Optimisation of the Deflagration to Detonation Transition: Reduction of Length and Time of Transition.

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Key words: DDT, DDT length and time, detonation cell size, shock-flame system, hot jet, PDE

Introduction

The aim of this experimental investigation is the study of Deflagration to Detonation Transition (DDT) in tubes to reduce both length (or "run up distance") and time of transition (L_{DDT} and t_{DDT}) in view of Pulsed Detonation Engine (PDE) application. The detonation of a reactive mixture can be initiated via two means: i) by using a high energy initiation (explode wire, laser spark, HE) i.e. producing a strong shock in the mixture which turns out directly to detonation by SDT mechanism (Shock to Detonation Transition) or ii) by using a weak ignition source by the DDT mechanism. Considering the second case a laminar flame initiated in a tube naturally accelerates and transits in detonation if the tube is long enough and if the minimal condition of existence of the detonation is fulfilled (minimum criteria: $\lambda_{CJ} \le d$ (d is the i.d. delimited by the spiral cf. Figure 1) [1], or $L \ge 7\lambda_{CJ}$ [2]) i.e. if the detonability of the mixture (characterized by the cell length λ_{CJ}) is sufficiently high. The literature gives results of L_{DDT} that can reach several meters. The phenomenology of the DDT is qualitatively understood. It relies on two feedback mechanisms acting on the flame in the phase of the acceleration led by the hydrodynamic. At the beginning the flame accelerated by instabilities behaves as a hydrodynamic piston. The expansion of the combustion products induces turbulence and compression waves in the medium upstream. The turbulence makes the flame corrugated and the compression waves increases the temperature so that the flame is accelerated. When the piston accelerates both the turbulence rate and the compression level increase, so as the flame velocity and so on… Then the compression waves turns into shock wave and a shock-flame system appears. The shock-flame continues to propagate in the tube until the chemical induction length of the mixture becomes smaller than the distance between the shock and the flame that enables the autoinflamation of the mixture. An "explosion in the explosion" [3] is then produced locally which generates a detonation wave that tends towards the Chapman-Jouguet (CJ) detonation. In the DDT, the penalizing mechanism is the production of turbulence by long run flame propagation, then to shorten the DDT the rapid increase of turbulence and gradients in the mixture is necessary. The use inside the tube of obstacles as "Shchelkin spiral" or periodic plates with adapted Blockage Ratio (BR) will reduce substantially L_{DDT} and t_{DDT}. Another mean to drastically accelerate the flame is to force the early ignited flame to pass through a plate with an orifice of high BR, in order to create a flame jet that introduces locally high gradients of pressure, flow velocity, and concentration of species (free radicals) within a short distance. The BR induces a flow that stretches the flame (and accelerates it) and that creates vortex structures, which enhance the turbulence level and mixing between combustion products and unreacted mixture. From these different mechanisms the combustion rate strongly increases and is able to induce a shock-flame system propagating at high velocity, thus reducing the first stage of flame acceleration.

The experimental investigations about the reduction of L_{DDT}, which represents an experimental measure of the sensibility of a detonable mixture, and the attempt of scaling the results with the 3D structure of the detonation (λ_{CJ}) are reported here. In order to respect the geometric configuration of PDE, the tube used in the experiments has a diameter of few centimeters imposed. An experimental set up is designed to induce high turbulent initial flow in order to quickly obtain the chocking regime of flame propagation. It consists, at the beginning of the tube, in a double chamber ended with perforated plate. It enables the creation of a shock-flame system on a short distance. A spiral was installed in the tube to sustain the flame acceleration. To respect the condition of existence of a detonation in the tube, the stoechiometric at standard conditions H_2/air mixture was chosen since its λ_{CJ} obeys $\lambda < d$ and $L > 7\lambda$. The study is extended to other stoechiometric chemical mixture of CH_4, C_3H_8, C_2H_4, and C_2H_2 diluted with N_2 in order to obtain the same λ_{CJ}. The optimized L_{DDT} obtained is then compared to λ_{CJ} and this correlation is checked out on the different mixtures.

