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On the possibility of non-dimensionalizing DDT limits and distances

V. Rodriguez, V. Monnier, P. Vidal, R. Zitoun
Institut Pprime, UPR 3346 CNRS, ENSMA, BP 40109,
86961 Futuroscope-Chasseneuil, France

1 Introduction

Understanding the onsets of fast flame and deflagration, and their transition to detonation in tubes is one of the oldest motivation for studying quasi-sonic and supersonic combustion waves. The main phenomena that participate in the deflagration and detonation processes, and the transitions from the former to the latter, are qualitatively well understood today. However, each remains a numerical challenge, and predicting how they combine in complex reactive flows is currently out of reach. The prevailing approach today is to address and model the DDT processes jointly with simplified macroscopic analyses to bring out salient relevant parameters. Ciccarelli and Dorofeev [1] presented a review of DDT processes that includes the many pioneering works by Shchelkin.

Most laboratory DDT processes are triggered using low-energy ignition techniques such as an automotive spark plug. In smooth tubes with large enough transverse dimensions, the dynamics of the initial flame is then subjected to strong effects of curvature and acceleration, a shock forms ahead of the flame front, an overdriven detonation suddenly forms between the flame and the shock, propagates in the transverse and backward direction with respect to the frontward-propagating leading shock, and this complex eventually relaxes to the CJ detonation regime [2-3]. The overdriven detonation usually forms at the tube wall, and preferentially at the inner edges in square or rectangular tubes which indicate that dissipation effects in boundary layers strongly influence the flame acceleration. A consequence is that, in narrow enough tubes and low enough energy of ignition, the transition process can include a quasi-steady, slowly-accelerating, quasi-planar combustion wave with velocity about one-half that of the CJ detonation - the so-called ``strange wave" - before sudden one-dimensional transition to the CJ detonation regime without precursor shock [4-6].

The DDT phenomenon is thus a set of individually complex processes, and the objective of our work is to conduct and analyse experiments for measuring the transition limits and distances, and for possibly non-dimensionalizing them using a proper selection of parameters. Our aim is to investigate whether the transition limits and distances (R) can be anticipated based on macroscopic information rather than the detailed numerical description of the dynamics of the re-ignition processes.

Correspondence to: vincent.rodriguez@ensma.fr

2 Experimental set-up and methodology

Our investigation is restricted to the DDT process generated by jets of hot gases uniformly distributed over most of the cross section of a smooth-wall square tube. This surface ignition ensures a simpler hydrodynamic field ahead of the subsonic flame front and, therefore, a better reproducibility of the transition limits and lengths. The hot jets were obtained from the impact of a CJ detonation on a multi-perforated plate.

The detonation tube consists of two main elements, namely the driver section and the re-ignition section, separated by the multi-perforated plate (Fig.1). The methodology was to generate detonation at one end of the driver section, to quench it through the plate, and to study the conditions for re-ignition depending on the properties of the plate, the compositions of the mixture and the initial pressure p_0. The driver and re-ignition sections are 2.25 and 1-m long, respectively, with the same 40×40-mm^2 square cross section. Soot foils positioned on the bottom walls of the driver and re-ignition sections were used to record the structure of the detonation cells upstream and downstream the plate. The detonation in the driver section resulted from the deflagration generated by the spark of an automotive plug, and the transition to detonation was enhanced using a 1-m long Shchelkin spiral positioned immediately ahead of the plug.

Three Kistler 603B pressure transducers (Fig.1, P1, P2, P3) with 1-μs response time, 300-kHz natural frequency, each coupled with a Kistler 5018 A electrostatic charge amplifier with 200 kHz band width, were used to check that the CJ detonation regime was achieved before the plate. The transducer P3 is located 125 mm before the plate, and the distance between each transducer is 250 mm.

