamics of Explosions and Reactive Systems, Hakone, Japan, July 27 - August 1, 2003

Communicated by J.E. Shepherd

S. P. Medvedev (✉) · S. V. Khomik · A. N. Polenov · A. M. Bartenev · B. E. Gelfand
RAS, Institute of Chemical Physics, Kosigina Street 4,
119991 Moscow, Russia
E-mail: medvedev@polymer.chph.ras.ru

H. Olivier
RWTH Aachen University, Shock Wave Laboratory,
Templergraben 55, 52062 Aachen, Germany

increase in the scale of the experimental setup by Berman [7], Moen et al. [8, 9], and Dorofeev et al. [10] and the results achieved in this paper give experimental evidence on successful jet initiation of detonation in hydrogen–air and acetylene–air mixtures.

The attempt of a detailed study of the mechanism of direct detonation initiation by a turbulent jet of combustion products was made by Inada et al. [11] on the basis of photographic observations. The experiments revealed that the distinctive difference between the known process of transmission of a detonation wave from the tube into an unconfined space and the process of detonation initiation by a jet is due to the absence of a transverse wave structure in the latter case. To draw the analogy with the re-initiation of a detonation wave, Inada et al. [11] assumed that a turbulent jet (high-speed compressible reactive flow) is by itself the source of acoustic disturbances, which could amplify and transform into a regular transverse wave structure. Local conditions of amplification and interactions of transverse waves remain unclear. Nevertheless, Inada et al. [11] and others, e.g. Knystautas et al. [1], Moen et al. [8], Carnasciali et al. [2], and Bezmelnitsin et al. [3], denote that most probably the processes mentioned earlier take place in the region of self-ignition, which appears as a result of a fast mixing between combustion products and fresh mixture. Ultimately, the interpretation of the phenomena related to jet initiation of detonation seems to be logically connected to the concept of spontaneous detonation initiation in systems with non-uniform temperature and concentration distribution in combustible mixtures under self-ignition conditions.

The phenomenon of spontaneous initiation of strong explosion regimes in combustible gaseous mixtures was theoretically proved by Zel'dovich et al. [12]. During the past two decades, this work served as a basis for numerous theoretical investigations, which are reviewed by Bartenev and Gelfand [13]. The fundamental fact established in Zel'dovich et al. [12] is that the presence of a proper gradient of self-ignition delay in a combustible mixture can lead to the initiation of strong shock waves and detonation. The "gradient" mechanism of detonation initiation is realized without a powerful source (such as high explosive or strong electrical discharge) and at distances, which are incomparably smaller than those required for a deflagration-to-detonation transition (DDT). Lee et al. [14], whose paper is devoted to photochemical detonation initiation, formulated the gradient mechanism of amplification of pressure waves by the abbreviation SWACER (Shock Waves Amplification by Coherent Energy Release). An external manifestation of the phenomenon of jet initiation of detonation gives considerable support to the gradient mechanism. However, till now, the quantitative theoretical description of the phenomenon of jet initiation meets with difficulties, and one of the reason of that is the lack of systematic data collected in the experiments for properly defined conditions.

The inconsistency in the experimental data of different authors can be due to different jet formation techniques used. The disadvantage of the flame jet drivers Knystautas et al. [1], Berman [7], Moen et al. [8, 9], Mackay et al. [15], Ungut and Shuff [16], and Thomas and Jones [17] is caused by the continuous outflow of the unburned mixture in front of the flame front. This outflow can lead to a significant turbulization of the mixture ahead of the jet and therefore, the detonation starts under uncontrolled conditions. This difficulty can be overcome by the use of the bursting membrane technique [2, 3, 10, 11]. In this case, the jet upstream stagnation conditions immediately in front of the jet forming part are properly defined and easily to be determined. However, the ruptured fragments of the bursting membrane can significantly influence the flow properties of the jet.

Recently, Chao et al. [18] suggested a newly developed technique of jet formation. The method is based on the use of a multiple-orifices perforated plate occupying the whole inner cross-section of a tube in which a stable detonation wave propagates. Similar to the bursting membrane used by Inada et al. [11], the perforated plate serves to destroy the regular cellular structure of the incident detonation wave. The detonation wave reflects at the perforated plate and a flow of hot detonation products through the multiple orifices is generated. In accordance with Chao et al. [18], the flow through the orifices is choked. In this case, the velocity of the jet is equal to the local speed of sound. The size of the individual holes of the perforated plate should not exceed the cell width to ensure a reliable quenching of the transverse wave structure. The described method of jet formation was used in Chao et al. [18] for the detonation initiation in hydrocarbon–oxygen–nitrogen mixtures downstream of a perforated plate in a quasi one-dimensional arrangement, i.e., the diameter of the perforated plate was equal to the inner tube diameter. However, there is no doubt that the perforated plate technique can also be employed to the problem of jet initiation of detonation in two-dimensional confined and semi-confined geometries.

Numerous experiments under different conditions give decisive evidence that detonation initiation by jet mixing can be accomplished in both confined and unconfined geometries. A variety of jet formation techniques were used. The most promising among them are the formation of a jet by the rupture of a membrane, exposed to either a reflected detonation wave or a constant volume explosion, and the reflection of a planar detonation wave at a multi-orifice plate. Concerning the hydrogen safety problems, one can note that large-scale experiments performed by Berman [7] and Dorofeev et al. [10] with hydrogen–air mixtures are very important for the comprehension of the phenomenon of jet initiation of detonation under real conditions. Nevertheless, some questions are still open, and additional experiments are necessary for a more complete understanding.

The important directions of investigations are: (1) systematic study of the influence of the confinement on the dynamics of jet initiation of detonation in a wide range of geometrical parameters; (2) direct comparison of different jet formation techniques; (3) determination of the proper non-dimensional parameters and criterions which could be important for analysis of jet initiation of detonation under the real larger-scale conditions. In the present work, jet-initiated hydrogen detonation/combustion phenomena are studied by using jet formation techniques based on the perforated plate and bursting membranes.

2 Experimental procedure

2.1 Experimental setup

The experiments were performed in the TH-1 shock/detonation tube of the Shock Wave Laboratory of RWTH Aachen University. The scheme of the setup is presented in Fig. 1. The inner diameter of the tube amounts to $D_0 = 141$ mm and the overall length of the tube is 14.5 m. Functionally, the setup is divided into three main parts in the following way: (1) accelerating section; (2) test section; (3) tracking section.

The accelerating section is intended for the initiation of a stable detonation wave. An exploding wire at the closed end of the accelerating section ignites the combustible mixture. Obstacles in form of a Shchelkin spiral or equidistantly placed rings fill the first part of the accelerating section. The obstacles enable the acceleration of a flame and the controlled DDT process. The length of the obstacles-filled part of the tube is 2 m. The preliminary experiments revealed that a stable detonation wave in stoichiometric hydrogen–air and hydrogen–oxygen mixtures is established at a short distance downstream of the obstacles. Thus, the minimum length of the accelerating section of 5 m was found to be acceptable. Some experiments were performed with an accelerating section of 9 m in length.

