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Detonations in Gas-Particle Mixtures

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I. Introduction

UP to now, most jet engines (turbojets, pulsejets, ramjets, and rockets) work in the deflagrative combustion mode. They are mature and their technology is robust, but, also, they have practically reached their theoretical potential and few gains can be expected in the near or long term future. Because of its high energetic potential, detonation is foreseen as a very attractive possibility for aerospace vehicle propulsion. The design of engines working in a pulsed detonation mode or with a rotative detonation is currently under study. One important problem is the choice of the fuel. Condensed fuels (liquid or solid) are often considered, on account of their availability, but also for safety requirements of storage and transportation. However, such fuels need to release their heat in a controlled way to be finely dispersed in an ambient gaseous reactive mixture. Thus, detonations in this kind of media do not resort to classical detonations in homogeneous media but are strongly governed by the heterogeneous character of the reactive mixture.

II. General Considerations

A. Long-Term Interest of Detonations in Heterogeneous Media

It is interesting to remember that combustion science developed during the 19th century largely due to the occurrence of many accidents resulting from the development of industrialization. Safety problems were already at that moment a powerful motivation to go further in the understanding of combustion phenomena. The most typical example is that of explosions in coal mines. Some of these "explosions" were probably detonations, but such a characterization was uncertain at that moment. In 1881, Berthelot and Vieille [1,2] discovered "l'onde explosive." During this period, Mallard and Le Chatelier [3] improved the classical apparatus to study the formation and the propagation of this reactive wave. But, they focused their investigations on gaseous mixtures. However, as soon as the beginning of the detonation phenomenon investigation, detonation studies were connected to practical observations involving heterogeneous mixtures met in coal mines. Early on, a difference was made between the "coup de grisou," which is a gas explosion due to gaseous reactions between the methane contained in pockets inside the rocks and the air, and the "coup de poussières," which is a dust explosion due to heterogeneous reactions between the coal dust present everywhere in a coal mine and the ambient air. A classical scenario of an accident was in most cases a complex process, involving a gaseous primary explosion followed by a secondary explosion originating from the suspension generation of coal particles under the blast effect of the primary explosion. Fundamentally, such a scenario for detonation propagation is very similar to that which may be met during the detonation of a heterogeneous reactive mixture introduced in a combustion chamber. However, detonations in heterogeneous mixtures remain a domain in which the knowledge is poor as compared with detonations in homogeneous mixtures, and the available data are limited.

B. Specificities of Detonations in Gas–Solid Particle Mixtures

One may distinguish different categories of heterogeneous media, according to the physical nature of the different phases, their distribution in the mixture, and their chemical properties. A two-phase mixture may consist of gas–solid, gas–liquid, or solid–liquid components. Moreover, different distributions of components may be met. Either the two phases are separated, as is the case of dust layers or liquid films deposited to the walls, or the two phases overlap, as, for example, in porous media or emulsions. Another situation is that of one phase finely dispersed in the other, as in the case of sprays or mists of liquid droplets and suspensions of solid particles. Only this last case will be considered here.

One may classify the detonations involving fine solid particles suspended in a gaseous phase, according to the chemical nature of the different components:

1) If all the combustible is contained in the solid particles, and the oxidizer in the gaseous phase, one speaks of "heterogeneous detonations."

2) If part of the combustible is contained in the solid particles and another part in the gaseous phase, whereas the oxidizer is in the gaseous phase gas, such a situation gives rise to "hybrid detonations."

3) If the combustible and the oxidizer are mixed in the gaseous phase, whereas the suspended particles are chemically inert, one speaks of "dusty detonations." We shall see that this situation may be treated as a particular case of hybrid detonation.

4) A last case may be met when the combustible and the oxidizer are mixed in the solid particles: it is the case of particles of monopropellant. They can be suspended in a gas of any chemical composition: for example, an inert gas, which may be rarefied, or even absent in the case of vacuum. Detonations of this kind will not be examined within this paper.

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Table 1 Enthalpy of reaction per unit of mass of different stoichiometric mixtures with air

CH_4	2760 KJ/kg
C_3H_8	2795 KJ/kg
$C_6H_{10}O_5$	2675 KJ/kg (starch)
Al	6432 KJ/kg

Such a classification is widely accepted and was proposed similarly by other researchers [4].

From the point of view of detonation performance, one manifest advantage of fuels made of reactive solid particles in suspension in a gaseous oxidizer is their high energetic potential. An illustration is provided in Table 1 where the specific enthalpy of reaction $\Delta_r H^*$ (i.e., per 1 kg of reactive mixture) of two gaseous mixtures is compared with that of two solid particle-gas mixtures. Stoichiometric mixtures of methane and propane with air display close values of $\Delta_r H^*$, of the order of 2750 kJ/kg. It is remarkable that a dust mixture prepared from a product as common as starch exhibits a value of $\Delta_r H^*$ of the same order of magnitude (2675 kJ/kg). If aluminum particles are considered, $\Delta_r H^*$ becomes 2.5 times greater than for a classical hydrocarbon air mixture. Moreover, for most of the equivalent ratios (from lean to moderately rich), the reaction products of the solid particles with gas are mainly in a gaseous phase, which provides an expansion work responsible for an additional pressure increase. Such characteristics are of great importance for safety applications: it is obvious that detonations of such two-phase mixtures will generate severe damages. Because lower detonability limits are obtained for particle concentrations of the order of 50–100 g/m^3, critical detonable compositions may be achieved for very thin layers of dust deposited on the walls (<1 mm). On the opposite, it is a great advantage for propellant applications, as an important quantity of energy may be stored in a limited volume (of course, to take profit of this situation, it is necessary to improve efficient dispersion devices to prepare the reactive mixture; but it is not the purpose of the present paper).

However, the characteristic chemical reaction time for heterogeneous reactions is greater than that of homogeneous gaseous reactions, often by one or several orders of magnitude. This characteristic reaction time varies very rapidly with the particle size (roughly increasing with the square of their diameter). Hence, one can predict that most of the solid particles–gas mixtures will be more difficult to detonate than classical gaseous mixtures. As, in addition, achievement of experiments in well controlled and reproducible conditions is particularly difficult in mixtures of suspended solid particles in gases (on account of the difficulties to generate uniform dispersions in the whole experimental volume), one can understand why the available data on detonation characteristics, detonation structure, and detonability of solid particle-gas mixtures are not very abundant, and comparison between them is quite difficult.

III. Heterogeneous Detonations

A. Experimental Tube Studies

The reference work displaying detonation propagation in a solid particle-gas mixture is that of Strauss [5] in 1968. He performed experiments in suspensions of aluminum flakes or granular particles with oxygen contained in vertical glass tubes (see Fig. 1). This allowed him to record x–t diagrams of propagation of the reactive front. An example is shown in Fig. 2 which was obtained in a 2.7 m long , 26.4 mm internal diameter tube. One can observe the wave front propagation at an average quasiconstant velocity. This indicates that a quasisteady propagation regime has been reached. However, as shown by Fig. 3, there is a great deficit of the measured values of the front velocity in comparison with the calculated values predicted by the Chapman–Jouguet (CJ) theory. It should be noted that ignition was performed by means of detonators. Thus, due to the limited length of the tube, one can conjecture whether a fully steady, self-sustained detonation regime was reached or not. This question will be discussed later. Moreover, in most of his experiments, Strauss observed a spinning propagation regime of the detonation front. This

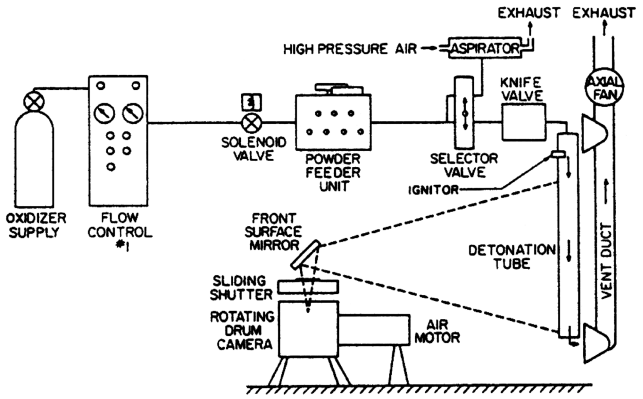

Fig. 1 Original experimental setup of Strauss (from Strauss [5]).

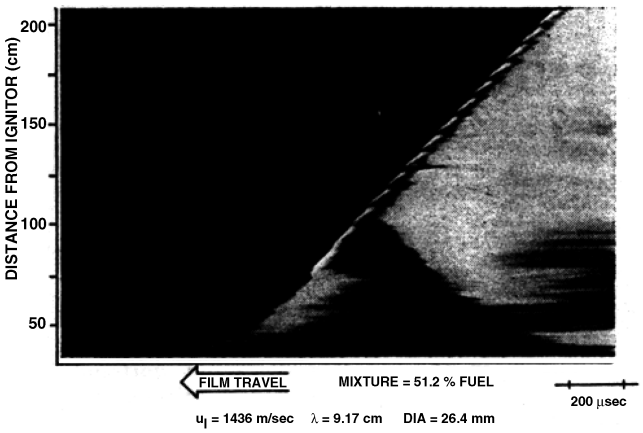

Fig. 2 Typical streak photograph recorded by Strauss in experiments of aluminum powder–oxygen mixture detonation (from Strauss [5]).

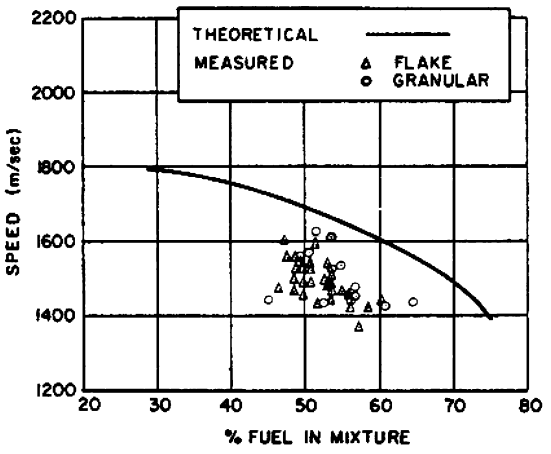

Fig. 3 Detonation velocities recorded by Strauss in his experiments on aluminum powder–oxygen mixture detonations (from Strauss [5]).

suggests that the propagation regime is strongly influenced by the confinement.

In the last 30 years, several research teams have performed experiments in various configurations to get evidence of the possibility for a self-sustained heterogeneous detonation to propagate. Nettleton and Stirling [6], in England, studied detonation of coal dust–oxygen mixtures in vertical tubes. At the University of Warsaw (Poland), Wolanski and coworkers [7] used two different vertical tubes: a 4.5 m long one with a circular 8 cm diam cross section and the other one, 3.2 m long with a 5 cm × 5 cm square cross section. They tried to detonate different dusts suspended in oxygen mixtures. Similar to experiments of Strauss, the common feature of these experimental

setups is the vertical position of the tubes. This is mainly motivated by the techniques of dust dispersion which is obtained, in most cases, by particles settling down from the top to the bottom of the tube, either freely or in a gas flow. As a result of this vertical arrangement, the size of those setups is not very large. In these conditions, one can understand that it is considered necessary to perform experiments with pure oxygen if one wants to observe the detonation formation within the limited travel length. On the opposite, Kauffman [8,9] and coworkers at the University of Michigan (U.S.) attempted to get evidence of detonation existence in air-based dust suspensions. They used horizontal tubes of large dimensions, especially a 71-m long one with a circular cross section with a 30 cm internal diameter. Dust was deposited at the bottom of the tube wall and dispersed by a turbulent air discharge, just before ignition. They observed steady, self-sustained propagation regimes in mixtures of cornstarch particles suspended in air, but with a significant velocity deficit in comparison with the ideal thermodynamical detonation velocity value. Gardner et al. [10], at CEBG in England, conducted experiments in a 0.6 m internal diameter, 42 m long tube. They studied the acceleration of a flame in coal dust–air mixtures. The pressure levels and velocities recorded at the end of propagation in some experiments lead one to believe that a detonation could be formed in these mixtures.

At the University of Poitiers (France), Veyssiere [11] performed experiments in a 6 m long , 69 mm internal diameter vertical tube (see Fig. 4). It was equipped with smoked foils to record the cellular detonation structure. The tube was filled with the suspension by means of a laminar flow going through a fluidized bed disposed at the bottom of the tube. This technique insured an efficient desagglomeration of particles and a good quality of the suspension. Attempts to detonate aluminum particles with air or oxygen failed, probably because of the too large size of particles (13 μm) used for these experiments. Peraldi and Veyssiere [12] observed, in a tube quite similar to the preceding one, quasidetonations of starch particle–oxygen mixtures. These detonations were obtained with the help of a strong initiator (an auxiliary shock tube, disposed at the top of the tube, in which was detonated a stoichiometric hydrogen–oxygen mixture, thus generating a strong shock wave traveling down in the main tube); they were most likely not self-sustained and the front velocity was smaller than the thermodynamical CJ value by about 30%.

At IITRI (U.S.), Tulis et al. [13] tried to detonate aluminum atomized particles and flakes with air in a vertical tube with a circular 15.2 cm cross section and 5.5 m long (Fig. 5). With strong initiators, they observed quasiconstant velocity detonationlike regimes with velocity values fairly smaller than CJ detonation values. Thus it is unlikely that self-sustained detonation had been reached. More recently, Carvel et al. [14,15] performed experiments in a vertical 2.45 m long tube. But it is unlikely that a steady detonation could be formed over such a limited travel distance.

Borisov et al. [16] at the Institute of Chemical Physics of Moscow performed experiments to detonate aluminum particles with air. They used horizontal tubes of different diameters (5.5, 12.2, and 14.5 cm) and lengths (2–4.5 m). They observed propagation regimes with typical values of the front velocity ranging from 1400 m/s to about 1800 m/s according to the concentration and kind of aluminum particles in the mixture, experimental values which are close to the CJ detonation values. Thus, the detonation regime is suspected to have been reached. However, in most of their experiments they observed a spinning regime. This attests to the determinant role played by the tube confinement in the process of propagation and leads one to believe that propagation of a detonation in a tube of larger diameter is not guaranteed.

The most relevant experiments have been appropriately performed by Zhang and Grönig [17,18] at RWTH of Aachen (Germany). They used a horizontal shock tube having a 17.4 m long test section with a

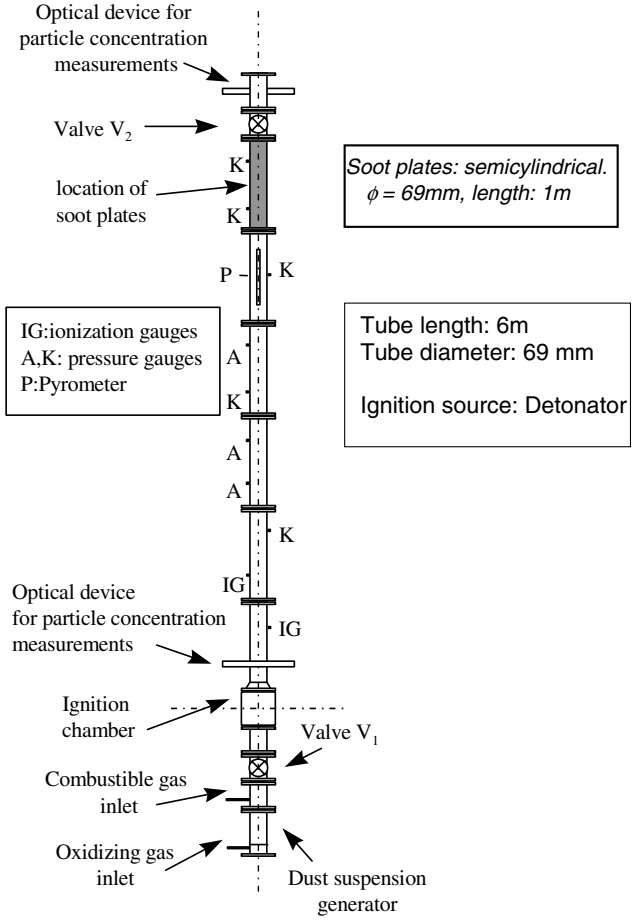

Fig. 4 Schematic diagram of the detonation tube of Veyssiere (from Veyssiere [11]).

