Detonation Diffraction Through Different Geometries

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Introduction

The development of an air-breathing Pulsed Detonation Engine (PDE) functioning with kerosene needs the improvement of the initiator design. The main design of the initiator consists in a pre-detonator tube that ignites the detonation (via deflagration to detonation transition (DDT)) in a small volume (i.e. a small diameter d) compared with the combustion chamber. In the case of air-breathing operation, the detonability of the reactive mixture is quite low (large detonation cell size λ) and even if DDT happens on a short distance, the direct transmission into the chamber is not ensured.

The criterion for successful transmission of a self-sustained detonation from a tube of inner diameter d to a free space was established and expressed as $d = k_c.\lambda$ with $k_c = 13$ for most common hydrocarbons/O_2/N_2 mixtures (Matsui and Lee, 1978). This value can be modified in reactive mixtures highly diluted by a mono-atomic gas (He, Ar, Kr) (Desbordes et al, 1993). Many studies show that significant improvement of detonation transmission from a cylindrical tube can be obtained by different means based on: (i) shock reflection and focalization (Moen et al. 1986), and (ii) reduction of lateral expansion by a cone or a limited increase of the diameter of the tube (Khasainov et al. 2003).

The aim of this study is to promote the detonation transmission by considering different geometric configurations. Two experimental devices were designed. The first one corresponds to a brutal opening from a cylindrical tube to another of larger diameter D (D/d = 1.5 and 2). The second one is an original device using the two means described: reflection (normal and lateral) and confinement. It consists of a cylindrical tube of varying diameter D (D/d = 2-3 and 3.86) closed at one end that is reversed at the exit of the initiator tube so that the flow is inversed and the normal reflection of the diffracted detonation is obtained at the closed end. This inversed intermediate tube forces the detonation (shock) to undergo 2 successive reflections between the initiator tube and the tranquilization chamber. We used different stoichiometric mixtures with O_2 containing C_2H_2, C_2H_4 and H_2 and with various dilutions of Ar, in order to check the similarity of the diffraction process. The diffraction was studied by varying the ratio d/λ of the detonation before entering the device.

Experimental Details

The experimental device consists of a 2 meter long tube of inner diameter d = 26 mm which is connected to a 400 mm long tranquilization chamber of inner diameter D_{ch} = 200 mm. The detonation is ignited by deflagration to detonation transition. Two pressure transducers are positioned at the end of the tube to check that the self-sustained quasi-detonation is obtained before diffracting. At the end of the tube we can install 2 different devices:

(1) a brutal increase in tube diameter up to the value of D = 39 or 52 mm (corresponding to D/d = 1.5 or 2) cf. Figure 1,

(2) a 110 mm long inversed tube of diameter D = 52, 78 or 100 mm (corresponding to D/d = 2, 3 or 3.86) cf. Figure 2. Its closed end is located at a distance h with h/d = 0.5-1-1.5 or 2 from the end of the tube. The inversed tube presents 2 successive wall reflections, RW1 and RW2 as defined in Figure 2. The distance H between the end of the inversed tube and the tranquilization chamber wall (RW2) is H = 52 mm.

Five reactive mixtures of different cellular regularity were investigated i.e. C_2H_2+2.5O_2, C_2H_2+2.5O_2+3.5Ar, C_2H_2+2.5O_2+15Ar, C_2H_4+3O_2 and H_2+0.5O_2 for the device (1) and C_2H_4+3O_2 for the device (2). For each mixture, we vary the ratio d/λ of the diffracting detonation wave by varying the initial pressure. In both configurations the diffraction is recorded by the soot tracks technique. A smoke stainless steel foil is positioned along the axis of the system such that the diffraction and re-ignition of the detonation can be observed.

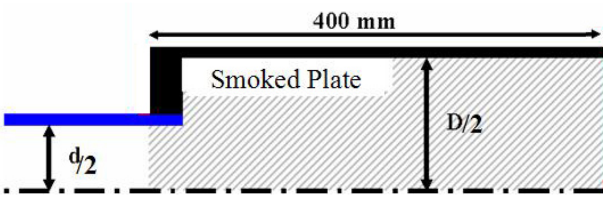

Figure 1 : Schema of the diameter jump configuration, device (1)

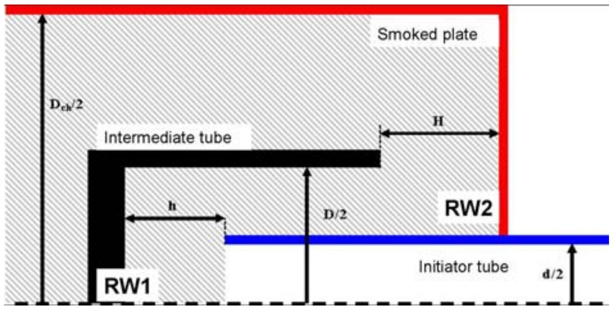

Figure 2: Schema of the reversed intermediate tube configuration, device (2)

Results and Discussion

All the detonation waves obtained by the DDT mechanism are quasi-CJ before diffracting. Their velocities are close to the CJ ones within 1%.