The test section is attached to the accelerating section and presents the most important part of the facility (see Fig. 1). It houses a specially designed support for the mounting of the jet forming parts. The length of the test section amounts to 0.3 m. This part of the setup is the most extensively instrumented one including multiple holes for pressure and other gauges and optical windows as well.

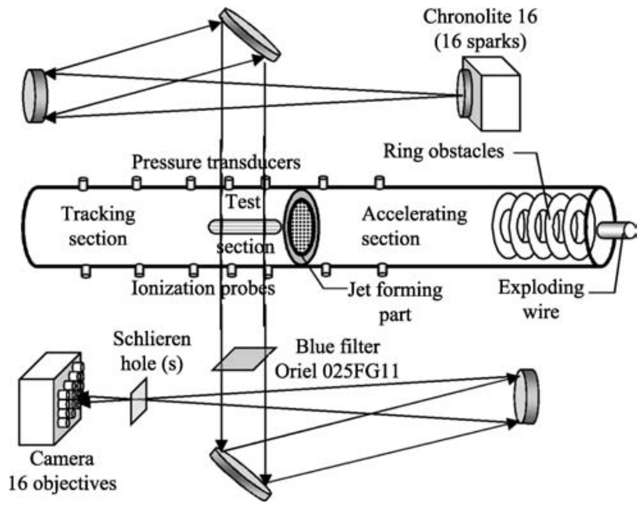


Fig. 1 Scheme of the experimental setup

The tracking section is placed downstream of the test section (see Fig. 1). It is equipped with instrumentation ports for monitoring the development of explosion processes outside of the test section. The length of the tracking section was varied between 2 and 5 m. The 30% hydrogen in air and different hydrogen–oxygen–nitrogen mixtures investigated were prepared by the partial pressure technique in a separate vessel (mixer), where the mixing time was at least 24 h.

The pressure measurements were performed by Kistler 603B pressure gauges. The ionization probes were used to determine the time of arrival of the detonation/combustion products. For the purpose of schlieren visualization, the sidewalls of the test section are equipped with windows 130 mm in length and 20 mm in height. The scheme of the optical system and the optical paths is given in Fig. 1. Optical visualization was performed by means of a 16-frame Cranz-Schardin camera. The light is generated by 16 high-voltage sparks (Chronolite 16). The spark generator has a separate high-voltage supply and a delay control unit, combined with a manual selector for time intervals between the flashing of the sparks. The time interval between two successive sparks can be varied in the range of 1 μs to 1 ms.

2.2 Experimental conditions and jet forming parts

The task of the jet forming part is to generate a jet of detonation products. Two techniques of jet formation have been used, namely the bursting membranes and perforated plates. In the first case, the jet is formed after the rupture of a membrane at the detonation wave reflection. The reflected detonation wave presents by itself a source of high-temperature detonation products. The use of a perforated plate requires close consideration of the detonative properties of the mixture considered. In order to destroy the cellular structure of the incident detonation wave, the diameter of the individual holes in the perforated plate should not exceed the width of the detonation cell.

Figure 2a shows the jet forming part based on the principle of a perforated plate. The main parameter, which characterizes the dimensions of the jet, is the diameter D. Each perforated plate has an array of closely spaced small holes

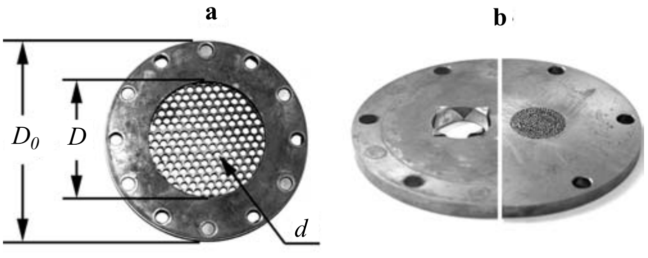


Fig. 2 Jet forming parts: **a** perforated plate $D = 80$ mm, $d = 4.8$ mm ($D_0 = 141$ mm is the inner tube diameter), OAR = 0.58; **b** perforated plate $D = 30$ mm, $d = 1$ mm, OAR = 0.49 (*right*) and 0.5 mm copper membrane $D = 30$ mm (*left*) after rupture

with diameter d. In special cases, an additional parameter is given by the thickness h of the plate. Most of the experiments were performed with perforated plates of 5–10 mm thickness. Finally, for the perforated plates an important parameter is characterized by the open area ratio (OAR) that can be calculated in the following way: $\mathrm{OAR} = Nd^2/D^2$, where N is the total number of the holes. In case of the bursting membrane the geometrical parameters are given by the diameter of the opening D, the thickness and the material of the membrane.

The mixtures considered consist of 30% H_2 in air and different hydrogen–oxygen–nitrogen mixtures ($2H_2 + O_2$, $2H_2 + O_2 + 0.5N_2$, $2.1H_2 + O_2 + 2.2N_2$). The analysis of the cell widths data available in the data base of Kaneshige and Shepherd [19] shows that for a mixture of 30% H_2 in air, the diameter d of the individual holes of a perforated plate should be less than 10 mm for a pressure range of $p_0 \leq 1$ bar. For elevated initial pressures $1 < p_0 \leq 6$ bar, the condition $d \leq 5$ mm fulfills the requirement of quenching the cellular structure of a detonation wave. The experiments with 30% hydrogen in air mixture were performed by using perforated plates with the arrays of holes of $d = 3$, 3.3, 3.6, 4, 4.5, 4.8, 6, and 9.5 mm in diameter. The total diameter D of the jet was varied by applying spacers (thin flanges) with diameters ranging between $D = 20$ and 110 mm. The main set of experiments was performed with circular spacers, which provide an axisymmetric shape of the jet. The OAR was varied in the range of $\mathrm{OAR} = 0.33$–0.64.

For a more sensitive stoichiometric hydrogen–oxygen mixture, the condition $d \leq 1$ mm for an initial pressure range of $p_0 \leq 1$ bar fulfills the requirement of quenching the cellular structure of a detonation wave. Besides, contrary to the case of hydrogen–air mixtures, in the experiments with hydrogen–oxygen mixtures the size of a jet can be significantly decreased. The main set of experiments for a mixture of $2H_2 + O_2$ was performed using perforated plates with the hole diameter $d = 1$ mm for different jet sizes of $D = 20$ and 30 mm, respectively.

The jet forming parts utilizing bursting membranes were used to compare different techniques of the jet formation. Figure 2b demonstrates an example of different jet forming parts based on the perforated plate (Fig. 2b, right) and bursting membrane (Fig. 2b, left). For hydrogen–air mixtures the axisymmetric design with $D = 75$ mm was used. For hydrogen–oxygen mixtures the jet forming parts have diameters of $D = 20$ and 30 mm, respectively. The material of the membranes was steel foil with a thickness of 0.05, 0.1 mm thick aluminum foil, and copper foils with a thickness of 0.5 and 0.3 mm, respectively. The 0.5 mm thick copper membrane was prepared with radial cuts of 0.45 mm in depth in two perpendicular directions. The advantage of pre-cutting is that the impact of the incident detonation wave causes a controllable bursting of the membrane along an opening as it is shown in Fig. 2b, left. This experiment was performed utilizing a stoichiometric $H_2 + O_2$ mixture at $p_0 = 1$ bar. As a result, no fragments are generated. However, the depth of the cuts should be not less than 70–80% of the membrane thickness. This implies restriction on the applicability of the pre-cutting to thin membranes with less than 0.2 mm thickness.