Experimental details

The scheme of the tube used in our experiments is shown in Figure 1. It consists in a cylindrical stainless steel tube of 2,6 m long and 26 mm i.d. in which L_{DDT} can be measured via the smoke foil technique over a 600 mm length. t_{DDT} was determine by measuring, on a Tektronix TDS420A oscilloscope, the time between the ignition, assured by an automotive spark plug, and the instant the detonation arrives at the end of the tube, determined by a Kistler 603B pressure transducer, assuming constant the speed of the detonation since its creation. Two additional pressure transducers were installed at L = 45 and 120 mm to help the comprehension of the flame acceleration phenomenon. A "Shchelkin spiral" with a BR = 1- $(d/D)^2$ of 0,52 and a length between 11 to 33 cm was inserted in the tube. The flame jet was obtained with a double 30 mm long chamber with a diameter of 25 mm positioned ahead of the tube. Each of the chamber was ended with a plate perforated with one to five holes of different size (0,54<BR<0,98) and geometry (the same BR can be represented by different geometries). The mixtures used for our study are H_2+0,5O_2+1,881N_2, C_3H_8+5O_2+8,75N_2, C_2H_4+3O_2+7,5N_2, CH_4+2O_2+1,5N_2, and C_2H_2+2,5O_2+11,08N_2, so that the cell size $\lambda_{CJ} \sim 10$ mm (at $P_0 = 1$ bar and $T_0 = 293$ K). These mixtures respect the limiting criteria for establishing detonation regime in the tube (i.e. d=1,8λ and L=8,5λ). The cell sizes were reported from bibliography ([6], [7]) and checked in a detonation tube. As an increasing dilution with N_2 induces cell irregularity, the values of λ_{CJ} are determined with an accuracy of 20%.

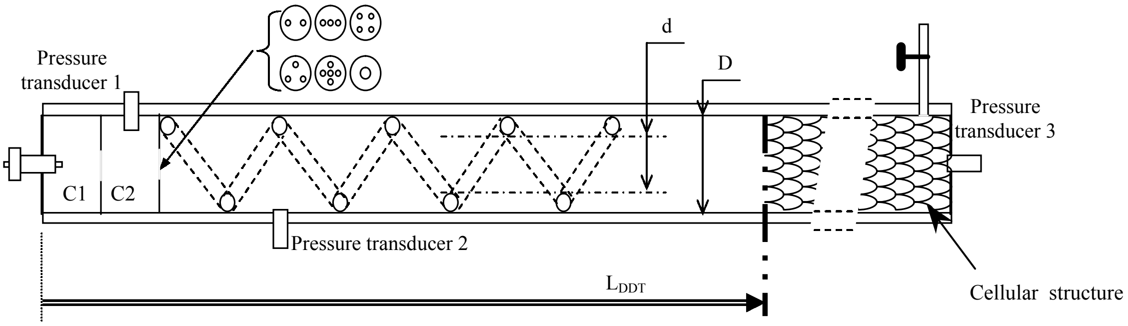


Figure 1: schematic of the transition device

Results and Discussion

Many of possible BR configurations of the two chambers were tested in H_2-air mixture in order to obtain the most effective configuration (of respective BR 0,87 and 0,85) for reducing L_{DDT}. A typical example of H_2-air shock and flame propagation is given in Figure 2.