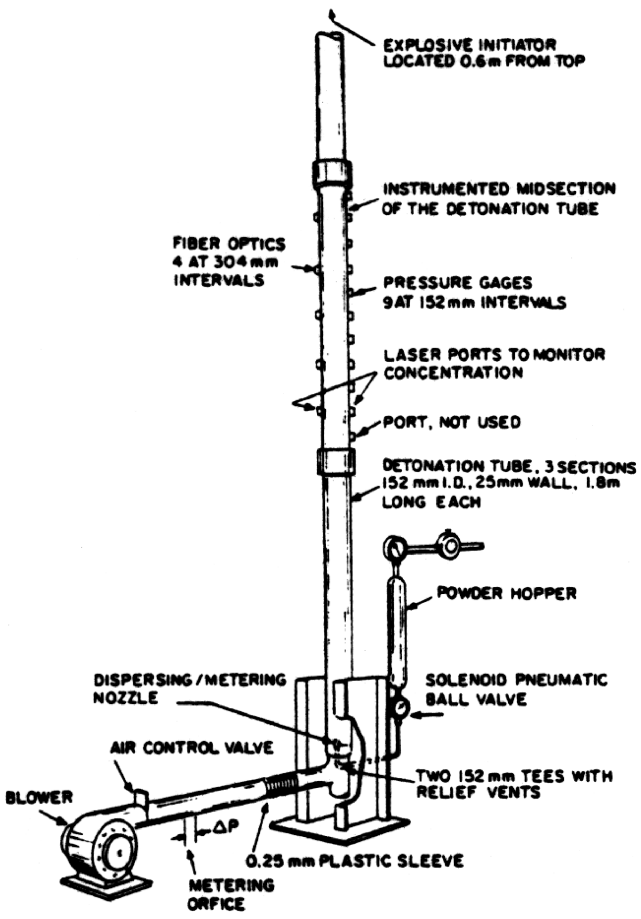

Fig. 5 Schematic of IIT Research Institute 5.5-m detonation tube facility (from Tulis and Selman [13]).

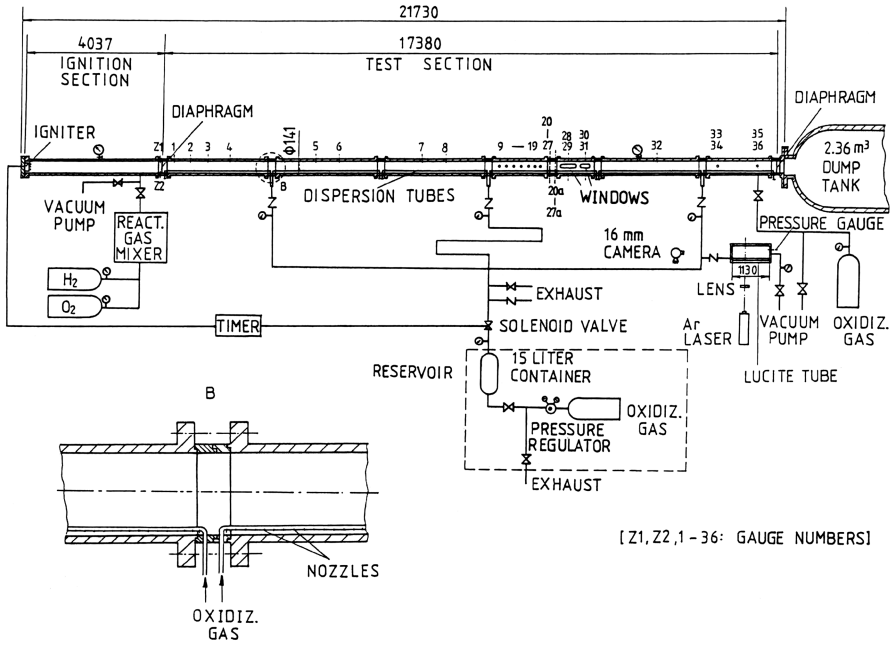

Fig. 6 Schematic diagram of the detonation tube of the RWTH Aachen (from Zhang and Grönig [17]).

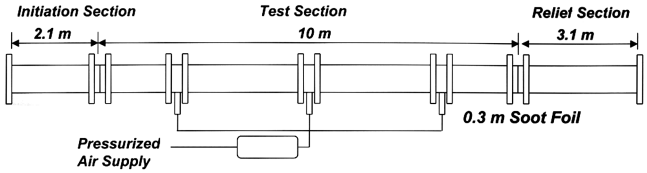

Fig. 7 Schematic diagram of the detonation tube used by Zhang at DRDC (Canada) (from Zhang et al. [21]).

14 cm internal diameter (Fig. 6). The dust was beforehand uniformly deposited along the tube ground and dispersed by turbulent jets just before ignition. They observed detonation formation and propagation in cornstarch, anthraquinine, or aluminum particles suspended in oxygen or air. Constant mean velocity of the detonation front was recorded with values quite close to those of the ideal CJ detonation.

More recently, Pu and coworkers [19,20] performed experiments in China to try to detonate aluminum air mixtures in two tubes: one of 5 m length with 0.14 m internal diameter, and the other one of 12 m long test section with 0.14 m internal diameter. Zhang [21] has undertaken a new series of experiments at DRDC (Canada) in a 80 mm internal diameter, 10 m horizontal tube (see Fig. 7) with a dust dispersion system rather similar to that used previously in experiments at Aachen, and ignition achieved by means of a detonator or an auxiliary 2.1 m long shock tube containing a hydrogen–oxygen mixture. Zhang et al. [22] also used a 0.3 m internal diameter, 37 m long tube with pyrotechnical ignitors [22]. Thus, they were able to observe detonation formation in anthraquinone, cornstarch, and aluminum suspensions in air. This tube was equipped with smoked foils to record the cellular detonation structure.

Large scale dust explosion experiments in confined configurations have also been performed in the experimental mine "Barbara" in Poland [23], either in a surface gallery 100 m long and 2.9 m^2 of cross section, or in an underground gallery 400 m long and of 7.5 m^2 of cross section. Even at such large scale, truly self-sustained, steady detonations in dust mixtures have not been reported by Lebecki et al. [23]; but in particular conditions, pressure measurements and the observed damages may suppose that a quasidetonation regime might have been reached.

B. Role of Particles

As displayed by the few previous examples, interpretation and comparison between the available experimental results is

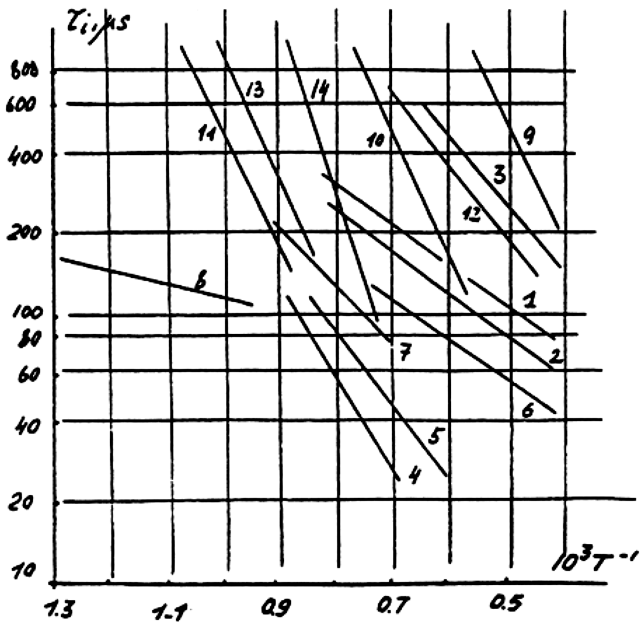

Fig. 8 Arrhenius plots of ignition delays of different dust suspensions compared to ignition delays of classical liquid sprays and gaseous premixtures (from Borisov et al. [24]).

complicated because the initial conditions of experiments are difficult to compare because of the presence of solid particles. Indeed, if the global heat to be released potentially by particle reactions with ambient oxidizers is determined by the chemical composition of particles, the way through which it is released is dependent on multiple factors, such as the mean size of particles, their granulometric distribution, their shape, specific surface, porosity, superficial oxidation, . . ., but also on the global and local mass concentration of particles in the gaseous mixture, the humidity of the ambient atmosphere, etc. All these parameters affect the heat release rate from reactions between particles and gases, and thus the flow structure behind the detonation front. Furthermore, reproducibility of experiments is problematic due to the difficulties in preparing reactive mixtures where particles are uniformly dispersed over the whole experimental volume.

This is why specific research has been carried out to investigate the kinetics of solid particles ignited behind a shock wave. Numerous works have been devoted to velocity relaxation of particles behind a shock wave. We will not examine them here in detail. Borisov and coworkers [24] investigated the ignition delay of particles of various chemical compositions and with different sizes in several ambient atmospheres. They displayed that particle ignition delays may be correlated to the temperature behind the shock according to an Arrhenius law in the same way as the induction delay of gaseous premixtures (see Fig. 8). One can observe a large scattering of ignition delays according to the particle size and nature of ambient atmosphere. These delays may be compared with those of liquid fuel droplets in air. From Fig. 9, one may conclude that for stoichiometric mixtures, the ignition delay of particles in a detonation wave is greater than that of droplets of a classical fuel (even for large droplets), and greater than the induction delay of gaseous mixtures by at least 1 order of magnitude. Experiments of the same kind have been performed by Fox and Nicholls [25]. More recently, Servaites et al. [26] studied the ignition of aluminum particles in shock tubes filled with water vapor–oxygen–argon and carbon dioxide–oxygen–argon atmospheres for propellant applications. Detailed studies of relaxation and ignition of small particles have been made by Boiko and coworkers: first, they studied ignition of single particles in incident and reflected shock waves [27]; then they visualized the interaction of a shock wave not only with single particles but with dust clouds [28,29], which permits one to determine the ignition delay of particles in more realistic conditions.

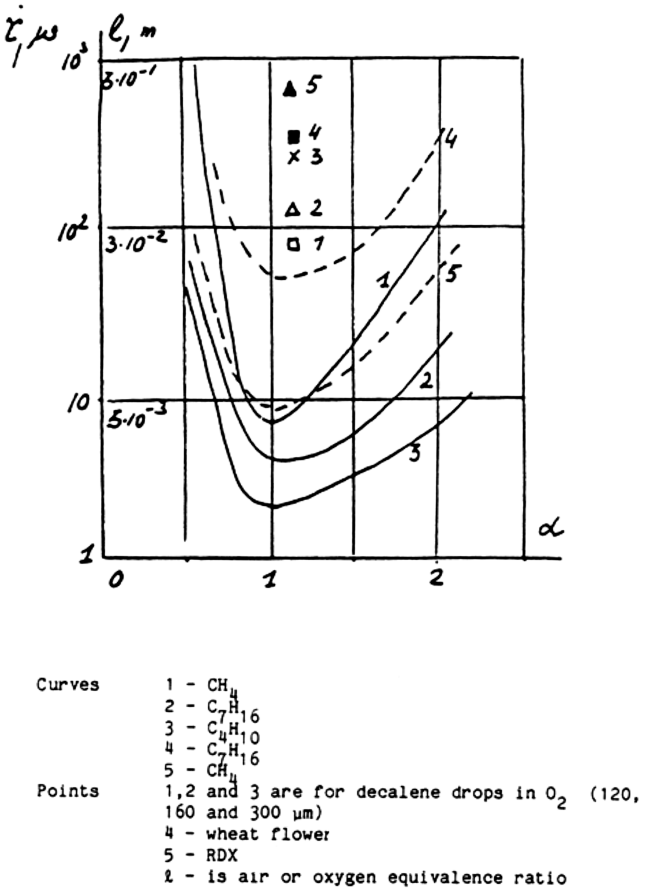

Fig. 9 Comparison of ignition delays and induction zone lengths in detonation waves of different combustible mixtures (from Borisov et al. [24]).

C. Results from Numerical 1-D Modeling

The previous remarks concerning the large delay necessary for particle ignition behind a shock or detonation wave substantiate the idea that the heat release zone behind the leading front is thick. Thus, it may be subject to heat losses, so that the classical CJ model based on the assumption of "instantaneous" heat release cannot apply in this situation. This can explain the important deficit of measured detonation velocities in comparison with the ideal CJ values, observed in most of the tube experiments. This problem has been studied by developing 1-D numerical models. All existing ones are based on the same set of assumptions. A scheme of the detonation wave as proposed by Lee and Sichel [30] is shown in Fig. 10. The two-phase flow is modeled in Euler coordinates by treating the two phases as separated fluids: mass, velocity, and temperature of particles and gases are different; interactions between the two phases are taken into account by phenomenologic laws representing velocity and temperature relaxation of particles in the gaseous flow behind the leading shock front. The detonation is described by the Zel'dovich–Von Neumann–Döring (ZND) model for nonideal detonations as proposed by Zel'dovich [31]. This model allows one to take account of a thick reaction zone between the leading shock front and the CJ plane. Chemical reactions between particles and gases are described generally by global one step kinetic laws or by very simplified kinetic models. As displayed in Fig. 10, one usually distinguishes an induction zone, corresponding to the delay for particle ignition, and the burning zone during which particles react with the gaseous oxidizer. But, contrary to the case of gases where the reaction zone of the detonation wave mainly consists of the induction zone, with a burning zone of negligible thickness, the burning zone of particles may be broad in the case of solid particle gas detonations. As a result, the length of the burning zone of particles may be as large as the ignition period, and, even, the combustion of particles may not be completed at the CJ plane and may continue in the flow beyond the CJ plane. As a result, friction and heat exchanges with the surrounding confinement (tube walls) may influence the reaction zone and must be taken into account. Exchanges by radiation between particles and the surrounding medium should also be considered.

With his numerical model based on the above assumptions, Sichel [30] compared his calculations with the experimental results of Kauffman and coworkers [4] and of Wolanski [7]. As displayed in Fig. 11 for oat–air and wheat–air mixtures, the calculated values of the detonation velocity are in acceptable agreement with the experimental ones for moderate particle concentrations corresponding to lean or stoichiometric mixtures. The numerical 1-D model indicates that the value of the detonation velocity should be smaller

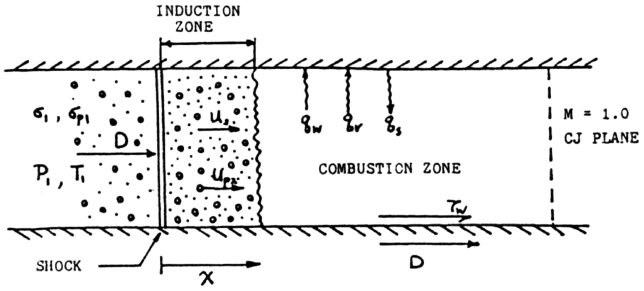

Fig. 10 Scheme of the heterogeneous detonation structure in shock fixed coordinates (from Lee and Sichel [30]).