3 Experimental results

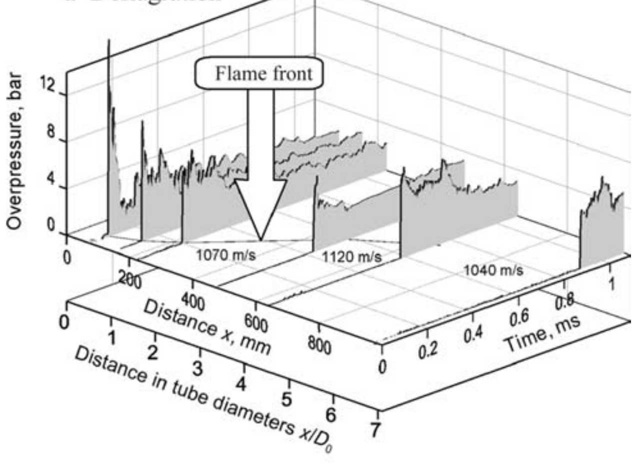
3.1 Explosive regimes triggered by a turbulent jet

To determine the critical conditions of initiation of different combustion/detonation regimes is of primary interest from both practical and fundamental point of view. In the particular case of jet initiation of detonation by hot combustion products, one can suggest two different approaches to solve this problem. In the first approach, the mixture sensitivity is changed for a fixed configuration of the jet forming part. This yields critical conditions for detonation initiation, which can be correlated with the sensitivity of the combustible mixture, namely with the detonation cell width. The sensitivity of a mixture given has been varied by the initial pressure. Another approach is to change the geometric parameters of the jet forming part while keeping the reactivity of the mixture constant. For this, the initial pressure is kept at a constant value, while the variable parameter is given by the jet size D and the OAR.

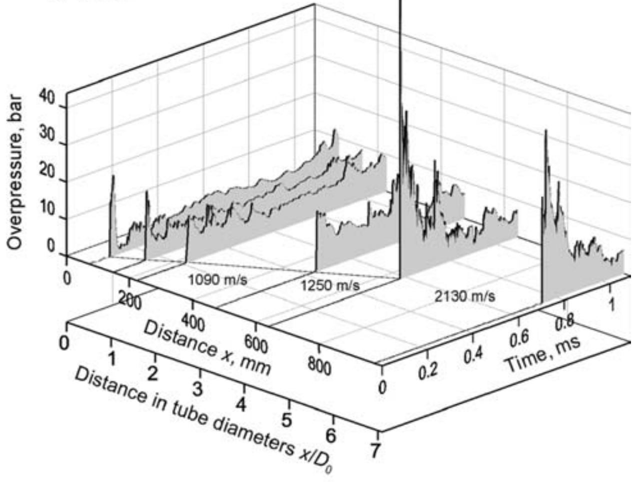
Figure 3 illustrates the three modes of jet-initiated hydrogen combustion phenomena revealed. The plots show pressure records at different distances behind the jet forming part and the apparent velocities of shock/detonation fronts. For subcritical conditions, deflagration is initiated downstream of the jet forming part (Fig. 3a). This regime is characterized by a shock propagating at a velocity of about 1100 m/s or less. The reaction front is decoupled from the shock front and travels with nearly constant velocity, which is typical for near critical conditions. This propagation mode has much in common with a fast-deflagration mode described by Eder et al. [20, 21]. In this paper, the combustion regime is referred to as a deflagration if no transition to detonation is detected up to the gauge position most downstream, i.e., up to a distance of approximately $15D_0$. During the propagation of the complex composed shock wave followed by a flame front, the transition to detonation can take place somewhere downstream of the jet forming part. Figure 3b presents an example of the onset of detonation at a distance of approximately $4D_0$. This regime has much in common with a conventional DDT event and has no obvious connection with the jet initiation problem. The third regime (Fig. 3c) is related to detonation initiation shortly after the appearance of a jet at a distance less than two diameters of the tube. This case is referred to as a jet initiation of detonation. The described detonation/combustion modes downstream of a perforated plate are somewhat similar to those reported by Ciccarelli and Boccio [22] for the case of interaction of detonation wave with a single orifice plate.

It should be emphasized that only deflagration and jet initiation of detonation rather than DDT regimes were found for 30% H_2 in air mixtures in the experiments with jet forming parts based on perforated plates. In other words, the DDT regimes as shown in Fig. 3b were observed in more sensitive

a Deflagration



b DDT



c Jet initiation of detonation

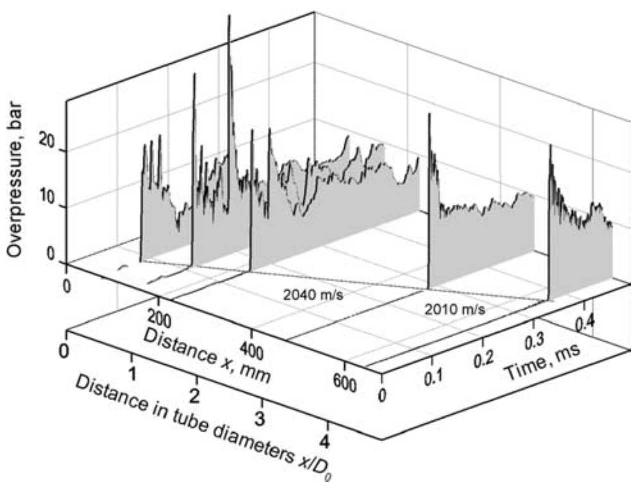


Fig. 3 Pressure records for different modes of combustion. **a** Deflagration, 30% H_2 in air, $p_0 = 0.8$ bar, $D = 80$ mm, $d = 4.8$ mm, OAR = 0.58; **b** DDT at $x \sim 4D_0$, $2.1H_2 + O_2 + 2.2N_2$, $p_0 = 1.5$ bar, $D = 52$ mm, $d = 3.3$ mm, OAR = 0.44; **c** Jet initiation of detonation, 30% H_2 in air, $p_0 = 1.3$ bar, $D = 80$ mm, $d = 4.8$ mm, OAR = 0.58

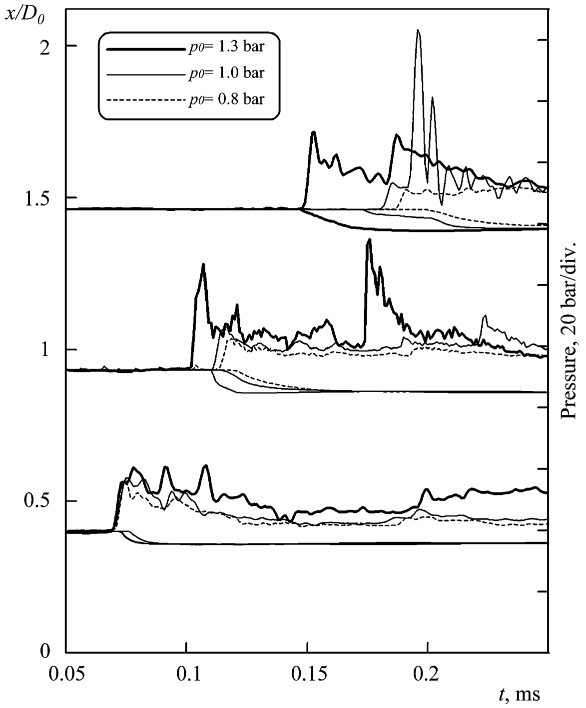


Fig. 4 Pressure records illustrating initial stages of different modes of jet-initiated combustion phenomena by using a perforated plate; 30% H_2 in air, $D = 80$ mm, $d = 4.8$ mm, OAR = 0.58

hydrogen–oxygen–nitrogen mixtures. For the initial pressure of $p_0 = 4.75$ bar the minimum jet size for detonation initiation in 30% H_2–air mixture was found at $D = 75$ mm. Reducing the overall jet diameter D leads to the initiation of deflagration.