At t = 0s an electric spark is generated and a flame is initiated in the first chamber (C1). For 0 < t < 1,2 ms a laminar flame burns the mixture in C1, that induces a slow increase of the pressure and a flow vented to the second chamber (C2). This flow carries and stretches the flame that is then strongly accelerated, sufficiently to make the pressure to increase rapidly in C2 (signal P_1) and in C1. The rapid increase of pressure in C2 tends to force high speed flame jet through the second orifice that leads to create an abrupt front of compression in the tube (called P_T) seen on the second transducer (signal P_2) that will turn into a shock wave. The velocity of the front (D_T) tends quickly to the value of the isobaric speed of sound of the burned gas, and the "Shchelkin spiral" helps the shock-flame system to attempt this speed and to sustain it. The constancy of the velocity is shown by the pressure "plateau" on P_2 after the steep ΔP (cf. Figure 3) (the periodic fluctuation of pressure observed is due to the interaction between the shock wave and the spiral). Until the flame leaves the spiral section, the strength of the shock is then sustained but the spiral avoids the onset of a CJ detonation because of the losses induced by the passage through the obstacles. However the reflection of shock on the wall may lead to the re-initiation of the mixture and a quasi detonation may exist and propagates in the spiral section [5]. The transition to detonation was observed outside of the spiral section at a distance of 0,4 m from the ignition, the shock issued from the retonation wave can be detected on P_2 (peak after the pressure "plateau") the detonation imposes a core pressure around one third of P_{CJ}, observed on the graph. The detonation reflects at the end of the tube at about t = 1,82 ms. We observed that when the pressure induced in the tube (P_T) is not high enough or when the spiral is not sufficiently long, the transition fails and, in that case, the pressure measured by the second transducer and the flame speed strongly declines when the flame quits the spiral section and the detonation transition may happen when the shock reflects on the end wall. On the flame trajectory diagram, the flame and shock propagation of the different mixtures used during the experimentation showed a similar evolution for the same geometrical configuration of the two chambers.

The Table summarises the results obtained during the experimental investigation and the data calculated. It gives the length and time of transition (L_{DDT}, t_{DDT}), the isochoric combustion pressure (P_V), the pressure measured on

P_2 of the compression front (P_T), the isobaric speed of sound of the mixtures (a_b), the average velocity (between the 2nd transducer and the detonation) of the compression front (D_T), the cell size of the mixtures (λ_{CJ}), the optimum length of the spiral (L_S) and the ratio of certain of these values. It can be notice that every results for DDT in Table were checked in a 2,6 m long tube in order to avoid the problem of sound wave reflection on the end wall that may interact with the flame and trigger the detonation if the tube is too small. From the analyze of the following results several points can be highlighted:

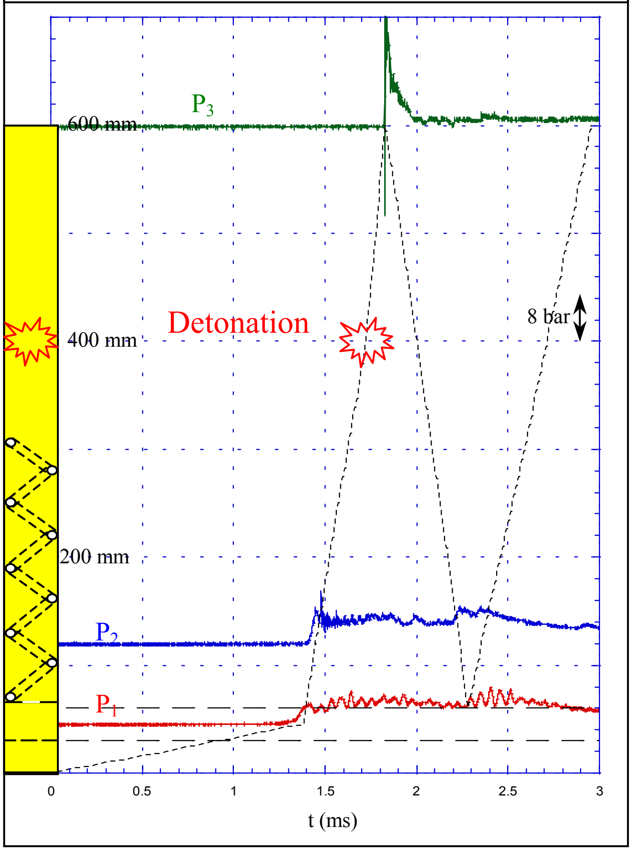
1) The ratio L_{DDT}/λ_{CJ} is quite constant and is ranging from 30 to 40, for the mixtures with $\lambda_{CJ} \sim 10$ mm. L_{DDT} for stoechiometric H_2-air mixture is found around 0,4 m whereas the literature gives results of 1 m in 5 cm i.d. tube with spiral of BR=0,44 [4].