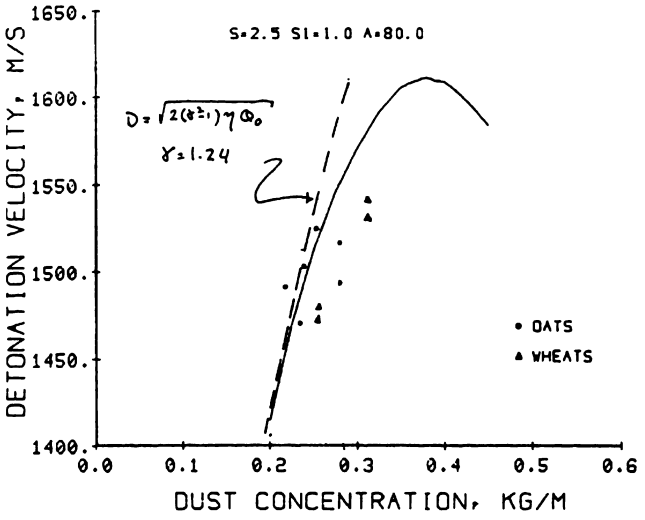

Fig. 11 Comparison between numerical calculations of Lee and Sichel [30] and experimental results of Kauffman et al. [4] (from Lee and Sichel [30]).

than that predicted by the approximate formula derived from the ideal CJ model. However, even with this improvement, it is visible that the experimental values are smaller than the calculated ones, and the agreement does not seem to be possible to obtain for larger particle concentrations.

Khasainov and Veyssiere [32,33] developed a numerical model in the case of starch particle oxygen mixtures. To describe accurately the heat release process behind the leading shock front, they calibrated the global kinetic law introduced in their model with the experimental data of Zhang and Grönig [17,18]. As can be observed in Fig. 12, the numerical results and experimental ones are in good agreement for a large domain of particle concentrations embracing equivalent ratios from lean to moderately rich mixtures. The velocity deficit with regard to ideal thermodynamic values is predicted by the model, by taking account of the lateral losses to the walls in the tube used for Zhang's experiments. When changing the tube diameter value to fit experimental conditions of Peraldi and Veyssiere [12], the calculated values match very well with experimental results obtained by these authors (see Fig. 12), which confirms the role played by lateral losses on the detonation parameters and the appropriateness of the considered numerical model. As for particle concentrations larger than 4000 g/m^3, for which experiments of Zhang display existence of detonations with high velocity values, this has been an unsolved problem until now. In detonation experiments with solid particle-gas mixtures, the existence of an upper detonability limit (for very rich

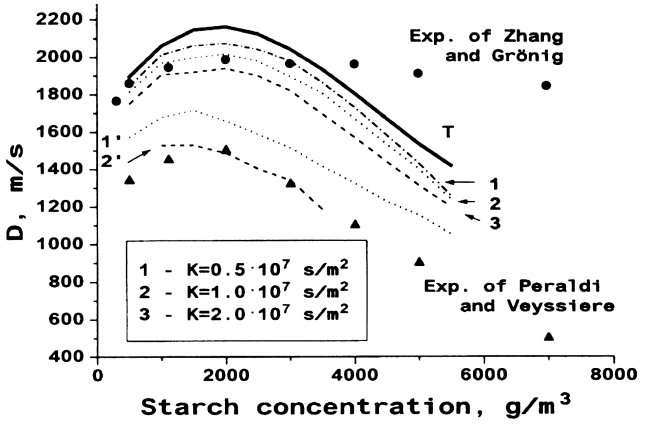

Fig. 12 Comparison between experimental and calculated values of the detonation velocity of starch/O_2 mixtures. Solid line: equilibrium thermodynamic values; ●: data of Zhang–Grönig [17]; ▲: data of Peraldi–Veyssiere [12]; 1, 2, 3, 1′, 2′: calculated values of Veyssiere et al. [32] (from Veyssiere et al. [32]).

mixtures) has never been displayed. Even, it is sometimes supposed that it would not exist; the reason could be due to the changes in the mechanisms of detonation propagation at such elevated particle concentration, with an increasing importance of radiative heat transfers. But there does not yet exist sufficiently solid proof of this assertion.

For their part, Fedorov and coworkers have undertaken to develop mathematical modeling of heterogeneous detonations. In the beginning, from a one-velocity, one-temperature model, they derived approximate analytical solutions [34]. Then, extending to two-velocity and two-temperature models, they performed 1-D calculations in various conditions, mainly on aluminum oxygen mixtures [35,36]. They tried to generalize their model to embrace different situations and discussed the conditions of existence of constant velocity and stable regimes [37]. But most of their results have not really been validated by any experiments, in spite of a reasonable agreement with certain experimental values of the detonation velocity reported by Strauss.

2-D numerical modeling of heterogeneous detonations has begun to be developed during the last decade. This aspect will be examined further in Sec. V.

D. Problem of Detonability

As it follows from experimental works (see Sec. III.A), the existence of truly steady, self-sustained detonations in gas–solid particle mixtures has not been definitely established. Even when quasi-constant supersonic propagation regimes have been observed, it is not certain that propagation of these detonations was completely independent on the presence of a confinement and initiation conditions.

1. Spinning Detonations

The most reliable experimental results all display that, in most cases, the detonation propagates in the spinning mode. This phenomenon has been observed by Strauss [5], Borisov [16], and Zhang [17,18] as well. In Fig. 2, the traces recorded on streak films by Strauss indicate clearly the spinning nature of the detonation regime. Borisov et al. [16] observed in aluminum suspensions (see Table 2) that for a given particle concentration the detonation velocity and the spin pitch depend on the size and shape of particles. Zhang et al. [38] studied in detail the structure of the spinning wave. They disposed pressure gauges on the circumference of the tube in the same cross sections and thus observed pressure evolution at a different radial position in the same cross section (see Fig. 13). From these records, they are able to reconstruct the structure of the spinning wave and evolution of the triple point (see Fig. 14). All these experimental facts emphasize the determining role played by the tube in supporting detonation propagation. Thus, it is not certain that the observed detonations are completely self-sustained, and one might speculate about the existence of steady self-sustained detonations in tubes of larger diameters. Further discussion of this problem will happen when examining the initiation of unconfined two-phase detonations

Table 2 Experimental results obtained by Borissov et al. [16] in aluminum–air mixtures (from Borisov et al. [16])

Measured detonation velocity, pressure, spin pitch, Mach number M, and luminosity fluctuation period τ

Aluminum	α, g/m^3	D, m/s	P_f, atm	Λ, cm	Λ/d	M	τ, μs
PAP	210	1760	33.0	43	3.52	6.26	240
	270	1800	33.0	40	3.28	6.29	220
	330	1790	33.5	38	3.11	6.32	210
	400	1810	35.0	38	3.11	6.32	210
UDA	140	1420	19	40	3.28	4.89	280
	170	1670	23	33	2.70	5.78	200
	210	1720	25	13	1.07	5.98	80
	270	1750	25	15	1.23	6.11	90
	330	1800	26	11	0.90	6.31	60
	460	1760	26	——	——	——	——
	560	1780	26	——	——	——	——
	750	1810	27	——	——	——	——

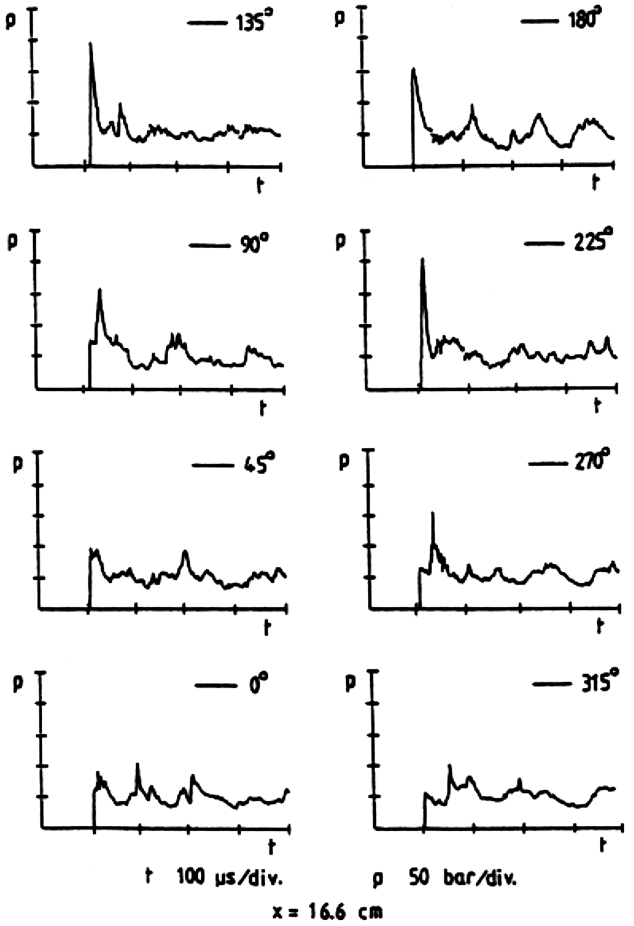

Fig. 13 Typical pressure records of a two-head detonation during the propagation in a cornstarch–oxygen mixture (from Zhang et al. [38]).

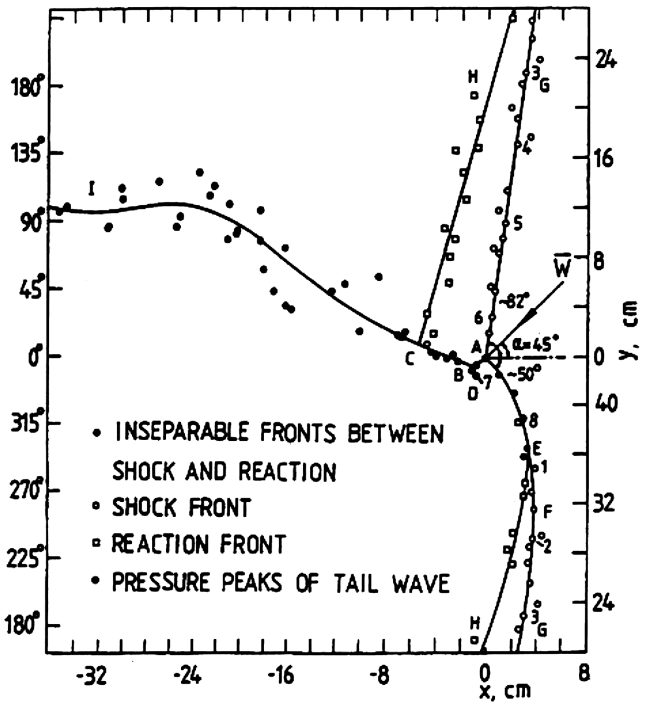

Fig. 14 Example of structure of a single-head spinning detonation obtained by Zhang et al. [22] by recording pressure at multiple positions during detonation propagation in a cornstarch–oxygen mixture of $\phi \approx 1$ at an initial pressure of 0.5 bar. x: axial coordinate; y: circumferential coordinate (from Zhang et al. [22]).

(Sec. III.D.3) and when trying to estimate the characteristic size of the cellular detonation structure and comparing it with the spin pitch (Sec. V).

2. *Deflagration to Detonation Transition*

The possibility of reaching the detonation regime through the DDT process (deflagration to detonation transition) is a relevant criterion to decide of the existence of detonation in a given mixture. Existing experimental data on this problem are rather insufficient. Gardner [10] tried to accelerate flames of coal dust suspensions initially at atmospheric pressure, initiated by a jet ignition of burnt products. Even if he succeeded in reaching elevated values of front velocities and shock pressures, it does not seem, from the reported experiments, that a truly self-sustained detonation was formed after 40 m of propagation of the flame in the tube. The same remarks can be done about the results reported by Pu et al. [19] for DDT formation in aluminum–air mixtures contained at atmospheric pressure in a 5 m long tube. As can be seen in Fig. 15, the leading shock front velocity in the terminal part of their tube remains far lower than the predicted detonation velocity for this mixture. More recently, the same authors [20] displayed that in a longer tube (12 m) they were able to record shock front velocities of the order of magnitude of 2000 m/s, which leads one to believe that the detonation regime has been reached. In suspensions of cornstarch with air contained under an initial pressure of 2.5 bars in a tube and ignited by a shock wave or a jet of burnt products, Zhang and Grönig [22] observed, first, the decaying of the incident shock wave in the dust suspension, and then, after ignition of particles, they recorded acceleration of the front wave and were able to observe formation of a detonation through the DDT mechanism (see Fig. 16). It appears from their experiments that the mechanism of shock front-flame coupling, which is characteristic of detonation formation, is noticeably different and more "gradual" than what is observed in homogeneous gaseous mixtures. Moreover, the characteristic distance for detonation formation is very important: a traveling distance larger than 120 times the tube diameter is required in their conditions. In their numerical simulations, Veyssiere and Khasainov [32] have tried to reproduce the experiments of Zhang and Grönig [22] with the same conditions. It appears that the numerical simulations clearly underestimate the distance of detonation formation. However that may be, it appears that investigation of the DDT phenomenon in solid particles gas mixtures requires very long tubes, of several ten meters.

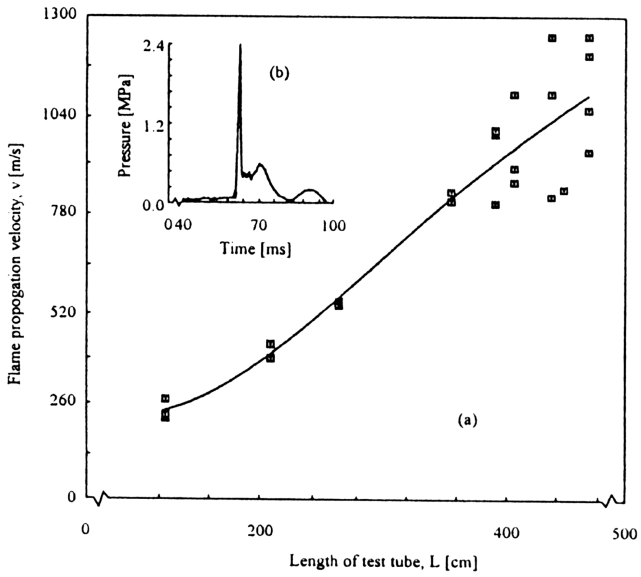

Fig. 15 Example of flame acceleration in fine aluminium dust air mixtures in the 5 m long horizontal tube of Pu et al. [19]. a) Flame propagation velocity as a function of tube length; b) pressure history measured on the tube wall at a distance of 4.8 m from the ignition place (from Pu et al. [19]).