The appearance of different jet-initiated hydrogen combustion phenomena at the initial stage of interaction between jet and unburned mixture can be illustrated by the following example. Figure 4 presents the pressure records for experiments with 30% H_2 in air mixture at slightly different initial pressures and the same jet forming part. The zero line of each pressure trace in Fig. 4 indicates the location of the proper pressure gauge downstream of the jet forming part. The coordinate x indicates the distance from the surface of the perforated plate. Time is counted from the instant of detonation reflection at the jet forming part. The analysis of the pressure histories and the measurements of the shock front velocities reveal apparently different outcomes even for minor changes of the initial conditions. Additionally, the signals of the ionization probes (negative voltage outputs) are presented in Fig. 4 to compare the positions of shock and flame fronts. In all three cases, the pressure profiles in the vicinity of the jet forming part at $x \sim 0.4D_0$ are of similar behavior. At the location $x/D_0 \sim 0.9$ more downstream, one can observe the decay of the shock wave for $p_0 = 0.8$ and 1 bar and vice versa the amplification of the shock in case of $p_0 = 1.3$ bar up to a pressure, which is much higher than the C–J value, which in this case amounts to 16 bar. Further downstream, at $x/D_0 \sim 1.4$, the detonation wave is recorded for $p_0 = 1.3$ bar. Simultaneously, significant differences for the cases of $p_0 = 0.8$ and 1 bar become apparent. At $p_0 = 1$ bar a strong secondary explosion behind the precursor shock leads to the transition of detonation, while at $p_0 = 0.8$ bar the shock further decays and a decoupling of shock and flame front takes place. The latter case is referred to as initiation of deflagration.

It is important to mention that for both cases of detonation initiation shown in Fig. 4 the discharged combustion products follow the leading shock wave. Thus, the jet interacts with shock waves reflected from the surrounding tube walls. Nevertheless, a distinction needs to be drawn between the modes of detonation onset observed. The detonation initiation for $p_0 = 1.3$ bar at a distance of about one tube diameter is likely due to a local explosion, resulting from the first interaction between the jet and the precursor shock reflected from the tube wall. In particular, this local explosion is recorded by the second pressure transducer in Fig. 4 ($p_0 = 1.3$ bar). The resulting shock wave of this local explosion and its nearly normal reflection at the tube wall is responsible for the first high-pressure spike. In the second case (at $p_0 = 1$ bar), the onset of detonation by a strong secondary explosion behind the precursor shock takes place further downstream and is promoted by multiple shock reflections. The phenomena described have much in common with the interpretation of the influence of confinement on the process of jet initiation of detonation given by Bezmelnitsin et al. [3].

The schlieren visualization of the flow pattern at the initial stage of the jet-initiated processes can give additional information about the details of the phenomena to be investigated. Figures 5 and 6 show an example of the flow visualization for the cases of initiation of deflagration (Fig. 5) and detonation (Fig. 6) for conditions, which are similar to those considered in Fig. 4. The vertical lines in the middle of the pictures in Fig. 5 are due to the use of two stacked blue filters. In both cases, the jet of combustion products appears in the test section with a velocity of about 1,100 m/s. For the lower initial pressure (Fig. 5) a visible decoupling between shock and combustion products takes place at about 90 μs. Simultaneously, a decrease of the propagation velocity of the reaction front is observed. This decoupling is inherent to the jet-initiated deflagration mode. At a case of higher initial pressure (Fig. 6) no decoupling is observed as it takes place for jet initiation of detonation.

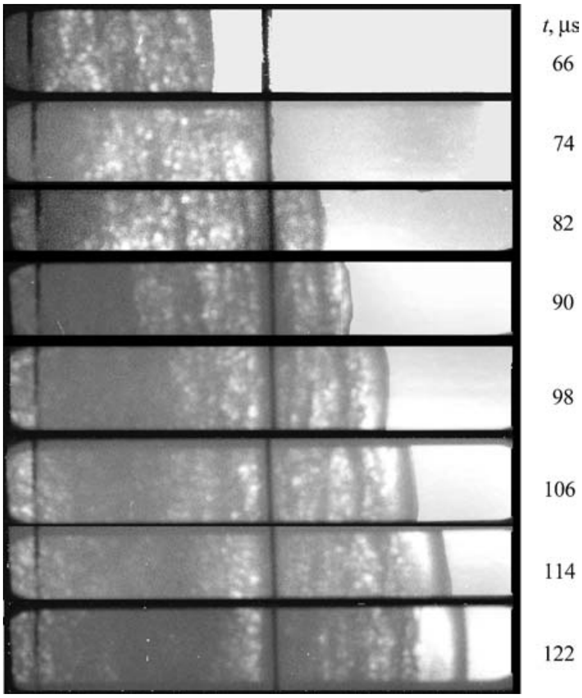


Fig. 5 Schlieren pictures illustrating initiation of deflagration by using a perforated plate (30% H_2 in air, $D = 80$ mm, $d = 4.8$ mm, OAR = 0.58); $p_0 = 0.8$ bar; time is counted from the instant of jet starting

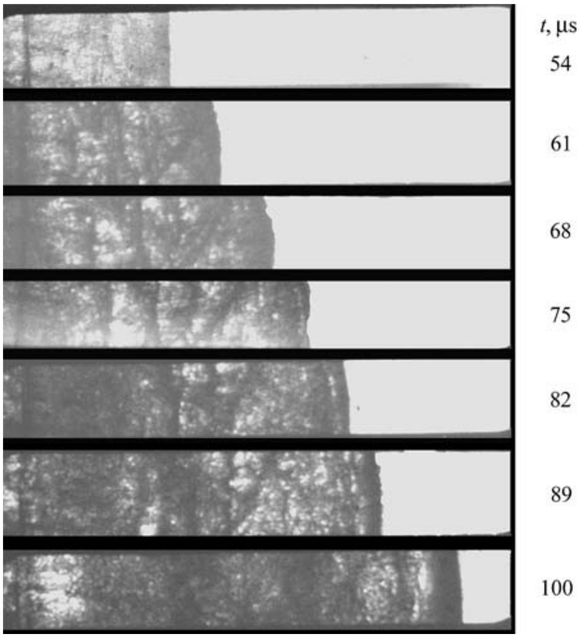


Fig. 6 Schlieren pictures illustrating initiation of detonation by using a perforated plate (30% H_2 in air, $D = 80$ mm, $d = 4.8$ mm, OAR = 0.58); $p_0 = 1.3$ bar; time is counted from the instant of the jet starting

