Investigation of Detonation Propagation Regimes in Liquid Sprays

B. Veyssiere, B.A. Khasainov, M. Mar, M.A. Benmahammed Institut Pprime, UPR 3346 CNRS, Poitiers- Futuroscope, France.

1 Introduction

If the possibility of observing propagation of detonation regimes in liquid sprays is well known since a long time, according to the reference works by Dabora and Ragland [1], existing knowledge on the propagation mechanisms and structure of such detonations is far to be as much advanced as that of gaseous mixtures. Until now, it is generally claimed that in standard conditions of pressure and temperature in air, it is not possible to initiate a detonation unless the mixture has been heated beforehand to permit prevaporization of the fuel or if the dilution of the gaseous phase has been decreased down to pure oxygen. Moreover, the existence and characteristics of a detonation cellular structure, similar to that exhibited in gaseous mixtures is not firmly established. The experimental evidence of this cellular structure in heterogeneous liquid sprays is limited to the only results of Papavassiliou et al. in decane-oxygen mixtures [2] and of Alekseev et al. in gasoline-air sprays [3]. As liquid propellants are foreseen as possible fuels in prospective future aeronautical or spatial engines, such as the pulsed detonation process in liquid sprays is needed. Therefore, the objective of the present work is to acquire new experimental results on the detonability of reactive liquid sprays and to study the propagation regimes of a detonation in these media, in order to improve the

understanding of these regimes and to build a numerical model of two-phase spray detonations. Hence, it is necessary to develop an experimental setup and methodology, particularly in order to investigate the cellular detonation structure in liquid sprays.

2 Experimental setup

The experimental set up (see Fig.1) consists of a vertical detonation tube of 4.3 m length and square cross section (53 mm x 53 mm), closed at its two ends by rotating valves. The spray is generated at the bottom end by an ultrasonic atomizer which delivers a quasi-monodispersed spray with a quasi zero initial velocity. At the atomizer exit, the spray is lifted off in a mixing chamber by the sustaining gaseous flow. Then, the resulting two-phase mixture is conveyed, at atmospheric pressure, in laminar regime, along the detonation tube toward the top end. The transit of the spray is detected by an opacimeter, the output signal of which is modulated by the light attenuation through the two-phase flow. The composition of the mixture is varied by monitoring the liquid and gas flowmeters. When the tube is filled with the two-phase mixture, both the liquid and the gaseous flows are stopped and, simultaneously, the detonation tube is closed by actuating the two rotating valves at the bottom and top ends. Initiation is triggered at once, within a delay less than one second, so that the displacement of the spray inside the tube, due to gravity forces, can be considered as negligible. Initiation is achieved by means of an auxiliary shock tube (the "booster", 1.6 m long, 69 mm diameter) connected to the main tube just above the bottom rotating valve (see Fig.1) and separated from it by a thin mylar

membrane. It is filled by a stoichiometric ethylene-oxygen mixture at 2 bar initial pressure; this driver mixture is ignited by a pyrotechnic ignitor. As a result, the detonation of the gaseous mixture in the auxiliary shock tube bursts the membrane and launches a shock wave in the main detonation tube.



Figure 1. Experimental setup

The progression of this shock is followed along the tube by seven piezo-electric pressure gauges K1-K7 (Kistler 603B). The spacings between them are indicated on Fig.1. In the top part of the tube, at 2.82 m from the initiation zone (between pressure gauges K5 and K7, see Fig.1), a steel plate covered

Veyssiere et al.

with soot is disposed to record the detonation cellular structure by the method of soot tracks over a distance of 0.40 m.

3 Experimental results

Experiments have been performed with sprays of several liquid fuels of high or weak volatility, suspended in different O_2/N_2 oxidizing gaseous mixtures, under atmospheric initial conditions (p = 1 bar, T = 293K). Sprays having different mean granulometry (d = 8µm, 30µm and 45µm) have been tested.

In mixtures of iso-octane $30\mu m$ and $45\mu m$ sprays suspended in air, we observed that, under the above mentioned conditions, a detonation was formed with a quasi steady propagation velocity (± 10 m/s) beyond the pressure gauge K2. Variation of the mean detonation velocity as function of the equivalent ratio of the mixture is displayed in Fig.2.



Figure 2. Variation of the mean detonation velocity of iso-octane/air 30 μ m sprays as function of the equivalent ratio.

It follows from Fig.2 that, in the lean and near-stoichiometric part of the experimental curve, there exists a velocity deficit of the detonation front, as compared with the theoretical CJ values, varying between 5 and 10%. On the opposite, in the rich side, the experimental values of the detonation velocity are very close to the CJ ones, and even slightly larger for equivalent ratios larger than 2. We believe that the velocity deficit is due to the two-phase character of the mixture and to losses toward the tube walls, on account of the limited cross section size of the tube. The experimental results obtained in the rich part of the curve are consistent with observations made in other conditions in two-phase mixtures which lead to conjecture that the rich detonability limit would not exist in two-phase mixtures.