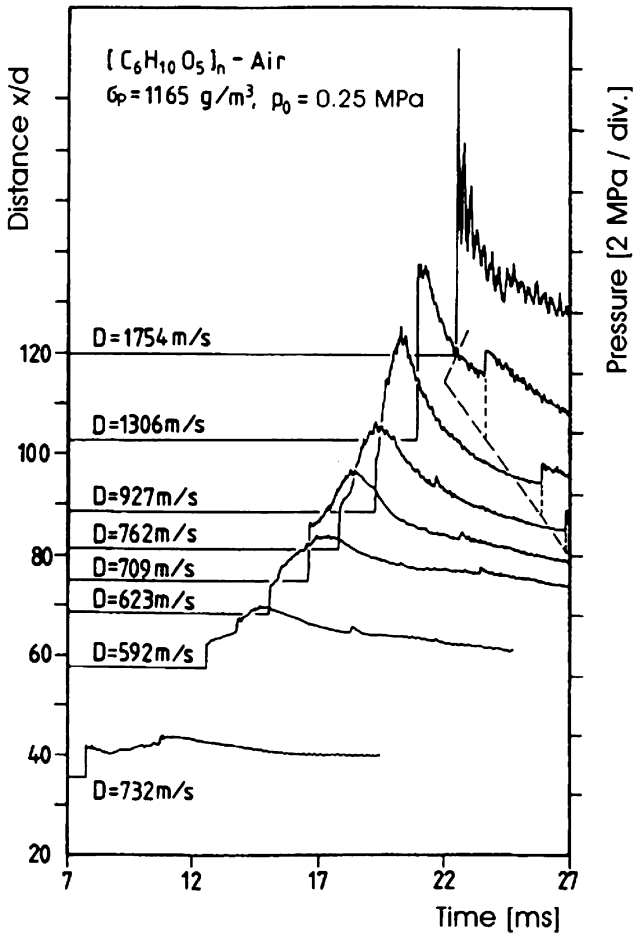

Fig. 16 Example of transition to detonation in a 10 μm cornstarch–air mixture, with $\phi = 2$ at an initial pressure of 2.5 bar, observed in the experiments of Zhang et al. [22] (from Zhang et al. [22]).

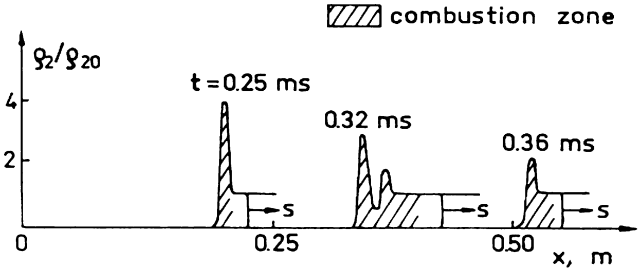

Fig. 17 Evolution of dust density profile behind the leading shock front during detonation formation in a heterogeneous mixture (from Korobeinikov [40]).

An illustration of the difficulty to decide whether the self-sustained detonation regime can be obtained or not in a tube is given in Table 3 in the case of aluminum suspensions. It appears that, in spite of the various experimental conditions tested (tube length, tube diameter, size and shape of aluminum particles, nature of the oxidizing atmosphere, nature of the ignition source) the question remains not clearly elucidated even 35 years after the first experiments of Strauss. In all cases, a somewhat strong ignition source was necessary to get the detonation regime. However, it appears that with a tube with sufficiently large diameter and length it is likely to obtain a self-sustained detonation with aluminum particles.

To progress in the knowledge of detonation formation, it is necessary to better understand how the coupling between the shock front and the reaction zone arises. Indeed, contrary to the case of gaseous mixtures, the shock front changes the composition of the reactive mixture in the flow downstream because of the relaxation of solid particles in the high speed gaseous flow. This problem has been particularly investigated by Korobeinikov et al. [39,40]. They showed that the shock front generates important gradients of particle concentration in the dust suspension: just behind the shock front the concentration of particles is depleted and farther downstream a zone with high particle concentration is formed. Korobeinikov called this phenomenon the "ρ-layer" effect. The thickness of this zone, its position behind the leading shock, and the value of particle concentration evolve during time with the shock strength as depicted in Fig. 17. As a result, in spite of the high temperature existing behind the shock, coupling between the shock front and the reaction zone may not take place because the concentration of particles in the considered zone is under the lower detonability limit. In other words, the process of coupling requires a "synchronization" between the relaxation of particles and the heat release from heterogeneous reactions. Both phenomena depend on the size and shape of particles. Further analysis of this problem was done by Fedorov et al. [37].

3. Direct Initiation

To discard the influence of tube walls on supporting the detonation wave, a few attempts have been done to detonate solid particle–gas mixtures in unconfined configurations. Tulis [41] conducted large scale experiments in aluminum–air clouds. He tried to detonate either cylindrical clouds with a radius of about 3 m (see Fig. 18) or linear-type clouds elongated over about 10 m. Initiation was achieved in the center for the cylinder or at one end for the linear-type by means of solid explosive. With a mass of 2.27 kg of solid explosive, he recorded for the detonation velocity, values of the order of 1500 m/s at the boundary of the dust cloud. These values remain smaller than the theoretical ideal ones, and the pressure records do not permit one to decide if the propagation regime evolves toward a shock induced combustion of particles or a heterogeneous detonation.

Veyssiere et al. [42,43] performed experiments in dust clouds contained in a 0.385 m^3 polyethylene bag. Because of limited available propagation distance, they experimented mixtures with pure oxygen as the oxidizer to get faster chemical reactions. Ignition was achieved with TNT solid explosive charges up to 125 g (see Fig. 19). With starch particles [42] they observed only a decaying blast wave followed by a shock induced burning zone of starch. With atomized aluminum particles [43], they made rather similar observations. But with certain aluminum flakes (thus more reactive),

Table 3 Summary of main tube studies on detonation of aluminum suspensions

	Date	Tube length	Tube diameter	Gas	Particle size	Ignitor	Terminal velocity
Strauss	1968	2.7 m	26.4 mm 44 mm	O_2	Flakes 40 μm Atomized 5 μm	Detonators	1400–1600 m/s
Tulis	1982	5.5 m	152 mm	Air	Spherical 5 μm Flakes 1 μm thick	3 g solid explosive	1300–1500 m/s
Borisov et al.	1992	4.2 m 2 m	122 mm 55 mm, 145 mm	Air	Flakes 1 μm Atomized 1 μm, 11 μm, 33 μm	Detonators Solid explosive	1400–1800 m/s
Zhang et al.	2001	37 m	300 mm	Air	Flakes 36 μm (1 μm thick)	Pyrotechnical	$\geq$2000 m/s
Pu et al.	1997	14 m	140 mm	Air	Atomized 6 μm	Black powder	2000 m/s?

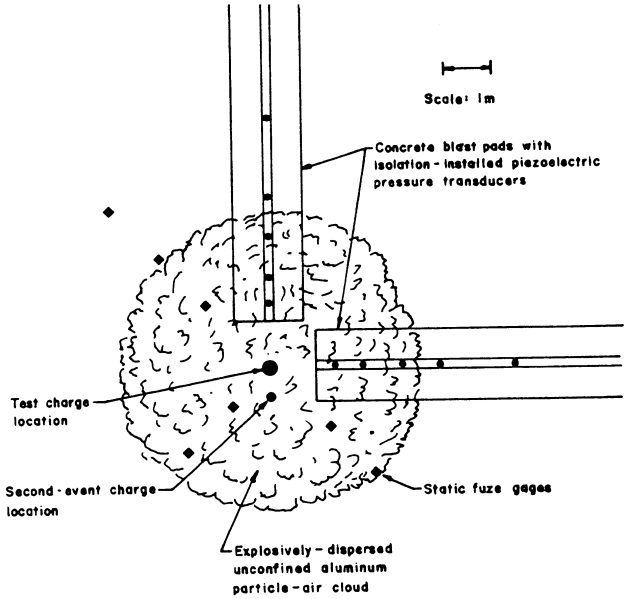

Fig. 18 Schematic layout of the IITRI blast pad facility to study the initiation of spherical unconfined aluminum–air detonations (from Tulis [41]).

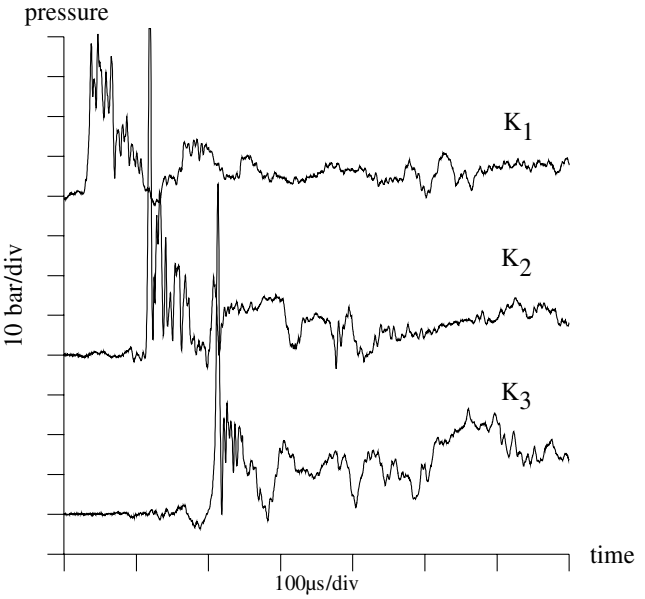

Fig. 20 Evolution of the blast wave inside the aluminum oxygen cloud of Fig. 19 experiment; initiation by a 125 g TNT charge (from Veyssiere et al. [43]).

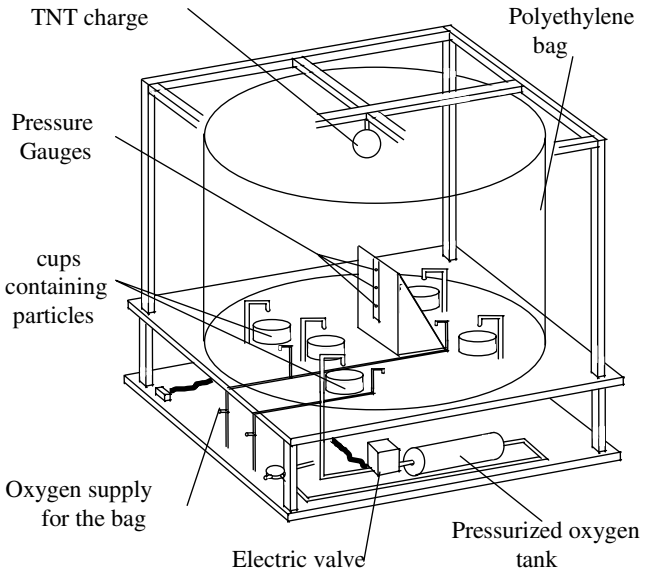

Fig. 19 Experimental setup used by Veyssiere et al. [42,43] to study the initiation of unconfined hemispherical detonations in solid particle–oxygen mixtures (from Veyssiere et al. [43]).

they recorded quasiconstant propagation velocity about 1200 m/s, after half the traveling distance inside the bag; and the pressure signals recorded at different locations display very comparable profiles (see Fig. 20). The exact nature of the propagation regime reached in these conditions is not clearly identified (quasidetonation, low velocity detonation), but it is obvious that the dimension of the bag is yet too small to allow observation of a CJ detonation. Note that in the same conditions, unconfined detonation formation would have been observed in most of the classical hydrocarbons with air.

All the results reported above indicate that although heterogeneous solid particle gas (air or oxygen) mixtures are susceptible to give rise to more powerful detonations than those supported by gaseous mixtures, on the opposite they are considerably less detonable than gaseous mixtures. Study of the detonation cellular structure and its characteristics in solid particles gas mixtures should permit one to go further in the investigation of the detonability of these mixtures. This question will be examined later in this paper.

IV. Hybrid Detonations

A. Different Detonation Structures

Hybrid mixtures, such as reactive particles suspended in a gaseous mixture are characterized by the fact that the fuel is contained partly in the solid particles and partly in the gaseous mixture. This confers specific properties to the detonation in hybrid mixtures: 1) heat release supporting detonation propagation comes from both gaseous reactions and reactions between particles and gases; 2) these two kinds of reactions may have different characteristic times (one or several orders of magnitude); 3) as a result, heat release is noninstantaneous and nonmonotonic; it occurs in a broad reaction zone behind the leading shock front. According to the sequence of heat release rate behind the shock front as a function of time, several detonation structures may exist. The first one which has been exhibited is the detonation with two successive discontinuity fronts. It was displayed at about the same time experimentally by Veyssiere [44,45] and theoretically by Afanasieva et al. [46]. Veyssiere [44,45] reported experiments in hydrogen–air mixtures with aluminum particles in suspension contained in the vertical, 69 mm internal diameter tube described above in Sec. III. He displayed that for an adequate choice of gaseous composition, particle diameter, and mass concentration, a "double-front" detonation propagates with the delay between the two front remaining quasiconstants over the distance of observation (2.5 m, see Fig. 21). Afanasieva et al. [46] demonstrated, for a spherical detonation, that when the heat release occurs in two stages, a "double detonation" may propagate (see Fig. 22). A first CJ point exists in the flow, behind the diverging detonation supported by a first heat release and is followed by a second detonation wave supported by the second heat release. Moreover, they showed that existence of the same structure may be predicted in the case of a plane detonation propagating in a tube under the condition that momentum and heat transfer between the reaction zone and the tube walls are taken into account (see Fig. 23).

Veyssiere and Khasainov [33,47,48] investigated in detail the different detonation structures in the frame of the model of nonideal detonations (Zeldovich [31]), which states that stationary propagation regimes are found by fulfilling the so-called equivalent CJ condition, that is, satisfying simultaneously two conditions: the local Mach number (relative to the leading front) must be equal to unity ($M = 1$) and the effective heat release rate $\mathrm{d}q/\mathrm{d}t$ equal to zero ($\mathrm{d}q/\mathrm{d}t = \mathrm{d}q_+/\mathrm{d}t - \mathrm{d}q_-/\mathrm{d}t$, a balance between the energy release rate from chemical reactions and the energy loss rate due to different sources of energy losses). Thus, they displayed three possibilities,

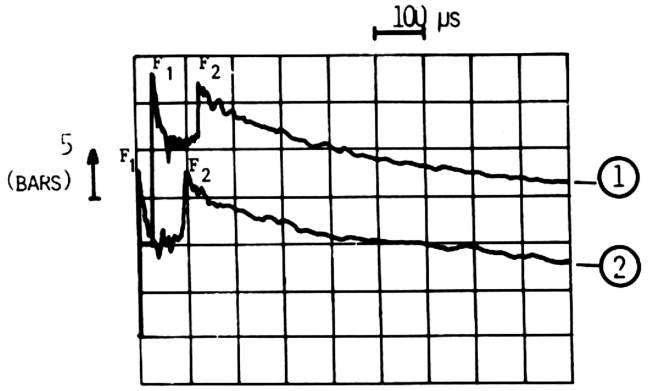

Fig. 21 Example of propagation of a "double-front" detonation in a hybrid mixture of hydrogen–air ($r = 0.78$) with aluminium particles (diameter $d = 10\ \mu$m, mass concentration $\sigma \cong 55\ \mathrm{g/m^3}$). Pressure profiles recorded: 1) at 1.945 m from the ignition point; 2) at 4.175 from the ignition point (from Veyssiere [45]).