3.2 The efficiency of different jet formation techniques

The use of more sensitive hydrogen–oxygen mixtures instead of the 30% H_2–air mixture enables a significant decrease of the jet size at which detonation initiation occurs. For the mixture of $2H_2 + O_2$ specific features of jet initiation of detonation are considered exemplarily in case of different jet formation techniques. Figure 7 represents three particular cases of detonation initiation. As it can be seen, the use of the perforated plate (case 1) results in the most fast initiation process. The substitution of the perforated plate by a thin steel membrane (0.05 mm, case 2) changes the flow pattern significantly. The rupture of the membrane results in the formation of a shock wave. A secondary explosion takes place behind the precursor shock with a time delay of approximately 50 μs. Transition to detonation occurs at a

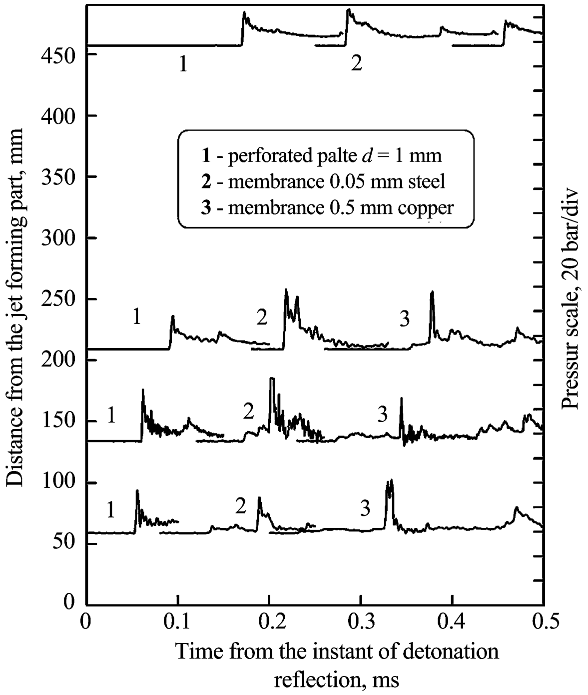


Fig. 7 Jet initiation of detonation using a perforated plate and bursting membranes; $2H_2 + O_2$, $p_0 = 1$ bar, $D = 30$ mm

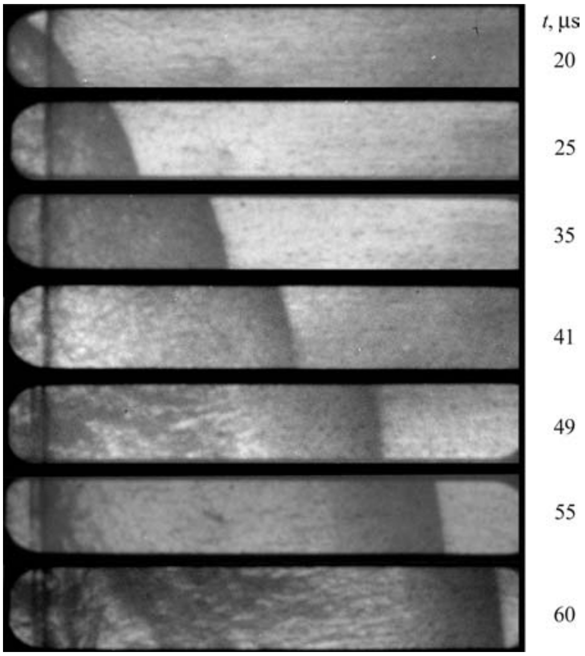


Fig. 8 Jet initiation of detonation using a perforated plate; $2H_2 + O_2$, $p_0 = 1$ bar, $D = 30$ mm, $d = 1$ mm, OAR = 0.49; time zero corresponds to the instant of jet starting

distance of about 150–200 mm from the membrane. The use of a more thick (0.5 mm) copper membrane with radial cuts of 0.45 mm in depth (case 3) results in a further significant increase of the initiation delay. It is reasonable to suggest that the opening time of the membrane plays an important role in the dynamics of jet ignition. In case of a membrane with cuts (see also Fig. 2b, left), the rupture starts at the central part, i.e., in the intersection of the cuts. Thus, at the initial stage, the jet is smaller in diameter than the total area covered by the membrane. Local explosions triggering detonation start when the membrane is finally opened and the size of the jet matches critical conditions. Contrary to this, the use of a perforated plate allows to instantaneously generate a jet of proper size.

Figure 8 represents a photographic sequence of the process of detonation initiation for a stoichiometric hydrogen–oxygen mixture by use of a perforated plate with geometrical parameters $D = 30$ mm and $d = 1$ mm, respectively. Obviously, no visible decoupling of the shock wave from the reaction front occurs. The processing of the photos available can elucidate the dynamics of the movement of the reactive front. The velocity increases continuously and in less than 60 μs it approaches a value of 2,810 m/s, which is close to the calculated C–J value of 2,840 m/s, thus indicating the formation of a detonation wave. The initial jet velocity is about 1,500 m/s. This value agrees quite well with the calculated local sound speed of 1,560 m/s for the choked flow at the exit of the orifices. The reservoir conditions of this flow correspond to those behind of the reflected detonation wave.

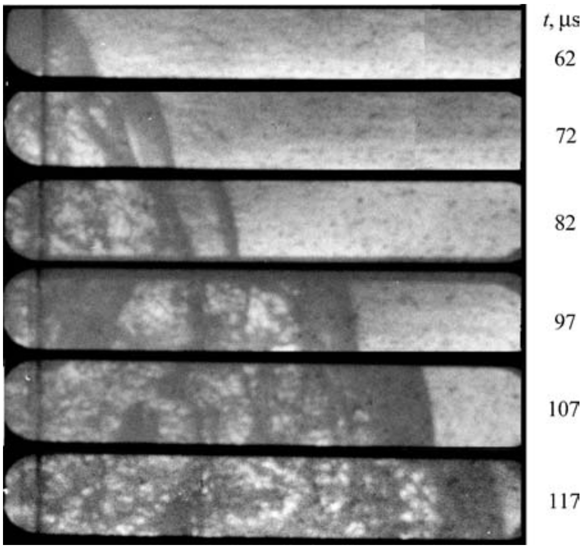


Fig. 9 Detonation initiation by local explosion in case of a bursting membrane; $2H_2 + O_2$, $p_0 = 1$ bar, $D = 30$ mm, steel membrane of 0.05 mm thickness; time is counted from the instant of reflection of the incident detonation wave

The schlieren sequence in Fig. 9 illustrates the initial stage of the process of detonation initiation for the jet forming part utilizing a bursting membrane. After the appearance of a decoupling between shock and reaction front (frames at $t = 72$ and 82 μs), pressure waves from a local explosion overtake the front, and detonation transition occurs downstream of the field of view. In the experiments with a stoichiometric hydrogen–oxygen mixture, a reduction of the overall jet diameter D to 20 mm results in initiation of DDT at a distance x downstream of the jet forming part larger than