The set-up was vacuumed before injecting the premixed composition prepared in a separate tank using the partial pressure method. We investigated the stoichiometric compositions of hydrogen, methane and oxygen $(1-x)H_2 + xCH_4 + 1/2\,(1+3x)O_2 \rightarrow xCO_2 + (1+x)H_2O$. We varied the composition parameter x from 0 to 1, namely $x = 0, 0.25, 0.5, 0.75$ and 1, to generate detonation cells ranging from regular to irregular, as defined by the soot recordings at the tube walls. We varied the initial pressure p_0 from 12 to 35 kPa, and the initial temperature was about 294 K.

We chose plates with hole diameters d smaller than the cell widths, so the detonation quenched through the plate [7]. Therefore, the possible re-ignitions behind the plates resulted from jets of burnt gases. In a first series of experiments, we kept constant the properties of the perforated plates, namely their thickness e, and the hole number and diameter N and d, and we studied the effects of varying p_0 and the composition parameter x. In a second series of experiments, we selected the more regular mixture, namely $x = 0$, and we studied the effects of varying the properties of the perforated plate e, N and d. All cell widths λ_{CJ} were measured on the plate upstream the obstacles.

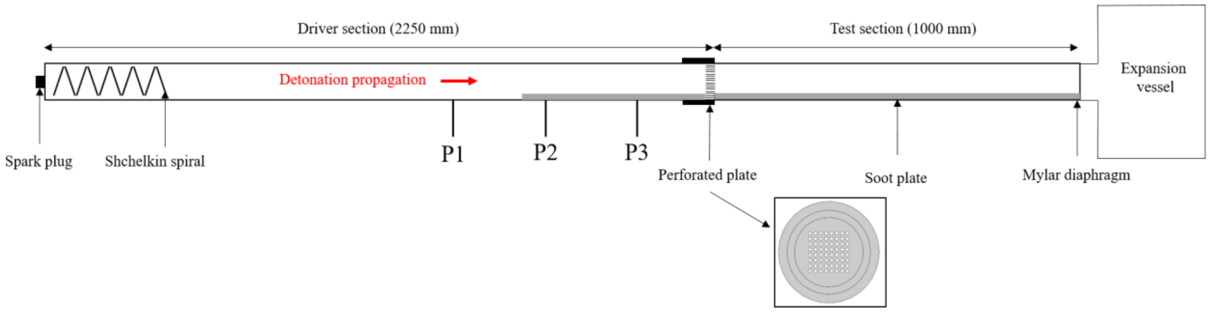

Figure 1: Schematic of the experimental set-up.

Figure 2 shows a typical soot recording of the DDT final stage, with detonation re-ignition at the bottom wall, at the distance R from the perforated plate. This detonation is first overdriven, as the very small cells indicate, and relaxes to a self-sustained regime, with larger, constant-width cells propagating parallel to the tube axis.

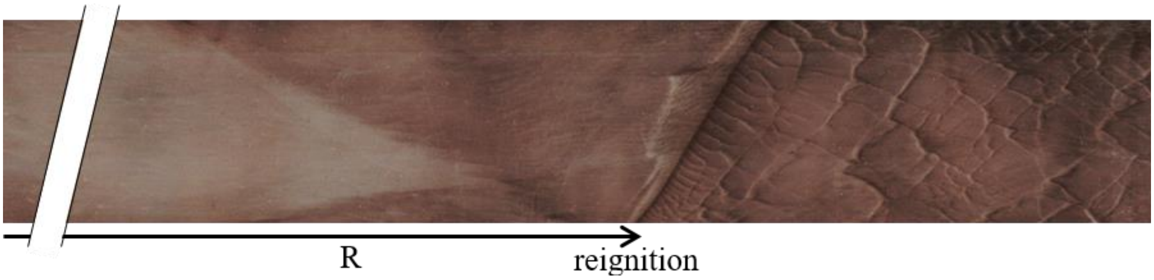

Figure 2: Soot recording showing the re-ignition of detonation downstream the perforated plate (R denotes the DDT distance) for the mixture $CH_4 + 2O_2$ (x =1), at the initial pressure p_0 =17.5 kPa.