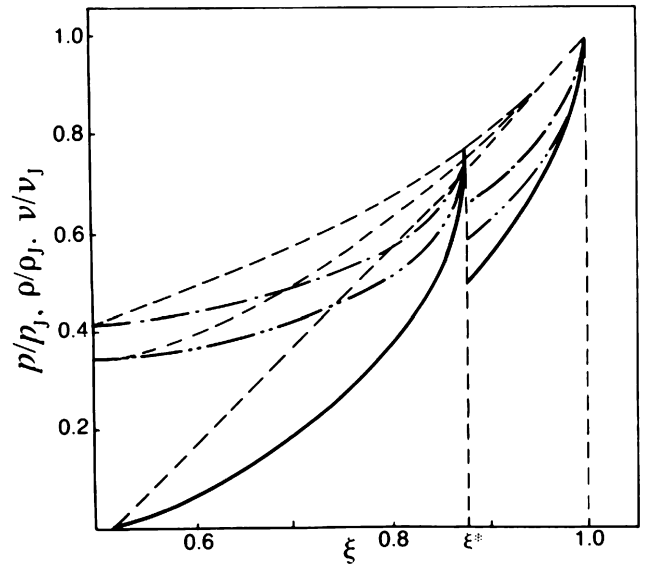

Fig. 22 Numerical simulation displaying the possibility of a double detonation wave in spherical propagation. $\nu = 3$, $Q_1/D_J^2 = 0.637$; (dash–double–dotted line) P/P_J; (dash–dotted line) ρ/ρ_J; (solid line) v/v_J (from Afanasieva et al.).

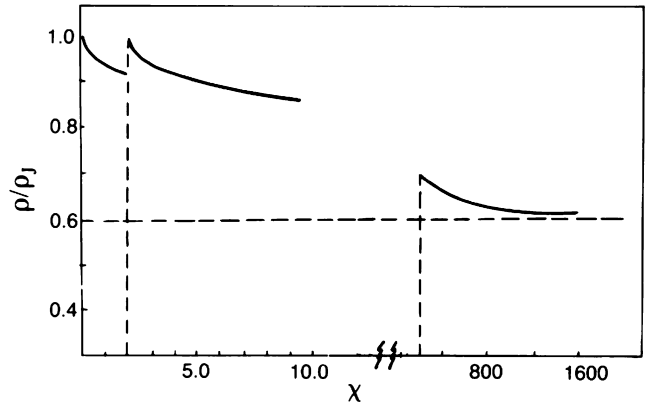

Fig. 23 Numerical simulation displaying the possibility of a double detonation wave in tube propagation with mechanical and heat losses to the walls. $D_J/v_0 = 1.667$; $C_pT_w/v_0^2 = 0.78$; $c_f/L^* = 0.01$; $Q_1/D_J^2 = 0.54$; $Q_2/D_J^2 = 0.07$ (from Afanasieva et al. [46]).

depending on the sequence of heat release behind the leading shock front. In the first case (see Fig. 24), the detonation is supported by the energy released both by gaseous explosives and solid particle–gas reactions. Only one discontinuity front exists and for this reason, it is called "single-front detonation" (SFD). The second case was called "pseudogas detonation" (PGD), because the detonation front is supported only by heat release from gaseous reactions (Fig. 25). The particles remain inert upstream of the CJ point and their reactions with gaseous products occur in the nonstationary flow downstream of the CJ plane. The third case is the so-called "double-front detonation" (DFD) introduced above: it is characterized by the existence of two detonation fronts, the first one is supported by heat release from gaseous reactions, and the second one by reactions between particles and gases (see Fig. 26). The propagation regime met in a given hybrid mixture will depend on the actual heat release

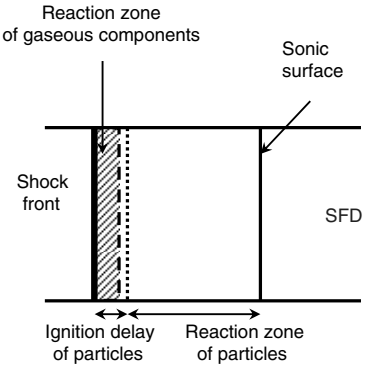

Fig. 24 Scheme of the single-front detonation (SFD) structure in hybrid mixtures (from Veyssiere and Khasainov [47]).

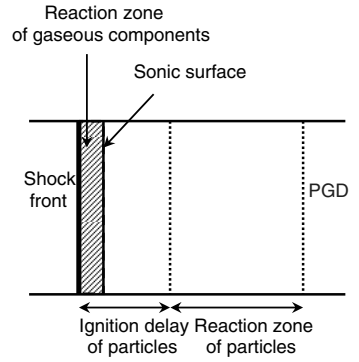

Fig. 25 Scheme of the pseudogas detonation (PGD) structure in hybrid mixtures (from Veyssiere and Khasainov [47]).

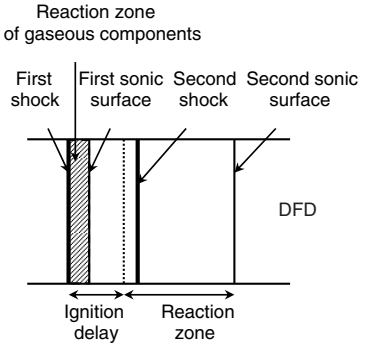

Fig. 26 Scheme of the double-front detonation (DFD) structure in hybrid mixtures (from Veyssiere and Khasainov [47]).

process, which is very sensitive to particle mass concentration and size, as illustrated by Fig. 27 for a hydrogen–air mixture with aluminum particles in suspension. In this figure, evolution of the leading front velocity is plotted as a function of the mass particle concentration in the initial mixture and for different particle diameters. The different detonation regimes and their domains of existence are indicated; it can be seen that they are very sensitive to particle diameter, which is not surprising as the particle diameter is a governing factor for their burning time, thus for the characteristic time of heat release. In the case of hydrogen–oxygen–nitrogen–aluminum mixtures, all the available experimental results fit quite well with the predictions [47] of the model of Khasainov and Veyssiere. Moreover, it is worth remarking in Fig. 27 that the increase of concentration in the hybrid mixture of, even reactive, particles does not induce necessarily an augmentation of the detonation velocity. On the contrary, it diminishes in many cases, even in the SFD regime. However, secondary compression of the products due to particle burning will contribute to reinforce pressure effects and increase the pressure impulse generated in an engine.

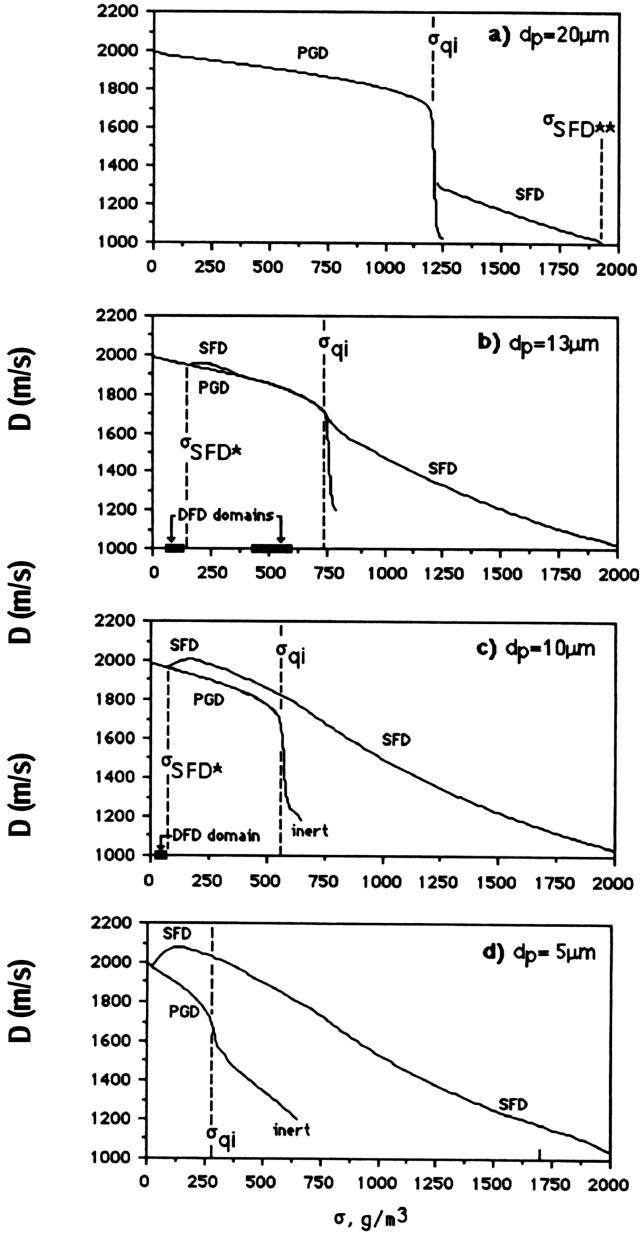

Fig. 27 Domains of existence of the different detonation structures in hybrid hydrogen–air–aluminium particles mixtures as a function of diameter d and mass concentration of particles σ (from Veyssiere and Khasainov [47]).

B. Multiple Detonation Regimes and Their Initiation

Generalizing the theory of nonideal detonations of Zeldovich to the case of detonations with nonmonotonic heat release, Kuznetsov [49,50] demonstrated that for given initial conditions, the detonation mode might be nonunique and several detonation regimes could be reached according to the actual energy release process. This statement was partially confirmed later by Menga [51] who established that in gaseous detonations with added inert particles able to generate heat losses in the reaction zone, three detonations regimes could exist (see Fig. 28): the normal one, a low velocity regime, and an intermediate unstable one. Existence of these three regimes depends on the heat losses generated by the particles. This problem was analyzed in detail by Veyssiere and Khasainov [47] in the case of detonations in hybrid mixtures of hydrogen–air with aluminum particles in suspension. An example is shown in Fig. 29, where the detonation velocity is plotted as a function of the particle concentration for a given particle diameter. The domains of existence of the different regimes are shown with the corresponding structures. From this example, it is clear that the mechanism of detonation propagation in hybrid mixtures is very complex and prediction of the detonation regimes is impossible without knowing precisely the actual sequence of heat release behind the leading front. Moreover, the case of inert particles (dusty detonations) appears to be a particular case of hybrid detonations: even if they do not contribute to a secondary heat addition, inert particles are, for suitable values of their physical parameters (diameter, concentration and heat transfer coefficient, ...), able to let the process of heat release to become nonmonotonic.

Another question arises about the stability of these regimes. Numerical simulations performed by Khasainov and Veyssiere [48] with an unsteady model confirmed that the different regimes displayed by the steady analysis could be reached after shock initiation of the mixture. Moreover, they showed that, in domains of initial conditions where two regimes (PGD and SFD) can exist simultaneously, PGD can propagate only over a limited distance (a few meters). After a certain time, finite perturbations due to secondary heat release in the unsteady flow behind the CJ plane are able to modify the leading wave and to accelerate it to the SFD regime. This conclusion is in agreement with the predictions of the approximate analysis proposed previously by Khasainov et al. [52] concerning the effect of secondary reactions downstream of the CJ plane. In any case, they conclude from their simulations that, for hybrid mixtures, buildup of steady detonation regimes requires long propagation distances, of the order of magnitude of 10 m or more (see Fig. 30).

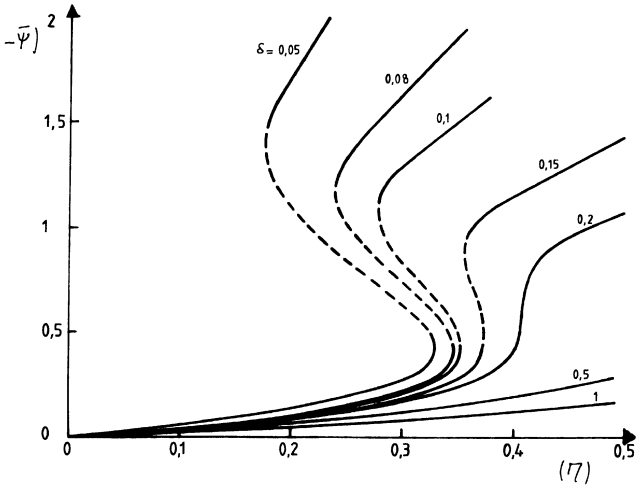

Fig. 28 Variation of the deficit of the detonation front velocity as a function of the magnitude of thermomechanical losses to a finely divided solid inert absorber (from Menga [51]).

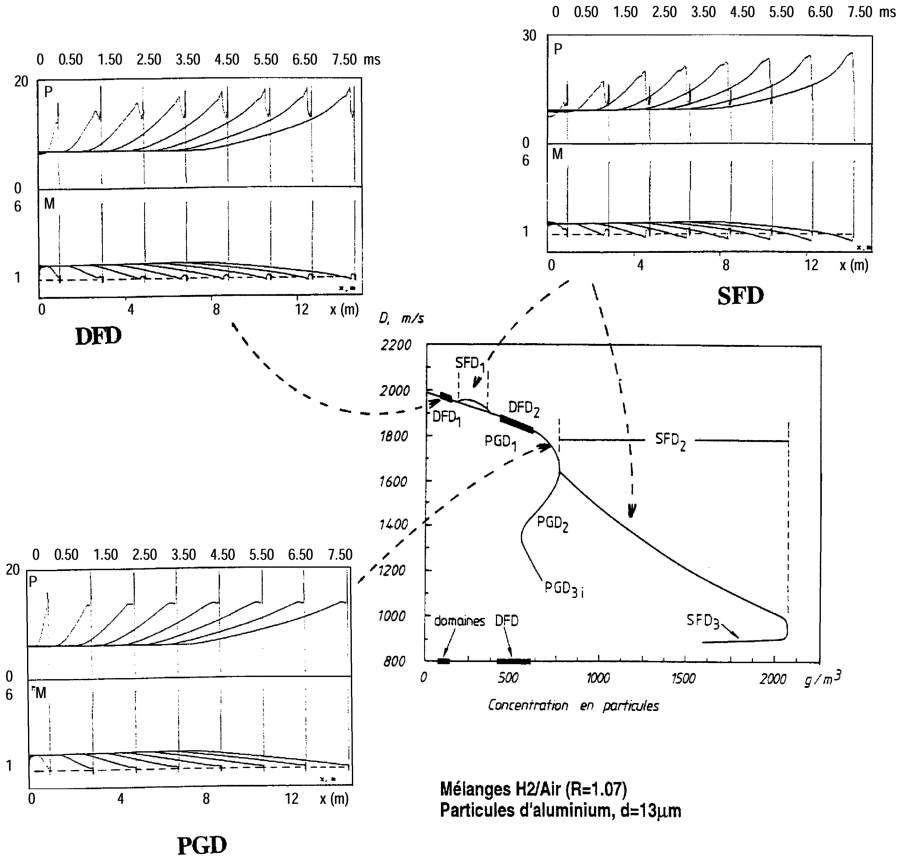

Fig. 29 Multiplicity of detonation regimes in hybrid hydrogen–air–aluminum particle mixtures (from Veyssiere and Khasainov [47]).

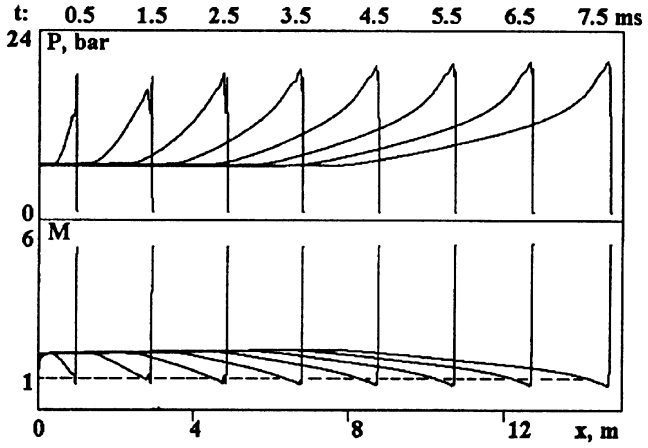

Fig. 30 Formation of a steady, self-sustained SFD detonation in hybrid hydrogen–air–aluminium particle mixtures (particle diameter $d = 10\ \mu$m, concentration $\sigma \cong 75\ \mathrm{g/m^3}$; initiation energy $E_p = 2.5 \times 10^5\ \mathrm{J/m^2}$ (from Khasainov and Veyssiere [48]).