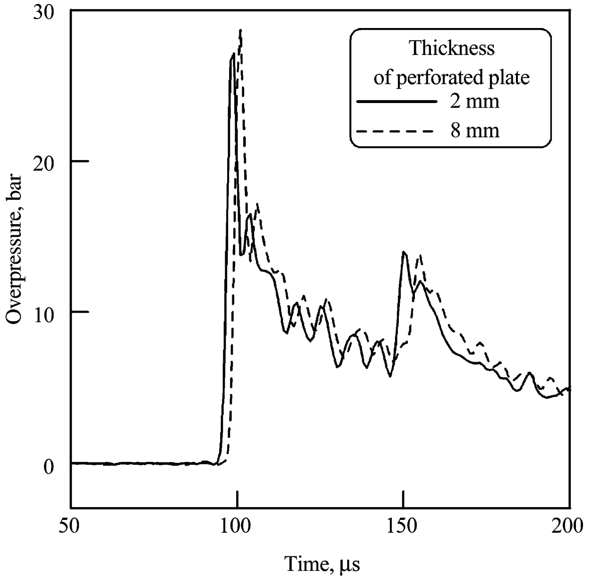


Fig. 10 Influence of thickness of a perforated plate on the process of detonation initiation. Pressure records taken at a distance of 208 mm from the jet forming part; $2H_2 + O_2$, $p_0 = 1$ bar, $D = 30$ mm, $d = 1$ mm, OAR = 0.49

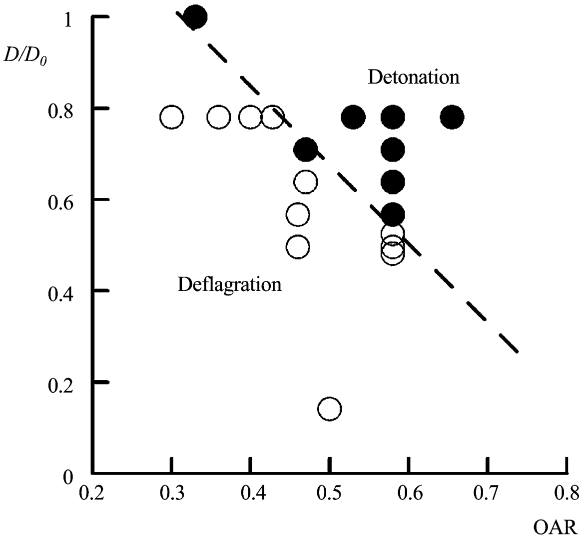


Fig. 11 Experimental results and critical conditions of different explosive regimes as function of the degree of confinement and OAR of a perforated plate; 30% H_2 in air, $p_0 = 1$ bar; *solid circles*, detonation; *open circles*, deflagration

$3D_0$. A high-speed flow of combustion products through multiple small orifices can be accompanied by heat and impulse losses in the case of relatively thick perforated plates. Some tests were performed to elucidate the conditions under which the thickness h of a perforated plate does not influence the jet parameters and therefore, the dynamics of detonation initiation. Figure 10 shows a comparison of pressure records taken at the same distance downstream of perforated plates with $h = 2$ and 8 mm, respectively. As seen, for this condition, minor changes (mainly for the delay of about 2–3 μs) take place for the thicker plate. Thus, for the conditions considered here, an influence of the plate thickness h at least in the parameter range of $h/d = 2$–8 seems to be negligible.

4 Discussion

The experiments performed for jet diameters D between 20 and 141 mm with 30% H_2 in air and different hydrogen–oxygen–nitrogen mixtures and initial pressures between 0.3 and 6 bar revealed critical conditions of detonation initiation. The boundary between "go" and "no go" is not a sharp one due to the stochastic nature of reactive flows accompanied by shock interactions. As a result, nearly the same critical conditions can be observed for different modes of detonation initiation and for the same initial parameters, i.e., the same jet forming part, mixture composition, and initial pressure. Nevertheless, the amount of experimental data allows to draw a line in the parameter field separating the regions of detonation and deflagration initiation. Later, the results of experiments are presented in the form of different correlations. The detailed description of the initial conditions and outcome of each experiment can be found in the JETHYD Database, which is available at http://albert.swl.rwth-aachen.de/expro.html.

It should be emphasized that in most of the cases studied the jet is subjected to lateral expansion accompanied by a leading shock in front of the jet. This shock wave reflects from the surrounding walls and, in these cases, detonation starts after localized explosions due to the interaction between the jet and the reflected shocks as it also was described by Bezmelnitsin et al. [3]. The parameter, which reflects a degree of confinement, is given by the ratio of overall jet diameter to tube diameter D/D_0. The experiments performed give decisive evidence on the role of the geometrical parameters of a perforated plate on the possibility of initiation of either detonation or deflagration. It is reasonable to use the ratio D/D_0, along with the parameter OAR in representing the experimental data as it is given in Fig. 11. Despite some scattering of the data available, one can indicate a boundary between the regimes of initiation of detonation and deflagrative regimes of combustion. The boundary found in Fig. 11 (broken line) demonstrates a strong interrelation between the diameter ratio and the OAR of a perforated plate for initiation of different explosive phenomena. This boundary in Fig. 11 relates to the practically important case of initial pressure of $p_0 = 1$ bar for a 30% hydrogen–air mixture. The experimental results at elevated initial pressures or with more sensitive hydrogen–oxygen–nitrogen mixtures indicate that the boundary detonation/deflagration is shifted to lower values of D/D_0 and OAR. For example, for a fixed OAR of OAR = 0.49 the minimum degree of confinement for jet initiation of detonation in stoichiometric hydrogen–oxygen mixture was found to be $D/D_0 = 0.2$ instead of 0.65 for 30% hydrogen in air mixture.

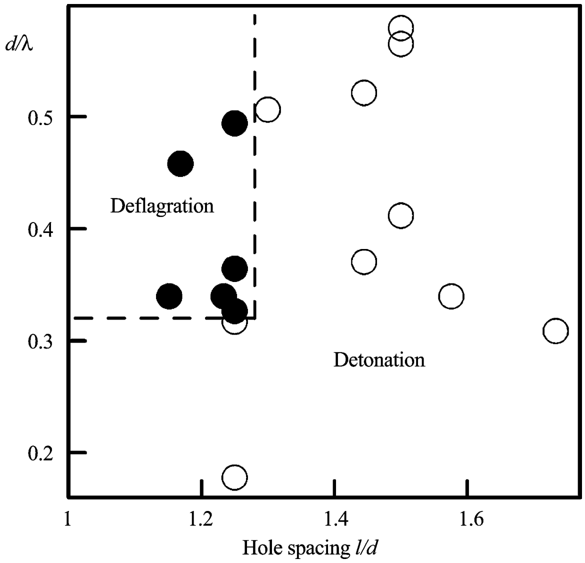


Fig. 12 Combined effect of relative hole spacing and scaled diameter of the hole on the realization of different explosive regimes; perforated plates with $D = 110$ mm; 30% H_2 in air, $p_0 = 0.3$–3 bar; *solid circles*, detonation; *open circles*, deflagration