2) The effect of losses in the chambers can be seen: $\Delta P_T/\Delta P_V$ depends on the burning rate of the mixture. If the burning rate is high, the thermic losses are reduced and the maximum pressure obtained increases. Then $\Delta P_T/\Delta P_V$ increases when the losses decrease, so as the compression front pressure P_T. The higher is P_T, the shorter L_{DDT} (cf. Table). Thus the product of $\Delta P_T/\Delta P_V$ and L_{DDT}/λ_{CJ} is a quasi constant value around 21. The L_{DDT} in this system depends on the dynamic of combustion since it seems to depend on the pressure history $P_2(t)$ induced by the chambers. This loss of energy that penalizes L_{DDT} is the drawback of the use of chambers to shorten DDT.

3) The Figure 3 shows the aspect of the compression front of the five different mixtures: the signals for CH_4, H_2, and C_2H_2 were obtained with a 2600 mm long tube, but the signal for C_3H_8 and C_2H_4 were obtained with a 600 mm long tube, which explains the second brutal step of pressure around 0,7 ms after P_T (shock wave issued from reflection of the detonation at the end wall). The principal point to observe is the influence of the laminar flame velocity of the mixture. The fastest is CH_4, the pressure signal shows a brutal increase of pressure followed by an oscillating "plateau" (oscillations due to the shock-spiral interaction), the transition happening at the end of the spiral, and then a core pressure around one third of P_{CJ}. The slowest is the C_2H_2 and it shows a totally different evolution: the elevation of pressure is continuous and extremely slow with regard to the others mixtures. In that case the losses in the chamber are more important (showed by the lower $\Delta P_T/\Delta P_V$) and the role of the spiral is different. The spiral does not only sustain the strength of the shock (and then sustain the velocity) but it enables the acceleration of the flame and the reinforcement of the shock (therefore the increase of pressure observed) so that the transition can happened at the end of the spiral. For the H_2, C_3H_8, C_2H_4 mixtures one can notice that the pressure slightly increases during the pressure "plateau" that indicates the effect of small reinforcement of the spiral. Thus the difference of velocity in the chambers induces a different behaviour of the mixtures in the spiral section.

4) The role of the chambers appears clearly: the flame jet produced enables to create a high pressure jump in the tube (P_T), corresponding to a coupling shock-flame propagating at D_T which is quite of the order of the isobaric speed of sound of the mixture (a_b) (the estimate overspeed for the C_2H_2 mixture comes from the difficulty of determining the passage of the compression wave on the pressure record cf. Figure 3). This value of a_b for the flame was already observed and pointed out by Lee et al. [4] and Theodorczyk et al. [5] before the obtaining of quasi detonation in tube with spiral. This flame velocity leads to

Figure 2: Flame trajectory and pressure evolution for H_2/air mixture at P_0=1 bar, T_0=293 K, L_{DDT}=40 cm and t_{DDT}=1,72 ms in a 600 mm long tube



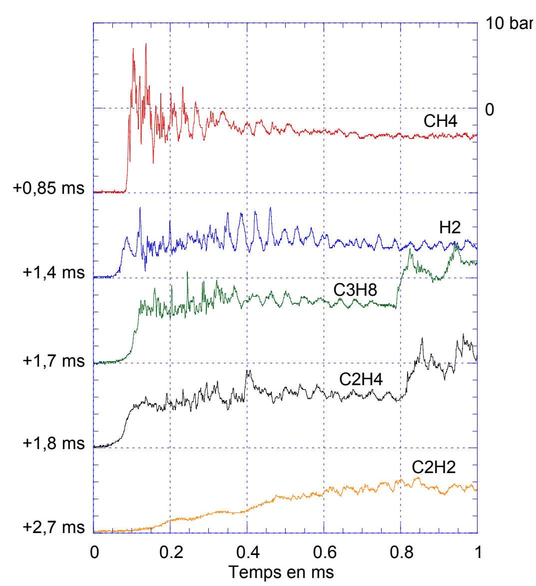


Figure 3: Typical P_2 pressure profiles in CH_4, H_2, C_3H_8, C_2H_4 and C_2H_2 based mixtures.

chemical induction time behind the shock that is compatible with the auto-inflammation of the mixture, and then with the transition to detonation.