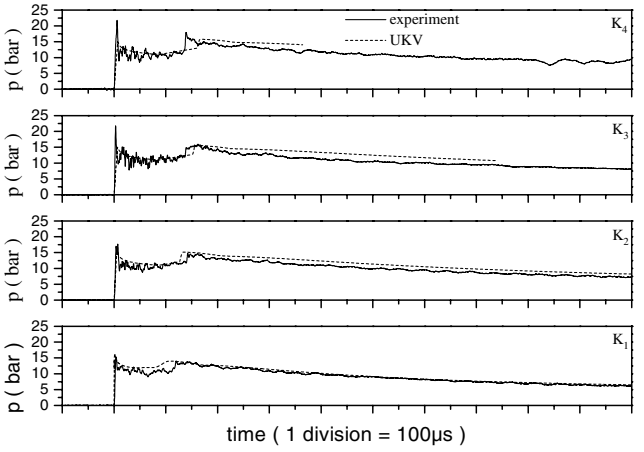

Fig. 31 Experimental pressure records and numerical simulations of the formation of a steady, self-sustained DFD detonation in a hybrid hydrogen–air–aluminum particle mixture (equivalent ratio: 0.87; particle diameter: 5 μm; concentration: 70 $\mathrm{g/m^3}$) (from Ingignoli [53]).

C. Recent Results on Hybrid Detonations

Until now the number of available experimental or numerical results is limited. All the experimental results obtained previously by Veyssiere [11] match satisfactorily with the model of Veyssiere and Khasainov [47,48] for hybrid detonations. Experiments of Ingignoli [53] in hydrogen–air–aluminum particle mixtures confirmed and extended the preceding results of Veyssiere (see Fig. 31 for the DFD case). Carvel et al. [15] attempted to precise the role of the aluminum particle by comparing the influence of aluminum and aluminum oxide particles on the detonation of a stoichiometric hydrogen–oxygen–argon mixture. However, the length of their tube was too short to exhibit any reliable conclusion. What they observed is only the formation of the "ρ layer" predicted by Korobeinikov [40] as the consequence of particle relaxation in the flow behind the leading detonation front. Zhang et al. [21] performed experiments in acetylene–air mixtures with suspensions of aluminum particles. The first results which they displayed indicate that the effects of aluminum particles on the detonation of acetylene–air mixtures are very similar to those observed by Veyssiere in hydrogen–air–aluminum particle mixtures. Variations of the detonation velocity and pressure evolution behind the leading front seem to be in good qualitative agreement with the predictions of the model of Veyssiere and Khasainov [47,48]. For example, it can be seen in Fig. 32, for the case of an acetylene–air mixture with an equivalent ratio $r = 0.8$, that burning of 2 μm aluminum particles behind the leading front generates a compression of products in the rear flow and accelerates

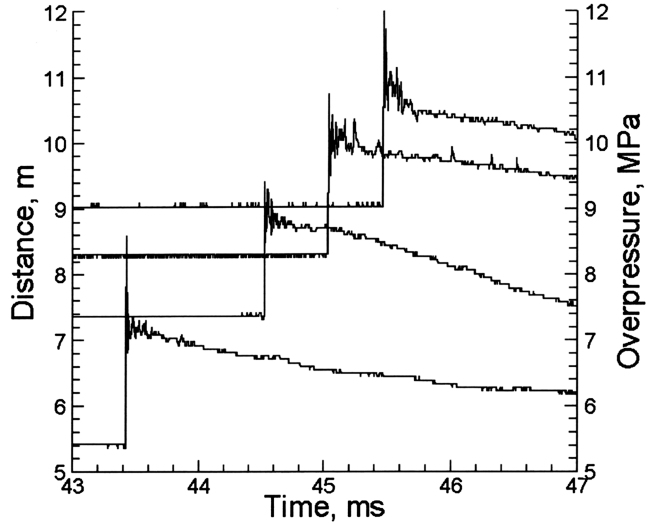

Fig. 32 Experimental pressure records of the formation of a steady, self-sustained detonation in a hybrid acetylene–air–aluminum particle mixture (equivalent ratio: 0.8; particle diameter: 2 μm; concentration: 500 g/m^3) (from Zhang et al. [21]).

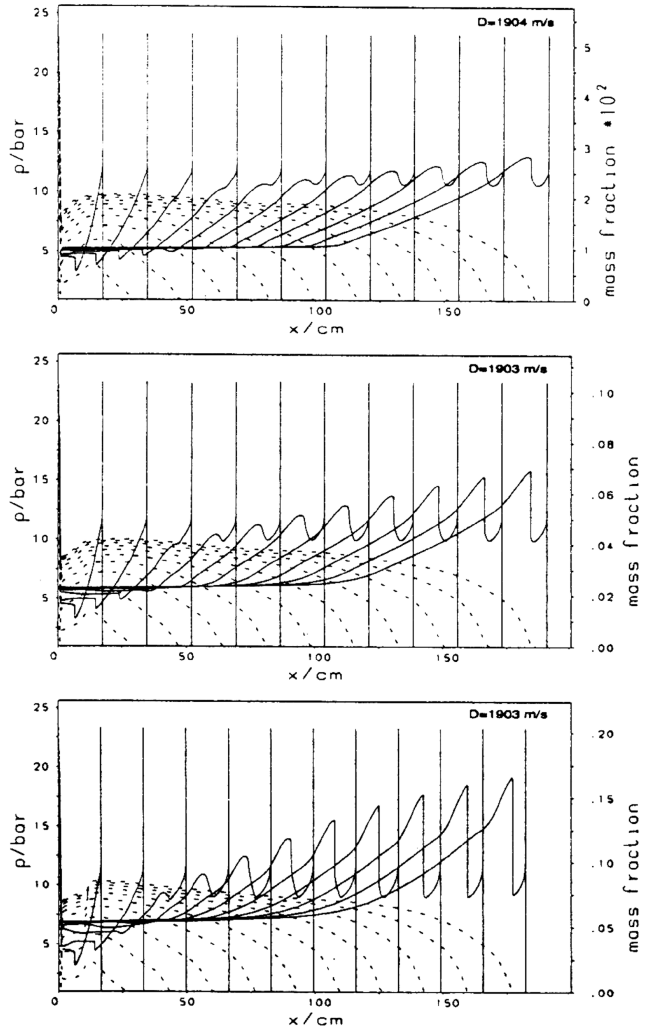

Fig. 33 Numerical simulation of detonation formation in hybrid hydrogen–air–aluminium mixtures at different numerical particle concentration. $n_p = 1.5 \times 10^4$ cm^{-3} (upper part); $n_p = 3 \times 10^4$ cm^{-3} (middle part); $n_p = 6 \times 10^4$ cm^{-3} (lower part) (from Uphoff et al. [55]).

the detonation front. It is likely that this propagation regime is of the SFD type proposed by Veyssiere and Khasainov [47,48]. Wolinski et al. [54] studied hybrid detonations in methane air mixtures with oats dust clouds. They observed that the addition of oats particles may promote the detonation formation in methane–air mixtures, which are known to be difficult to detonate. They also observed on their pressure records secondary compression waves due to the late reaction of part of the oats particles. These pressure evolutions can probably be analyzed according to the model of Veyssiere and Khasainov [47,48]. Moreover, they displayed that the addition of a large quantity of reactive particles is capable of quenching the detonation.

Several numerical models have been designed to compare with experimental results. Basically, they are constructed on the same assumptions as the model developed by Veyssiere and Khasainov [47,48], but the kinetic laws used to model the chemical reactions are different, and the numerical methods used to solve the set of differential equations of the problem may differ. In Fig. 33, one can see the simulations of Uphoff et al. [55] for a hydrogen air mixture with increasing values of the concentration of aluminum particles. The secondary compression of products generated by the burning of particles is clearly observed. Moreover, the amplitude of the compression increases with particle concentration augmentation. Figure 34 concerns the calculations of Carvel et al. [14] for a stoichiometric hydrogen–oxygen–argon mixture with aluminum particles which are considered either inert or reactive. In the inert case, one can see the compression generated by the relaxation of particles behind the detonation front. In the reactive case, heat addition is supplied in the products behind the front due to particle

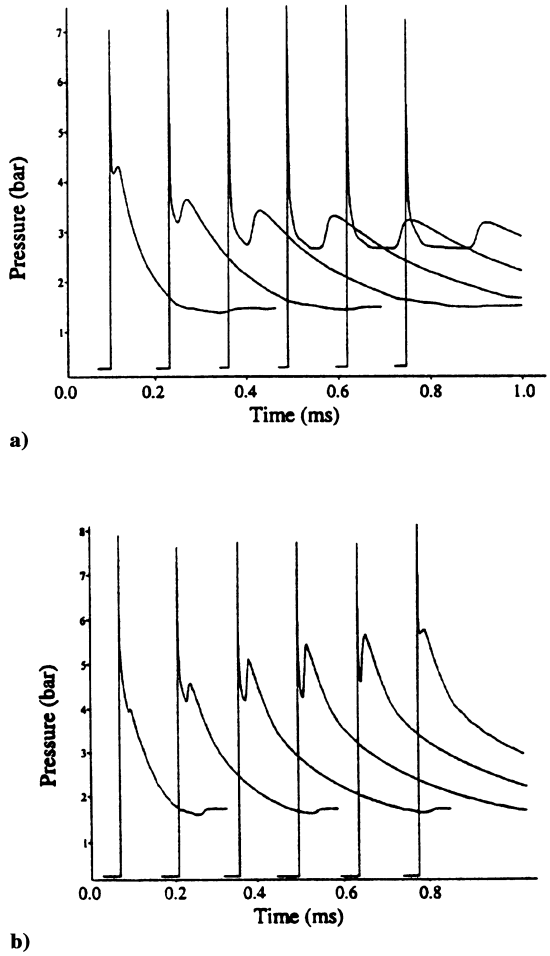

Fig. 34 Numerical simulation of detonation formation in hybrid hydrogen–air–aluminum mixtures (a) inert particles (b) reactive particles (from Carvel et al. [14]).

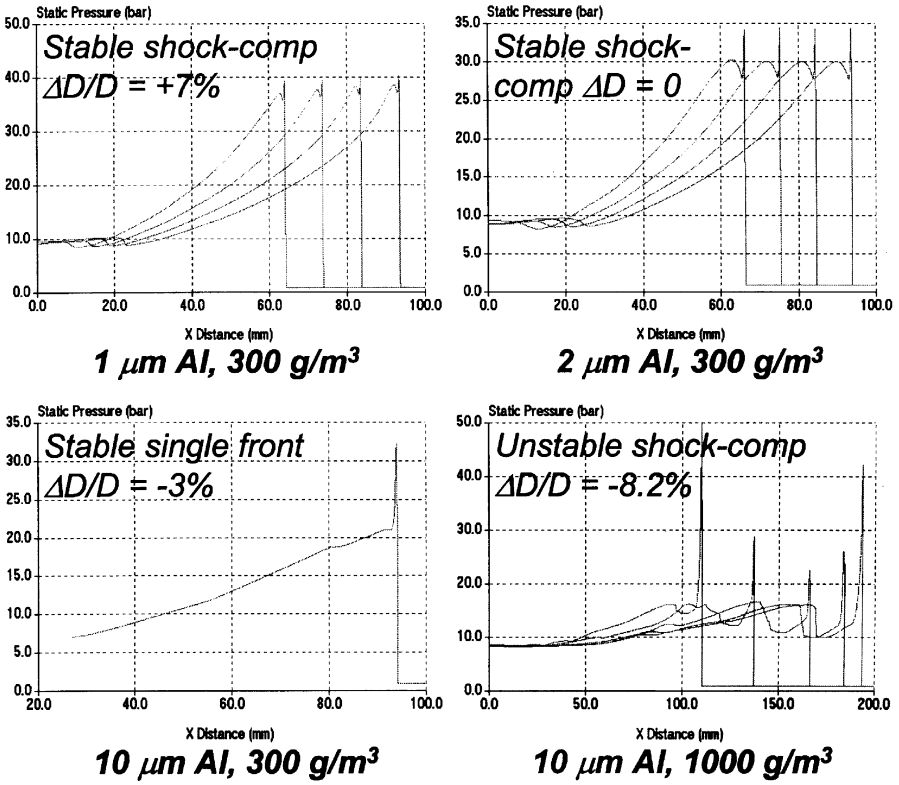

Fig. 35 Numerical simulation of detonation formation in a hybrid acetylene–air–aluminum particle mixtures for different values of the diameter and concentration of particles (from Zhang et al. [21]).

burning; thus the secondary compression wave has a greater amplitude and tends to become closer to the leading front, contrary to the inert case where they separated (see Fig. 34). Zhang et al. [21] performed calculations in conditions comparable to their experiments. In Fig. 35, one can see typical results for different values of particle sizes and concentrations. Small particles tends to reinforce the detonation front. On the opposite, larger particles decrease the value of the detonation velocity and the effect is more important at large particle mass concentration.

In these last numerical simulations, it is unlikely that steady propagation regimes have been reached because the lengths of calculation domains are smaller than 20 cm, which is far too short for a steady regime to be formed, as shown by Khasainov and Veyssiere [48]. Difficulty to perform calculations over a long domain is due to the multidimensional character of the problem which needs to discretize with a sufficient accuracy the gaseous reaction zone, the reaction zone of particles with gases, and the long propagation distance. All those parameters differ by several orders of magnitude. This imposes on one to perform calculations with a huge number of calculation meshes, which generates prohibitive memory sizes and computation times. As a result, simulations of Zhang et al. [21] do not permit one yet to interpret reliably experimental observations. On the opposite, this difficulty has been partially solved in the numerical simulations of Khasainov and Veyssiere [48] by using a suitable technique allowing one to get accurate precision of calculations in the zones of heat release, over long distances (several meters) of leading detonation front propagation (see Veyssiere et al. [56]). As can be seen in Fig. 31, the agreement is excellent on pressure evolution behind the leading front between calculations and experimental results, even for propagation distances of 6 m.

It is worth mentioning that Tunik [57] designed a numerical model to study the detonation of methane–air mixtures laden with coal particles. He investigated the problem of initiation of spherical detonations, but also of low-speed combustion regimes in methane–air–coal particle mixtures. But unfortunately, there does not exist, until now, experimental results to validate his numerical predictions.

V. Cellular Structure

As discussed in Secs. III and IV, we have a poor knowledge of the detonability of heterogeneous or hybrid solid particle–gas mixtures. Only scarce and qualitative data are available, for the most part because observation of steady, self-sustained detonation regimes requires experimental setup of large dimensions, which makes the experiments complicated and expensive. According to the results obtained in homogeneous gaseous mixtures, the detonability of a mixture can be estimated from the determination of the characteristic dimension λ of the detonation cellular structure: it assigns one dimension to the problem which is related to the thickness of the reaction zone. This dimension can be compared with other dimensions of the problem, particularly the geometric dimension of the confinement in which the detonation propagates. Hence, display of the cellular structure in gas–solid particle detonations and determination of its characteristic dimension is of major interest.