For the sake of complete description of the efficiency of a perforated plate for initiation of different explosive regimes, the influence of an additional parameter, namely the hole spacing l, should be considered in conjunction with the diameter d of the individual holes of a perforation. The parameter l is the distance between the centers of two adjacent holes. The relative hole spacing l/d can significantly influence the turbulent mixing process as it was also supposed by Chao et al. [18]. A representative set of experiments performed with different perforated plates with fixed $D = 110$ mm and 30% H_2–air mixtures at $p_0 = 0.3$–3 bar enables to elucidate the combined effect of the hole diameter, the relative spacing, and mixture sensitivity. Figure 12 represents the results of experiments in the d/λ–l/d plane, where λ is the detonation cell width taken from correlations given by Gavrikov et al. [23]. As seen from Fig. 12, both the relative hole spacing l/d as well as the ratio d/λ have a significant effect on the critical conditions of detonation initiation. For a relative hole spacing $l/d \leq 1.28$ the critical value of d/λ is about $d/\lambda = 0.32$ (horizontal broken line) that is a little smaller than $d/\lambda = 0.4$ found by Chao et al. [18]. For the perforated plates with $l/d > 1.28$ no detonation regimes were observed for 30% hydrogen in air mixtures at initial pressures between 0.3 and 3 bar.

As it is common use, the critical conditions of detonation initiation can also be expressed in terms of the overall jet diameter D and the mixture sensitivity (detonation cell width λ). The mixture sensitivity was varied by the initial pressure and/or the mixture composition. Numerous investigations of jet initiation of detonation demonstrate a wide range of critical values of the ratio D/λ. It was clearly shown that the critical values D/λ depend on both the type of fuel (hydrogen or hydrocarbon) and the geometry of the jet and the test volume. An attempt to apply a general criterion for the problem of jet initiation of detonation was undertaken by Dorofeev et al. [10], where the critical value $D/\lambda = 7$ was found to be a conservative (necessary but not sufficient) condition for the successful initiation of detonation. However, it is reasonable to suppose that in spite of the wide scattering of the experimental data on jet initiation of detonation, additional correlation parameters can be utilized. To avoid the influence of the fuel type in this paper, the experiments have been restricted to hydrogen–air and hydrogen–oxygen–nitrogen mixtures. Experiments on jet initiation of detonation relevant to these mixtures were also performed (or cited) by Berman [7], Carnasciali et al. [2], Bezmelnitsin et al. [3], and Dorofeev et al. [10]. In most of the facilities used in these papers, the geometry is such that detonation initiation takes place for a typical length x_0 to diameter (cross size) D_0 ratio equals approximately $x_0/D_0 = 2$. This means, jet-initiated hydrogen detonation phenomena reported by Berman [7], Carnasciali et al. [2], Dorofeev et al. [10], and Bezmelnitsin et al. [3] occur downstream of the jet forming part (orifice) at a distance x not longer than $2D_0$. Thus, for a correct comparison, the results of the experiments given in this paper (a facility with $x_0/D_0 = 15$) should be selected by the criterion x equals approximately $2D_0$. As mentioned earlier, we adopt that the experiments of successful initiation of detonation at distances $x \leq 2D_0$ directly relate to the problem of jet initiation of detonation and can be compared to the results of the other authors.

The second interesting parameter is given by the ratio D/D_0, where D is the overall jet diameter and D_0 the diameter of the surrounding vessel. Compared to previous results for the mixture considered, the experiments performed cover the not yet investigated range of relatively large values of D/D_0 up to and including $D/D_0 = 1$. Since the confinement plays an important role in the jet initiation problem, it is reasonable to use the parameter D/D_0 along with the ratio D/λ in representing the experimental data. Figure 13 gives the results of both, the experiments of Berman [7], Carnasciali et al. [2], Bezmelnitsin et al. [3], and Dorofeev et al. [10] and those of the present work. Both, the results of experiments with perforated plates as well as with bursting membranes are plotted in Fig. 13. The OARs of the perforated plates are in the range of 0.49–0.58 (except the case of $D/D_0 = 1$ where OAR = 0.33). To avoid an inconsistency in the interpretation of cell width measurements given by different authors, we use a unified approach of Gavrikov et al. [23] for the evaluation of the λ values. Despite some scattering of the data available, one can indicate a boundary between the regimes of initiation of detonation and non-detonative regimes of combustion.

An important specific feature of the boundary between jet-initiated detonations and no jet-initiated detonations is clearly evident by the dependence of the critical values of D/λ on the degree of confinement. In the range of $D/D_0 = 0.5$–0.8, the correlation D/λ = constant = 7 suggested by Dorofeev et al. [10] fits with the revealed boundary found in Fig. 13. Thus, the representation of experimental results in the D/λ–D/D_0 coordinate system demonstrates the role of the confinement for the problem of jet initiation

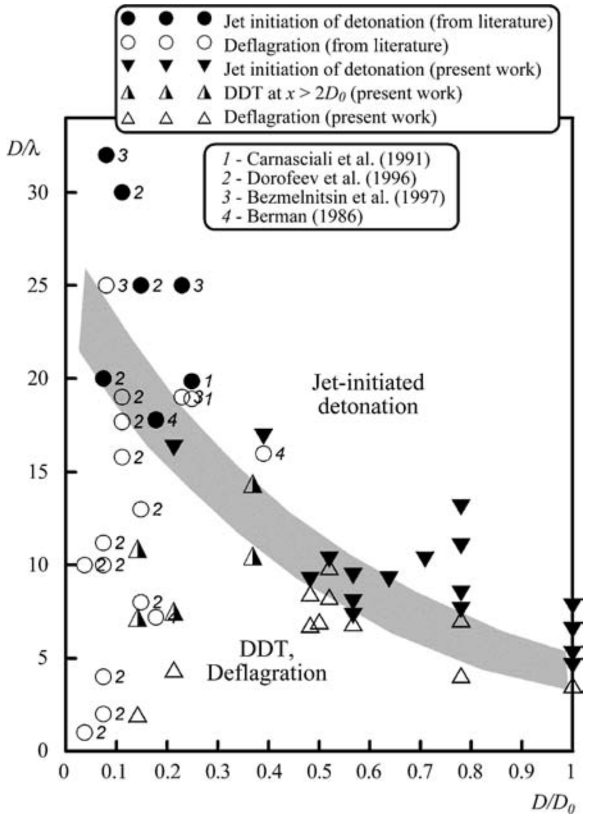


Fig. 13 Experimental results and critical conditions of the jet-initiated explosion regimes in hydrogen–air and hydrogen–oxygen–nitrogen mixtures for different degrees of confinement

of detonation. The strong confinement influence in the range of D/D_0 between 0.5 and 0.8 significantly facilitates the process of detonation initiation by the turbulent jet, since in this case the jet is not subjected to a significant lateral expansion (cooling), but it interacts with sufficiently intensive shocks reflected from the surrounding walls. For even smaller D/D_0 ratios the shock emitting from the expanding jet is more or less spherically shaped and strongly attenuates as it propagates towards the wall. Besides, the cooling effect becomes significant. Hence, a more sensitive mixture (larger ratios of D/λ) is required for the successful initiation of detonation. For $D/D_0 \leq 0.1$ the influence of the confinement becomes negligible and a spherical detonation is initiated directly in the jet. At the right end of Fig. 13 the case $D/D_0 = 1$ represents a quasi one-dimensional arrangement without lateral expansion of the jet and without reflected shock waves. In accordance with Chao et al. [18], the initiation of detonation occurs in this case at the turbulent interface between the hot detonation products and the unburned gas. For $D/D_0 = 1$ the critical ratio D/λ in the stoichiometric hydrogen–air mixture was found to be D/λ approximately 4.