3 Analysis

The premise is that the re-ignition process results essentially from the interplay of two competing phenomena, namely surface dissipation at the walls and chemically-enhanced hot spots from shock amplification. The analysis involves two dimensionless ratios that use the CJ cell mean width λ_{CJ} as the reference length for the effect of heat production by evolution of chemical composition. The first, Nd^2/λ_{CJ}^2 represents the relative effects of surface re-ignition resulting from the interaction of the jets coming out of the holes, and the second, Ned/λ_{CJ}^2, represents the relative effects of the surface dissipation phenomena. The dissipation effects at the tube walls are not involved in the analysis because they are too small compared to those at the walls of the plate holes, per unit length.

Figure 3 shows the domains of re-ignition and non-re-ignition in the $\lambda_{CJ} - x$ plane, depending on the initial pressure p_0. The cell width λ_{CJ} appears to be a linear increasing function of x at fixed p_0, and to increase with decreasing p_0 at fixed x. The values of λ_{CJ} that separate the re-ignition and non-re-ignition domains form a convex increasing function of x (Fig. 3, full line). The limiting pressures - defined by its intersects with the constant-p_0 lines - decrease with increasing x, that is, with increasing λ_{CJ}. Therefore, the less regular the cells (the larger x), the smaller the limiting pressure.

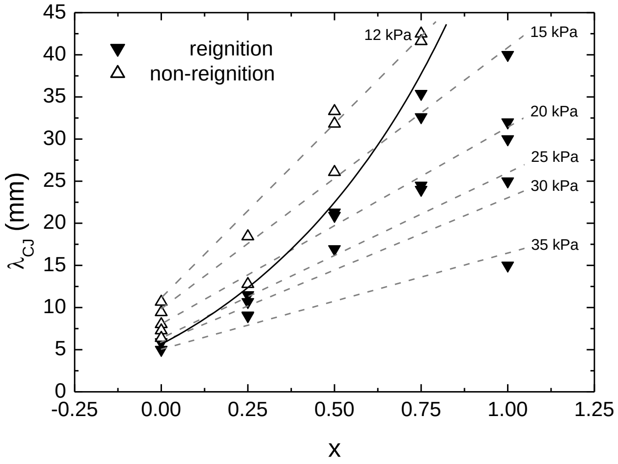

Figure 3: Re-ignition and non-re-ignition domains for the mixtures $(1-x)H_2 + xCH_4 + 1/2\,(1+3x)O_2 \rightarrow xCO_2 + (1+x)H_2O$ in the plane $x - \lambda_{CJ}$ depending on the initial pressure p_0 for the plate with $e = 7\ mm$, $N = 64$ and $d = 3\ mm$.