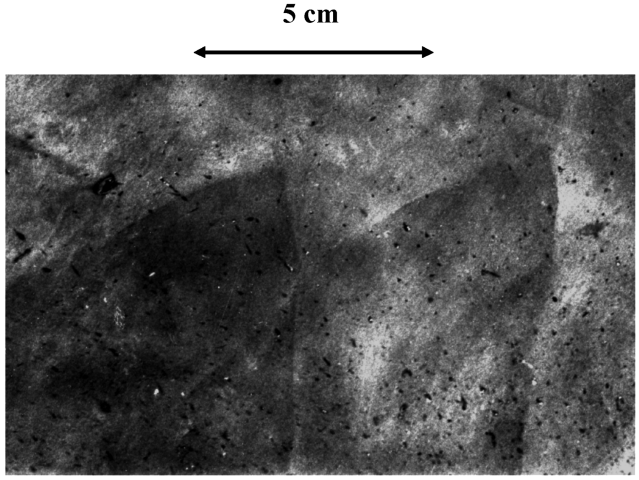

Fig. 36 Soot tracks obtained in aluminum oxygen unconfined experiments by Ingignoli et al. [43] (from Ingignoli et al. [43]).

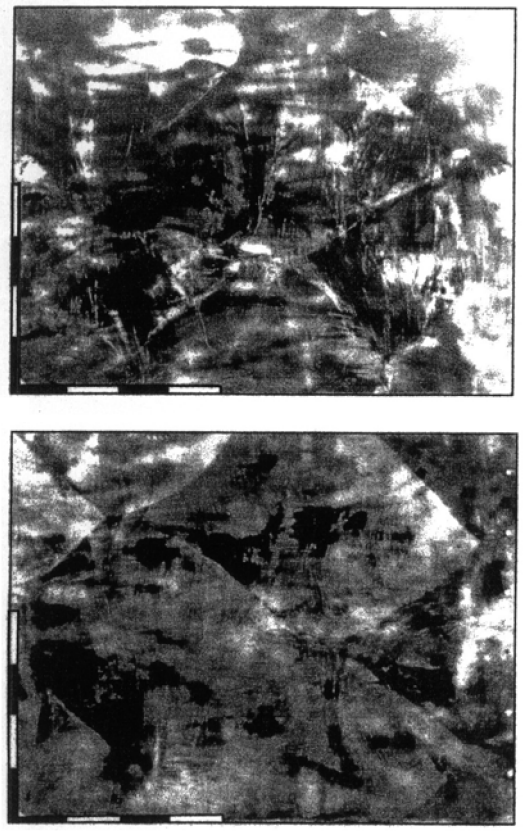

Fig. 37 Soot tracks of the cellular detonation structure recorded by Zhang et al. [22] in cornstarch–oxygen mixtures. (Top) cellular detonation structure of a smoked-foil record on the 0.3 m tube circumference at $x/d = 63.5$ in a 10 μm cornstarch–oxygen mixture with $\phi = 0.8$ at an initial pressure of 0.5 bar. Scale length is 0.1 m and the detonation propagates from left to right. (Bottom) Cellular detonation structure of a smoked-foil record on the 0.3 m tube circumference. Same conditions and scale (from Zhang et al. [22]).

A. Heterogeneous Detonations

Until now, proofs of existence of the cellular structure in heterogeneous two-phase mixtures are extremely limited: In their experiments in unconfined clouds of aluminum particles suspended in oxygen, Ingignoli et al. [43] recorded a few cellularlike structures with a characteristic dimension of 5–10 cm (Fig. 36). But these observations have been done at the external boundary of the cloud, thus it is not certain that these structures would exist at a further stage of propagation. Zhang et al. [22] observed the cellular structure in cornstarch–oxygen mixtures at 0.5 bar initial pressure: on smoked-foil disposed at the walls of a 0.3 m diam tube, they have registered between one and two cells within the tube circumference (Fig. 37). The average value of the cell width λ is, in their experimental conditions, of the order of 0.50 m. With aluminum–air mixtures at 1 bar initial pressure, a cell size of about 0.4 m was derived from measurements with a multiple pressure transducers technique. It is worthwhile noticing that the cell size of dust detonations seems to depend strongly on the particle size and shape. Besides, these few available data indicate that two-phase heterogeneous mixtures are far less detonable than the premixed gaseous mixtures, as their cell size is larger by at least 1 order of magnitude.

B. Hybrid Detonations

In hybrid mixtures, the first results displaying the existence of the cellular structure in the case of hybrid mixtures have been reported by Ingignoli et al. [58]. A more detailed analysis of the cellular detonation structure in hydrogen–air–aluminum particle mixtures was given by Veyssiere and Ingignoli [59]. When adding aluminum particles to a hydrogen–air mixture with equivalent ratio $r = 0.87$, different changes of the cellular structure can be observed (see Fig. 38), according to the characteristics of particles (three kinds: "A1," 3.5 μm atomized; "A2," 13 μm atomized, and "F," flakes with a characteristic thickness of 0.5–1 μm). With small particles A1 and flakes F (see Fig. 39), the cell width becomes smaller than for the pure gaseous mixture and the network is more regular. In conditions of Fig. 39, the cell width is $\lambda = 0.80$ cm. Simultaneously, important changes can be observed on pressure evolution: the front pressure is increased and the pressure level in burnt products is significantly higher than in the pure gaseous mixture. According to the results of Veyssiere and Khasainov [47], this propagation regime is that of a single-front detonation (SFD). With larger particles A2, opposite behaviors are observed. As shown in Fig. 40, the cell size is increased and its regularity becomes poor, with a large dispersion in cell dimensions. The average cell width for this case is $\lambda = 2.5$ cm. The pressure evolution displays a behavior completely different from that of Fig. 39: first, the front pressure is hardly changed by the addition of particles; then, during the first 100 μs in the burnt products, the pressure level remains close to that of the mixture without particles, but a second discontinuity front is observed at about 200 μs behind the leading one. At the same time, as shown in Fig. 38, the detonation

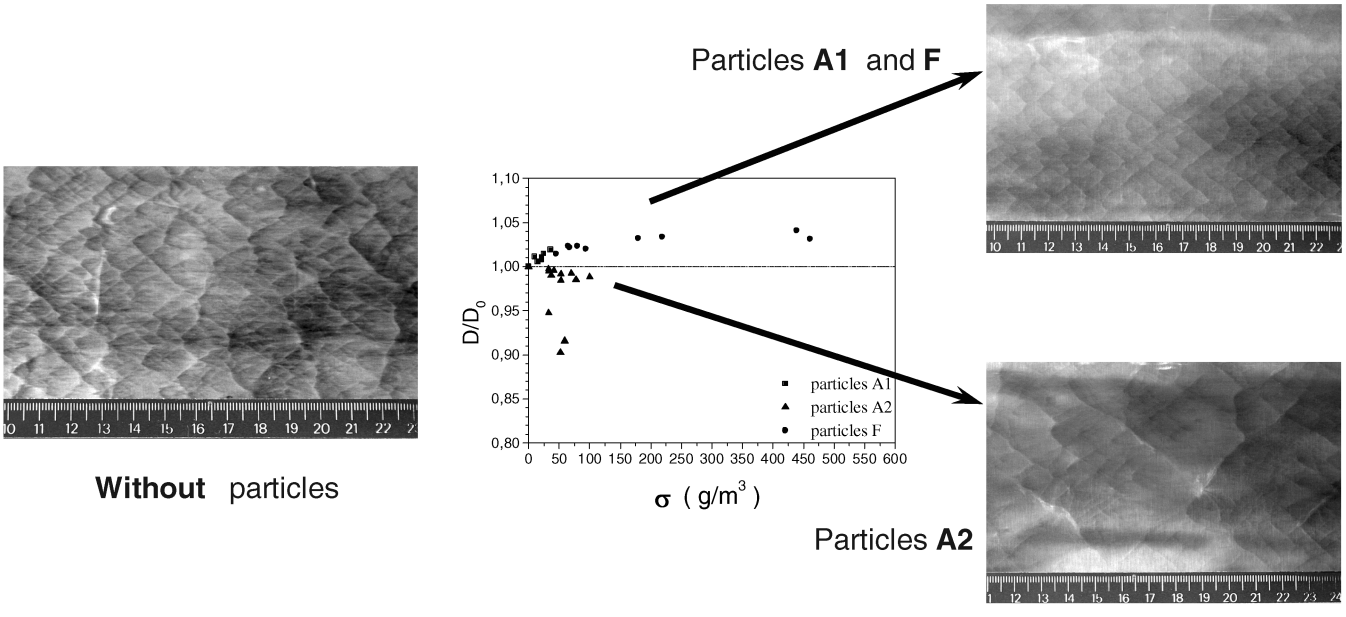

Fig. 38 Effect of aluminum particle addition on the cellular structure of the detonation in a hydrogen–air mixture (equivalent ratio 0.87).

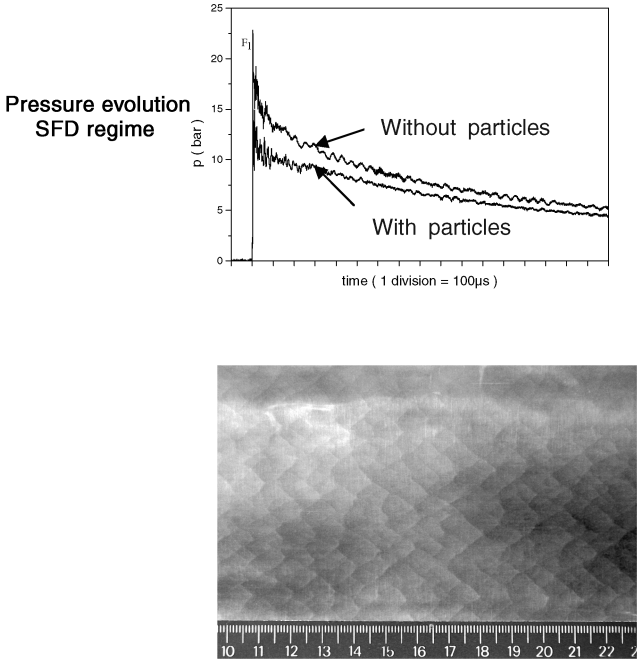

Fig. 39 Influence of "fine" aluminum particles on pressure evolution and cellular structure of the detonation in a hydrogen–air mixture (equivalent ratio 0.87), SFD case.

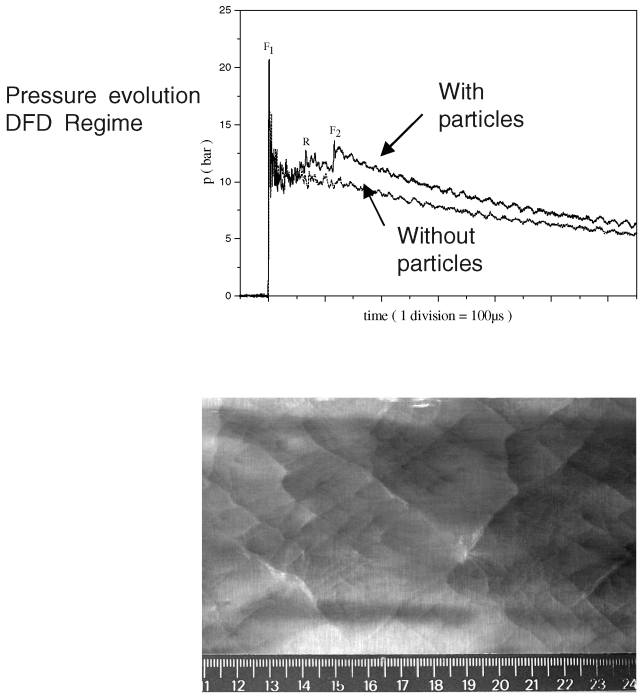

Fig. 40 Influence of "large" aluminum particles on pressure evolution and cellular structure of the detonation in a hydrogen–air mixture (equivalent ratio 0.87), DFD case.

velocity decreases. This situation has been shown to correspond to a double-front detonation (DFD) (Veyssiere and Khasainov [47]).

On the basis of their observations, Veyssiere and Ingignoli [59] proposed to correlate the variations of the cell size with the variation of the detonation velocity in the following way:

$$\frac{\lambda}{\lambda_0} = \frac{D_p}{D_0} e^{\frac{E_a}{RT_{ZND}}[(\frac{D_0}{D_p})^2 - 1]}$$

where D_0, λ_0, D_p, and λ are the detonation velocity and cell size, without and with particles, respectively. This is an extension of the correlation proposed by Desbordes [60] in the case of gaseous homogenous mixtures, linking the cell size of overdriven detonations to the cell size of the self-sustained CJ one. Comparison of variations of cell width predicted by the correlation with the measured values displayed in Fig. 41 indicates that agreement is quite good.

Another question arises from the nonmonotonic process of heat release due to the occurrence of secondary heat release from reactions of aluminum particles with gases. Because the characteristic times of gaseous reactions and reactions between particles and gases differ strongly (possibly by more than 1 order of magnitude), it is conceivable to conjecture the existence of a more complicated cellular structure connected to the different kinetic phases of the heat release process: two networks of cells having different characteristic sizes could exist. This possibility has been displayed by Lamoureux et al. [61] in the detonation of gaseous nitromethane oxygen mixtures, where they observed two cellular structures of different size, each of them corresponding to a kinetic phase of nitromethane oxidation. However until now, Veyssiere and Ingignoli [59] have not observed a secondary cellular structure in their experimental conditions. According to them, experimental difficulties encountered on account of the presence of solid particles, which spoil the soot tracks and weaken the quality of cellular structure registration, could partly explain this situation. But an

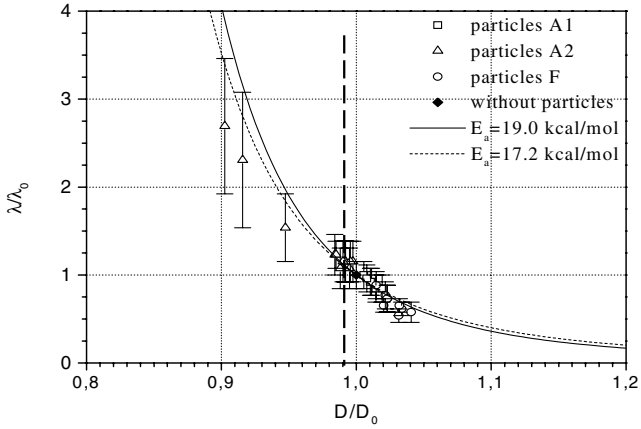

Fig. 41 Variation of the detonation cell width λ with the velocity of the leading front in a hybrid hydrogen–air–aluminum particle mixture (from Veyssiere and Ingignoli [59]).