5) The spiral length influences the transition to detonation. For each mixture an optimum spiral length can be determined: it means that with regard to L_S if the spiral is shortened the transition fails to happen rapidly and may take several meters. If the length is increased L_{DDT} is a few longer and may appear in the spiral in the form of quasi detonation, propagating like galloping detonation since d ~ 1,8 λ as described by Teodorczyk et al. [5] until the end of the spiral. Then it seems that the spiral is here to sustain the shock-flame system until the distance between the flame and the shock corresponds to the induction length behind the shock so that the transition to detonation can happen.

6) The influence of the early flame on t_{DDT} can be seen. The Table shows that the energetic content of the mixtures does not seem to influence t_{DDT}. By the way, we can observe in Figure 2, that most of the time of transition is spent in the first chamber where the flame is essentially laminar. Then if the laminar velocities of flame for these mixtures are compared one can notice that the faster mixtures transit before the slower ones. The influence of the laminar flame speed was verified: the volume of C1 was decreased, by varying the i.d. of the chamber, within keeping a sufficiently high BR (to keep high jet and then high P_T). A reduction of t_{DDT} was obtained with the reduction of volume within a L_{DDT} equivalent, the conclusion is that the time of transition is penalized by the early development of flame in C1 (laminar propagation).

Mixture	L_{DDT} (m)	t_{DDT} (ms)	P_V (bar)	P_T (bar)	$\Delta P_T/\Delta P_V$	a_b (m/s)	D_T (m/s)	D_T/a_b	L_S (cm)	λ_{CJ} (mm)	L_{DDT}/λ_{CJ}	$L_{DDT}/\lambda_{CJ}*\Delta P_{tube}/\Delta P_V$
$H_2+0,5O_2+1,881N_2$	0,4	1,72	8,15	5,28	0,598	978	968	0,99	27	10	40	23,9
$C_3H_8+5O_2+8,75N_2$	0,335	2,05	11,96	8,08	0,646	964	852	0,88	17	10	33,5	21,6
$C_2H_4+3O_2+7,5N_2$	0,34	2,14	10,75	6,64	0,578	939	882	0,94	14	10	34	19,6
$CH_4+2O_2+1,5N_2$	0,27	1,08	12,65	9,68	0,745	1045	989	0,95	14	10	27	20,1
$C_2H_2+2,5O_2+11,08N_2$	0,38	3,11	9,45	5,68	0,554	896	1111	1,24	30	10	38	21

Table: characteristic results for DDT obtained in λ_{CJ} = 10 mm cell size mixtures

Conclusion

The Deflagration to Detonation Transition of stoechiometric mixtures with the same detonability (fuel/O_2/N_2 with H_2, C_3H_8, C_2H_4, C_2H_2, and CH4) was studied in order to optimise L_{DDT} and t_{DDT} for PDE application. A double chamber with high BR was used to force a flame jet in a tube containing "Shchelkin spiral" and to induce within a short distance a shock-flame system. The shock-flame obtained propagates close to the isobaric speed of sound, regime that was observed previously [4]. The chocking regime obtained enables the conditions of local explosion of the mixture and then transition to detonation. In our experiments L_{DDT} can be scaled with λ_{CJ} and the ratio L_{DDT}/λ_{CJ} is ranging from 30 to 40 for mixtures with λ_{CJ} around 10 mm. The flame jet can obviously optimise the DDT since the dynamic of combustion is sufficient to limit the losses in the chambers and since the jet can induce high combustion rate and locally elevated gradients and thus detonation initiation is essentially controlled by chemical induction behind shock wave.

Aknowledgment

The authors thanks CELERG for supporting this work (contract CNRS/CELERG n°780882)

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