Soot tracks records in iso-octane/air $30\mu m$ sprays reveal the existence of several detonation propagation regimes. An example of soot tracks recorded for a lean (equivalent ratio r = 0.8) mixture is shown in Fig.3 (here and below the detonation propagates from left to right). One observes large inclined lines printed on the plates. With no ambiguity, one can interpret them as the tracks of a spinning detonation in the square tube (with a pitch of nearly 200 mm, which is about four times the tube width of 53 mm, and an inclination angle of about 45°). This conclusion is supported by pressure records.



Figure 3. Soot tracks of a r = 0.8, $30\mu m$ iso-octane/air mixture detonation

In near stoichiometric mixtures ($1 \le r < 1.1$), the soot tracks show a detonation cellular structure with a half-cell (see figure 4; the full cell width would be about 106 mm).



Figure 4. Soot tracks of a r = 1, $30\mu m$ iso-octane/air mixture detonation

For rich mixtures (r >1.1), a multi-headed detonation wave propagates. The cell size diminishes when r increases and reaches a minimum value around r = 1.4 (see figure 5) before increasing again.



Figure 5. Soot tracks of a r = 1.4, $30\mu m$ iso-octane/air mixture detonation

The different propagation regimes as function of the equivalent ratio are displayed in figure 6: zone A corresponds to the non-detonable domain, B to spinning regime, C to half-cell regime and D to multi-headed detonation.



Figure 6. Detonation propagation regimes as function of equivalent ratio r, in 30µm iso-octane/air mixtures. (blue points: measured cell size; red arrows: measured pitch of spinning detonations)

When decreasing the proportion of nitrogen as compared with that in air, the reactivity of the twophase mixture increases. Fig.7 shows the soot tracks of the detonation of a stoichiometric iso-octane/ O2 + 2N2 mixture. One observes 2 - 3 cells in the tube width, that is $\lambda \approx 18 - 26$ mm.



Figure 7. Soot tracks of a stoichiometric $30\mu m$ iso-octane/O2 + 2N2 mixture detonation. Similar results have been obtained with n-octane and heptane.

Veyssiere et al.

With low volatility fuels (decane and dodecane), attempts to initiate the detonation in $30\mu m$ and $45\mu m$ sprays in air were unsuccessful. On the contrary, when the droplet size is diminished to $8\mu m$, the detonation can be initiated as attested by the values of shock front velocity and the cellular structure registered on the soot tracks. Examples are shown on Figure 8 and 9 for decane and dodecane respectively. An irregular cellular structure is observed for decane-air, whereas a spinning detonation propagates in the dodecane-air mixture.



Figure 8. Soot tracks of a stoichiometric 8µm decane/air mixture detonation



Figure 9. Soot tracks of a stoichiometric 8µm dodecane/air mixture detonation

4 Numerical simulations

A numerical model was built, which is based on the model developed by Briand et al.[4] for studying the detonation initiation and propagation in two-phase liquid sprays. In addition, the mechanical disintegration of liquid droplets by interaction with the leading shock wave has been incorporated in the model.



Figure 10. Numerical simulation of detonation formation in a stoichiometric 30µm iso-octane/air mixture

An example of numerical simulation of detonation initiation and propagation in a stoichiometric 30μ m iso-octane/air mixture is shown in Figure 10. It can be seen that triple points appear after about 1m of propagation as the result of the instabilities of the leading front. Then a cellular structure is formed with a width of about 36mm, which corresponds to a strong detonation regime. When the detonation progresses along the tube, it relaxes toward the self-sustained detonation regime. At the same time, the cell size increases and results in a structure with a half-cell contained within the tube section, which is in agreement with the experimental observations.

5 Conclusions

An experimental setup has been designed which permits to study the initiation and propagation of a detonation in liquid fuel sprays in controlled (granulometry and concentration of the spray) and reproducible conditions.

It was shown that it is possible to initiate a detonation in liquid fuel in air under standard initial conditions of temperature and pressure without preheating the mixture. One can detonate weakly volatile fuel sprays under the condition that the droplet size is sufficiently small.

A numerical model including the mechanical disintegration of droplets by interaction with the leading shock front has been built. Numerical simulations performed with this model are in good agreement with the experimental results.

6 References

- [1] E.K. Dabora and K.W. Ragland (1996) A study of heterogeneous detonations. Astronautica Acta, (Vol. 12, No. 1, pp. 9-16).
- [2] J. Papavassiliou, A. Makris, Knystautas R., J.H.S. Lee, C.K. Westbrook, and W.J. Pitz. (1993) Measurements of cellular structure in spray detonation. Dynamic Aspects of Explosion Phenomena, (Edited by A.L. Khul, J.C. Leyer, A.A. Borisov and W.A. Sirignano, Progress in Astronautics and Aeronautics, Vol. 154, AIAA, Washington, DC, pp. 148-169).
- [3] V.I. Alekseev, S.B. Dorofeev, and V.P. Sidorov (1996) Direct initiation of detonations in unconfined gasoline sprays. Shock Waves, (Vol. 6, No. 2, pp. 67-71).
- [4] A. Briand, B. Veyssiere, B. A. Khasainov (2010), Modelling Of Detonation Cellular Structure In Aluminium Suspensions, Shock Waves (Vol. 20, pp.521–529).