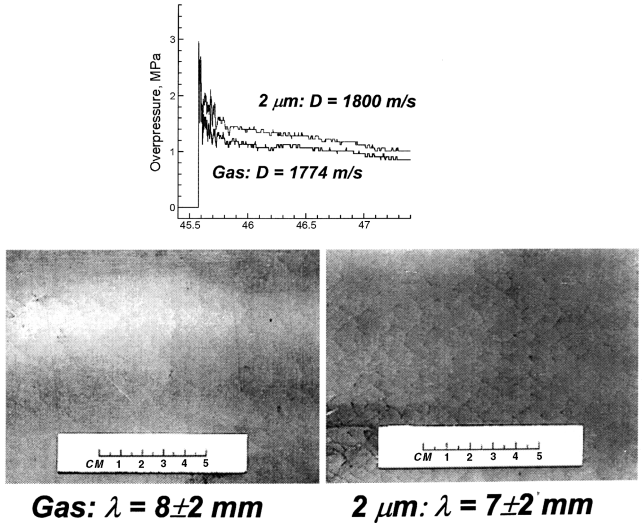

Fig. 42 Influence of fine aluminum particles on pressure evolution and cellular structure of the detonation in acetylene–air mixture (from Zhang et al. [21]).

important difficulty comes from the ignorance of the possible dimension of the cellular structure which could result from secondary reactions. The only available information is that mentioned previously in Sec. V.B for the cell size of heterogeneous aluminum air detonations, that is, several tens of centimeters.

In the recent experiments of Zhang et al. [21], in acetylene–air mixtures with aluminum particles, they also report soot tracks of the cellular structure. As can be seen in Fig. 42, these records are very similar to those obtained by Veyssiere and Ingignoli [59] with hydrogen–air–aluminum particles. Moreover, they observe the same trends: with small 2 μm particles able to increase the detonation front velocity, the pressure in the flow at the rear of the detonation front is augmented and the cell size diminished. All these findings lead one to think that the regime which they observed in this given case is of the SFD type, as proposed by Veyssiere and Khasainov [47].

C. Numerical Simulations

A few attempts have been done to simulate numerically the cellular structure in gas–solid particle detonations. Hayashi and coworkers [62,63] presented detailed 2-D and 3-D numerical simulations of the cellular structure in cornstarch–oxygen mixtures. Their choice of kinetic parameters allows them to fit qualitatively with some results of Zhang and Grönig [38], but the longitudinal dimension of their calculation domain (a few tens of centimeters) is definitely too small as compared to the characteristic distances at which Zhang observed steady, self-sustained detonations (>10 m). Benkiewicz and Hayashi [64] have performed numerical simulations of the cellular structure in oxygen–aluminum particle mixtures. The diameter of their channel is 0.12 m and the longitudinal dimension of their calculation domain is limited to 0.6 m. At the extremity of their computation domain, the detonation propagates in a two-headed mode (see Fig. 43), which corresponds to a cell size of 0.06 m. The only experimental data available in this case are those reported by Ingignoli et al. [43] who estimated an order of magnitude of 0.05–0.10 m. But, as discussed in Sec. V.A, the reliability of this value is not certain. Besides, the chosen value of the tube diameter is too small, as shown by experimental results of Zhang et al. [22], and the distance of propagation corresponding to their calculations is clearly insufficient to decide of the further evolution of their 2-D structure and of its characteristic size. By the way, they display that the cell dimension is extremely sensitive to the diameter of particles: decreasing the diameter of particles from 2.5 to 1 μm results in a reduction of the cell size from 6 to 1.1 cm. Khmel and Fedorov [65] also displayed calculation results of the cellular structure in aluminum–oxygen detonations. Their computations are performed so that they fit also the experimental estimation of Ingignoli et al. [43], which are the only available experimental data. The lack of experimental results relevant to the cellular structure of detonations in heterogeneous two-phase mixtures is a crucial problem because it stops, until now, the possibility to progress in the estimation of the detonation cell size of heterogeneous mixtures.

In hybrid mixtures, the only available numerical simulations of the detonation structure are those performed by Khasainov et al. [66]. The realization of such numerical simulations presents even much greater difficulties than for heterogeneous mixtures, because of the multidimensional character of the problem. As already underlined in Sec. IV, correct simulation of the detonation structure necessitates to calculate with a sufficient accuracy the reaction zones of gaseous reactions and of reactions between particles and gases: this fixes two characteristic dimensions in the problem, which may differ by one or several orders of magnitude. Another characteristic dimension is fixed by the solid particle size, and moreover, numerical simulations can provide relevant information only under the condition that they are performed over the propagation distances which have been shown in experiments to be necessary to reach a steady, self-sustained detonation regime, that is, several meters or more. Fulfilling these different requirements may lead to prohibitive computation conditions. However, a first set of simulations has been performed by Khasainov et al. [66]. They were able to calculate the development and evolution of the cellular structure of a detonation in hydrogen–air mixtures with suspended aluminum particles propagating over 6 m. As displayed in Fig. 44, the tracks of maximum pressure reproduce qualitatively well (dimension of the cells, irregularity of the network) the soot tracks obtained in experiments (see Fig. 38). In Fig. 45 displaying the pressure distribution in the flow, one can see the emergence of a bright zone

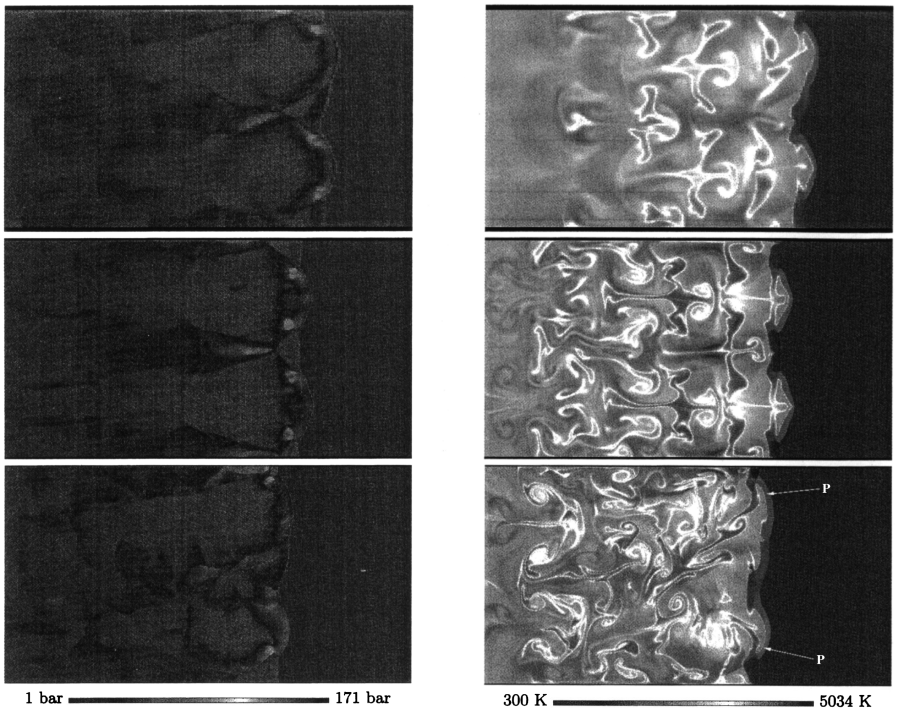

Fig. 43 Numerical simulation of the detonation structure in aluminium–oxygen mixture ($d_0 = 2.5$ μm, $c_{s0} = 0.3$ kg/m^3). Comparison (left) of the pressure P_g distributions and (right) of the gas phase temperature T_g distributions, for various spatial resolutions: 960 × 192 ($\Delta x = \Delta y = 0.625$ mm, $t = 290$ μs), 1920 × 384 ($\Delta x = \Delta y = 0.3125$ mm, $t = 280$ μs) and 3840 × 768 cells ($\Delta x = \Delta y = 0.15625$ mm, $t = 270$ μs) (from Benkiewicz and Hayashi [64]).

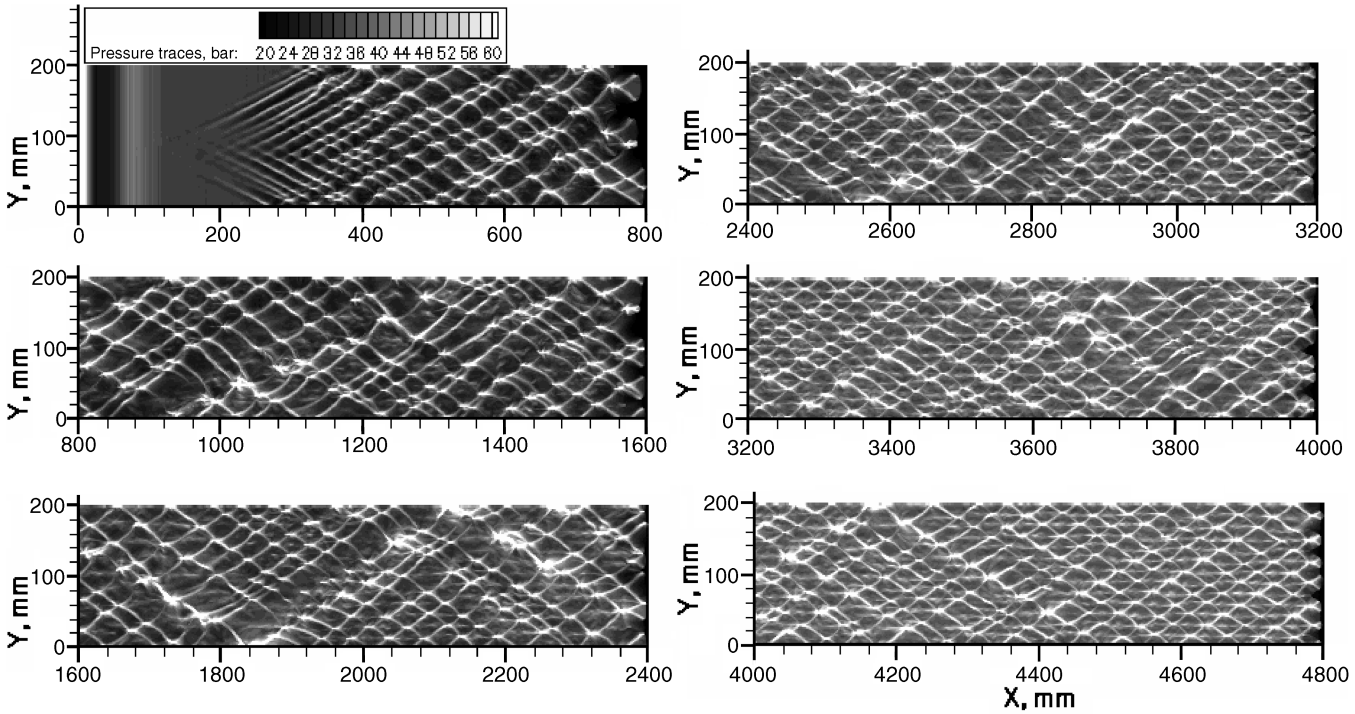

Fig. 44 Numerical simulation of the cellular detonation structure in a hybrid hydrogen–air–aluminum particle mixture (from Khasainov et al. [66]).

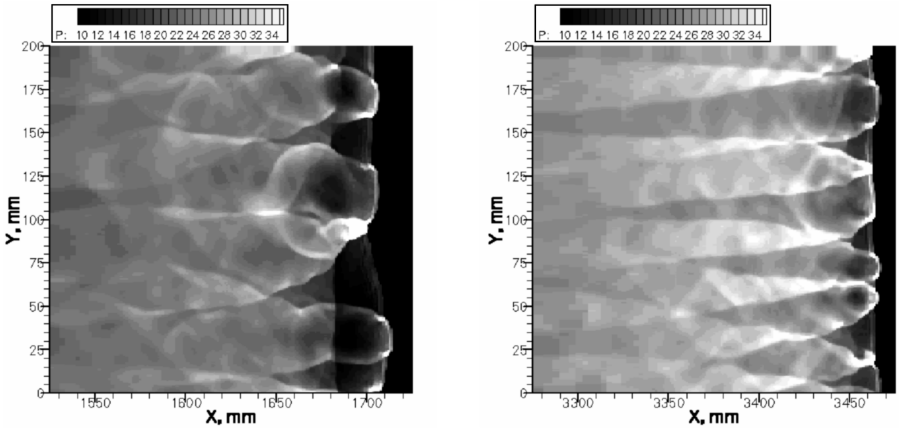

Fig. 45 Distribution of pressure at $t = 1$ ms (left) and $t = 2$ ms (right) computed behind the leading front of a hybrid detonation in a hydrogen–air–aluminum particle mixture (from Khasainov et al. [66]).

after some delay behind the leading front: this denotes the secondary compression of products generated by the burning of aluminum particles. Now, it would be of great interest to go further in these simulations to reproduce accurately the dependence of cell size on the particle properties, as was displayed in experiments. Then, numerical simulations should be also useful to investigate the problem of the possible existence of two networks of cells with different characteristic sizes: the smaller ones corresponding to the gaseous reactions, the larger ones originating from the reactions between particles and gases. Fundamental questions remain open: can we predict the size of larger cells or that of heterogeneous detonation? The answer is of first importance to determine the adequate dimensions of the experimental setups to design to perform experiments able to provide relevant results on the detonability and detonation structure of solid particle two-phase mixtures.

VI. Conclusions

This rapid survey of past and present works on gas–particle detonations indicates that detonation propagation in this kind of mixtures is far from being well understood. Further experimental and theoretical, as well as numerical works are needed to get a better knowledge of the detonation characteristics, structure of the wave, conditions of existence, multiplicity of regimes, detonability, etc. Particular attention should be devoted to the study of the cellular detonation structure: existence, cell width, dependence on the size, shape and concentration of particles. This is of utmost importance for detonability characterization and safety applications.

From the point of view of utilization of heterogeneous detonations in aerospace combustion chambers, and particularly in pulsed detonation engines, it appears that this perspective is problematic, because of the large dimensions required to initiate the detonation and obtain self-sustained, steady propagation. Such dimensions in length as well as in cross section are incompatible with the dimensions of a practical engine.

Hybrid detonation is an interesting possibility because self-sustained detonation is easier to obtain due to the presence of part of the combustible in gaseous phase. Reactive solid particles provide an additional heat release, which results in a compression of products behind the leading front, thus contributing to an increase of the pressure impulse. Certain particles such as aluminum present

interesting characteristics because they are able to burn not only in oxygen, but also in water vapor or in carbon dioxide, even in nitrogen. The possibility to improve detonation performances with hybrid mixtures has already been investigated in view of applications to propulsion (see, for example, Veyssiere et al. [67], Kobiera et al. [68]). Another option is to use the decomposition products of a solid propellant as the detonable fuel. A solid propellant presents the advantage of being easily loaded and transported safely. Its controlled combustion provides gaseous products containing several reactive species which can be used as a combustible and, mixed with an oxidizer (e.g., air, in the case of an airbreathing engine), can form the detonable mixture to run a pulsed detonation engine. But, such propellants often produce a lot of solid carbon particles. If one is capable of burning them in the detonation products by the addition of the adequate quantity of oxidizer, it is possible to reinforce the pressure impulse this way. Numerical investigation of this problem has been undertaken recently by Walton et al. [69]. They have studied hybrid detonations in hydrogen–air–carbon particle mixtures and displayed that under proper choice of size and concentration of carbon particles, an increase of detonation performances can be expected.

However, the potential performances of hybrid detonations may be reduced by the limited length of the combustion chamber of a practical pulse detonation engine. Because of the delay required for particle ignition, it may follow that they are incompletely burnt inside the engine. Achievement of reactions occurs out of the combustion chamber and the energy released during this terminal stage does not contribute to augmentation of the pressure impulse. Therefore, it is necessary to search for the most favorable initial conditions to get rapid buildup of a steady self-sustained detonation in the hybrid mixture, that is, the more adequate set of particle size and concentration. This sends us back to the necessity of conducting fundamental studies on propagation mechanisms of hybrid detonations.

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