5 Conclusions

The experiments performed revealed the peculiarities of the process of jet initiation of detonation and fast deflagration in hydrogen–air and hydrogen–oxygen–nitrogen mixtures for different confined conditions. It is demonstrated that the reflection of a detonation wave at a perforated plate is a powerful method of hot jet formation for the purpose of detonation initiation. Critical conditions of initiation of either detonation or deflagration regimes were found depending on the diameter and OAR of a perforated plate. It was also shown that both the hole spacing and hole diameter of a perforation have a significant effect on the critical conditions of detonation initiation. Particular attention was paid to the comparison of different jet formation techniques. It was found that the use of the perforated plate technique results in more fast jet initiation events and smaller lengths of detonation onset than in the case of the bursting membrane technique. Critical conditions of jet initiation of detonation in hydrogen–air and hydrogen–oxygen–nitrogen mixtures were established. A suitable procedure of scaling of the experimental results was suggested, which links geometric parameters and mixture detonability (detonation cell width).

Acknowledgements This research was supported within the Fifth Framework Programme of the European Commission under the Energy, Environment and Sustainable Development Contract No EVG1-CT-2001-00042 EXPRO.

References

1. Knystautas, R., Lee, J.H., Moen, I.O., Wagner, H.G.: Direct initiation of spherical detonation by a hot turbulent gas jet. In: Proceedimgs of 17th Symposium (International) on Combustion, The Combustion Institute. pp. 1235–1245 Pittsburgh (1979)
2. Carnasciali, F., Lee, J.H.S., Knystautas, R., Fineschi, F.: Turbulent jet initiation of detonation. Combust. Flame **84**, 319–330 (1991)
3. Bezmelnitsin, A.V., Dorofeev, S.B., Yankin, Y.G.: Direct comparison of detonation initiation by turbulent jet under confined and unconfined conditions. In: Proceedings of 16th International Colloquium on the Dynamics of Explosions and Reactive Systems. pp. 222–225 Cracow, Poland (1997)
4. Bezmelnitsin, A.V.: Experimental study of conditions for detonation initiatation by a jet of combustion products. Ph.D. dissertation, RRC "Kurchatov Institute", Moscow (in Russian) (1998)
5. Krok, J.C.: Jet initiation of deflagration and detonation. Ph.D. thesis, California Institute of Technology, Pasadena, California (1997)
6. Pfahl, U.J., Shepherd, J.E.: Jet initiation of deflagration and detonation in stoichiometric H_2–O_2–N_2 mixtures. Explosion Dynamics Laboratory Report FM99-1, California Institute of Technology, Pasadena, California (1999)
7. Berman, M.: A critical review of recent large-scale experiments on hydrogen–air detonations. Nuclear Sci. Eng. **93**, 321–347 (1986)
8. Moen, I.O., Bjerketvedt, D., Jenssen, A., Thibault, P.A.: Transition to detonation in large fuel-air cloud. Combust. Flame **61**, 258–291 (1985)
9. Moen, I.O., Bjerketvedt, D., Jenssen, A., Hjertager, B.H., Bakke, J.R.: Transition of detonation in a flame jet. Combust. Flame **75**, 297–308 (1989)
10. Dorofeev, S.B., Bezmelnitsin, A.V., Sidorov, V.P., Yankin, J.G., Matsukov, I.D.: Turbulent jet initiation of detonation in hydrogen–air mixtures. Shock Waves **6**, 73–78 (1996)
11. Inada, M., Lee, J.H.S., Knystautas, R.: Photographic study of direct initiation of detonation by a turbulent jet. Prog. Astronautics Aeronautics **153**, 253–269 (1993)

12. Zel'dovich, Ya.B., Librovich, V.B., Makhviladze, G.M., Sivashinsky, G.I.: On the development of detonation in a non-uniformly preheated gas. Acta Astronautica **15**, 313–320 (1970)
13. Bartenev, A.M., Gelfand, B.E.: Spontaneous initiation of detonations. Prog. Energy Combust. Sci. **26**, 29–55 (2000)
14. Lee, J.H.S., Knystautas, R., Yoshikava, N.: Photochemical initiation of gaseous detonation. Acta Astronautica **5**, 971–982 (1978)
15. Mackay, D.J., Murray, S.B., Moen, I.O., Thibault, P.A.: Flame jet ignition of large fuel-air clouds. In: Proceedings of 22th Symposium (International) on Combustion. pp. 1339–1353 The Combustion Institute, Pittsburgh (1988)
16. Ungut, A., Shuff, P.: Deflagration to detonation transition from a venting pipe. Combust. Sci. Technol. **63**, 75–87 (1989)
17. Thomas, G.O., Jones, A.: Some observations of the jet initiation of detonation. Combust. Flame **120**, 392–398 (2000)
18. Chao, J., Walker, M., Lee, J.H.S.: Detonation initiation at a turbulent interface. In: Proceedings of 19th International Colloquium on the Dynamics of Explosions and Reactive Systems, Hakone, Japan, Proceedings on CD ROM, Paper 20, pp. 1–4 (2003)
19. Kaneshige, M., Shepherd, J.E.: Detonation Database. Explosion Dynamics Laboratory Report FM97, California Institute of Technology, Pasadena (1997)
20. Eder, A., Gerlach, C., Mayinger, F.: Determination of quantitative criteria for the transition from deflagration to detonation in H_2/H_2O/Air-mixtures. In: Ball, G.J., Hillier, R.H., Roberts, G.T. (eds.) Proceedings of 22nd International Symposium on Shock Waves, University of Southampton, vol. 1, pp. 205–210 (2000)
21. Eder, A., Pingten, F., Mayinger, F.: Propagation of fast deflagrations and marginal detonations in hydrogen–air-additive mixtures. In: Proceedings of 18th International Colloquium on the Dynamics of Explosions and Reactive Systems, Seattle, Washington, Proceedings on CD ROM, Paper 181, pp. 1–4 (2001)
22. Ciccarelli, G., Boccio, J.L.: Detonation wave propagation through a single orifice plate in a circular tube In: Proceedings of 27th Symposium (International) on Combustion, The Combustion Institute. pp. 2233–2239 Pittsburgh (1998)
23. Gavrikov, A.I., Efimenko, A.A., Dorofeev, S.B.: A model for detonation cell size prediction from chemical kinetics. Combust. Flame **120**, 19–33 (2000)