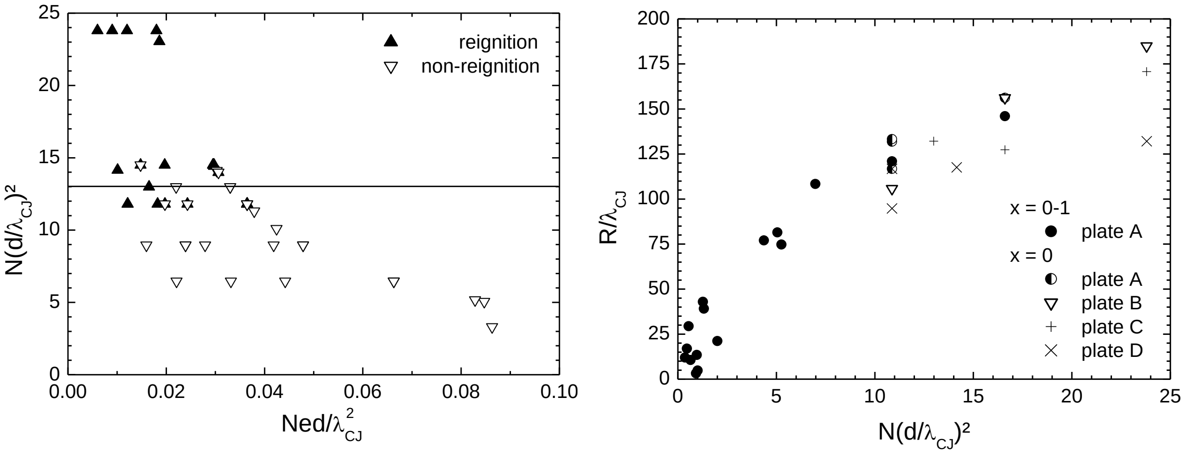

Figure 4: Left: Re-ignition and non-re-ignition domains for the mixture $H_2 + 1/2\,O_2$ (x =0) in the non-dimensional plane "Surface dissipation – surface re-ignition". Right: Non-dimensional re-ignition distance as a function of the non-dimensional surface re-ignition number for the mixture $(1-x)H_2 + xCH_4 + 1/2\,(1+3x)O_2 \rightarrow xCO_2 + (1+x)H_2O$.

Figure 4-left shows the domains of re-ignition and non-re-ignition in the plane Nd^2/λ_{CJ}^2-Ned/λ_{CJ}^2. The data were obtained with the same composition $x = 0$, that is, the mixture $H_2 + 1/2\,O_2$, by varying the parameters N, d, e of the plate and the initial pressure p_0. Each point in the graph corresponds to the change of only one parameter. The results indicate that a unique value of Nd^2/λ_{CJ}^2 separates the re-ignition and non-re-ignition domains (full line). Therefore, to within a reasonable accuracy, the limiting value of the non-dimensional number Nd^2/λ_{CJ}^2 for the surface re-ignition effects appears to be independent of the non-dimensional number Ned/λ_{CJ}^2 for the surface dissipation effects in the obstacle. Coherently, Figure 4-right shows a very good correlation of the non-dimensional re-ignition distance R/λ_{CJ} with the non-dimensional number Nd^2/λ_{CJ}^2 for the re-ignition surface effects for all values x ranging from 0 to 1 and for all plates.

4 Discussion and conclusion

This work reports on experiments about the deflagration-to-detonation transition in a square-cross section channel. Ignition was achieved using jets of hot gases generated by quenching CJ detonation through a perforated plate. Our goal was to investigate the possibility of non-dimensionalizing the DDT limits and distances using simple observable characteristics parameters. Those involved in our analysis are the CJ cell width, the thickness of the plates, the number and diameter of the holes in the plates, and the composition parameter. Our analysis thus indicates that the non-dimensional DDT limits, that is, the conditions that separate re-ignition and non-re-ignition, are independent of the relative effect of the surface dissipation phenomena in the holes, and that the non-dimensional DDT distances well correlate with the non-dimensional number Nd^2/λ_{CJ}^2 representing the relative effects of surface re-ignition resulting from the interaction of the jets coming out of the holes.

In general, DDT dynamics depends on the ignition mode, the set-up geometry and dimensions, and the mixture composition, so only high-resolution numerical simulations based on Navier-Stokes reactive equations will be capable of predicting this complex phenomenon when the necessary computations capacities are available. Thus, to date, given an industrial system, the DDT risk must be assessed based on full-size experiments.

In this respect, our analysis demonstrates that the proper choice of non-dimensional numbers determined by the system can help at anticipating the corresponding DDT limits and distances. Additionally, our non-dimensionalization appears to be independent of the regularity of the detonation cell, as defined by soot recordings at walls. This indicates that this regularity criterion may not always be relevant for interpreting dynamical behaviours of deflagration and detonation [8].

Acknowledgements

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