1) Diffraction through an abrupt area expansion (device 1)

For the 2 expansion ratios studied (D/d = 1.5 and 2), smoke foils records show three mechanisms of re-ignition of the detonation when the ratio d/λ varies:

- For d/λ > k_c, the detonation never fails at the axis of the tube and lateral re-ignitions start from the extinction cone.
- For d/λ < k_c (cf. Figure 3), the extinction cone is seen and the detonation is totally quenched up to the axis. A shock-flame system propagates in the receptor tube up to the wall where the lateral reflection of the decaying shock occurs. The oblique shock reflection is first regular, and as the shock moves away from the tube exit it becomes weaker and the angle of intersection decreases up to create the condition for the appearance of an irregular reflection and the formation of a Mach stem. For values of d/λ between k_c and k_{lim} (which depends on D/d) the re-ignition locus is positioned at the wall and corresponds roughly to the distance of appearance of the Mach stem. From this locus, the detonation propagates both along the wall and in the layer of unreacted mixture compressed by the diffracted shock (where smaller cells can be seen). The re-ignition seems symmetrical on the plate. It takes place at a number of points all around the wall of the receptor tube at the same distance from the exit of the initiator tube.

- For $d/\lambda < k_{lim}$ (cf. Figure 4), the re-ignition point becomes unique and moves away from the wall. In a first time, the re-ignition seems under the influence of shock reflection, re-ignition takes place on the path of the triple points created in the receptor tube and the distance of re-ignition increases smoothly. When d/λ continues to decrease the re-ignition takes place on much longer distance because the re-ignition happens after a DDT period.

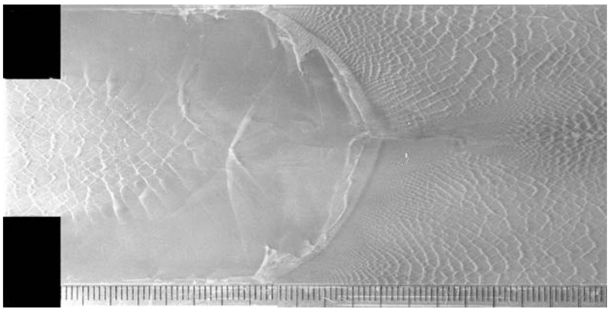

Figure 3: Wall detonation re-ignition, D/d=2, C_2H_2+2.5O_2, for $k_{lim}<d/\lambda<k_c$

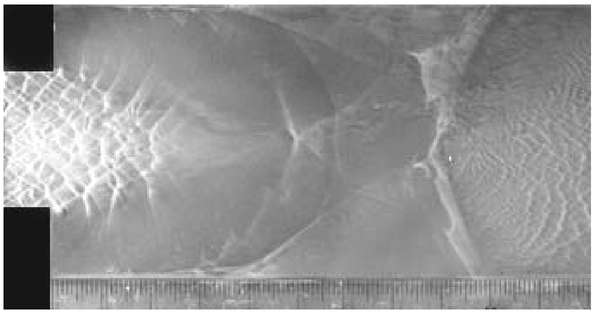

Figure 4 : Volume detonation re-ignition, D/d=2, C_2H_2+2.5O_2, for $d/\lambda<k_{lim}$

On Figure 5 and Figure 6, we have reported the re-ignition distance $L_{re\text{-}ignition}$ as a function of $(d/\lambda)/k_c$ for D/d=2 and D/d=1.5. $L_{re\text{-}ignition}$ is the distance from the diffraction section. The ratio k_{lim}/k_c depends only on D/d. For every mixture we find that $k_{lim}/k_c \sim 0.7$ for D/d = 2 and $k_{lim}/k_c \sim 0.35$ for D/d = 1.5 (see Figure 5 and Figure 6). This result confirms the similarity of the diffraction; each mixture is related to its own k_c value of the transmission critical criteria.

An exception comes from the H_2-O_2 mixture which shows classically $k_c \sim 13$ for transmission to free space. Using this value we obtain $k_{lim}/k_c \sim 1.17$ for D/d = 2 and $k_{lim}/k_c \sim 0.56$ for D/d = 1.5. In order to match to the value found for the hydrocarbon mixtures we must use $k_c \sim 21$. This value of k_c is very close to the one obtained by Ciccareli et al. (2002) but for the H_2-air mixtures.

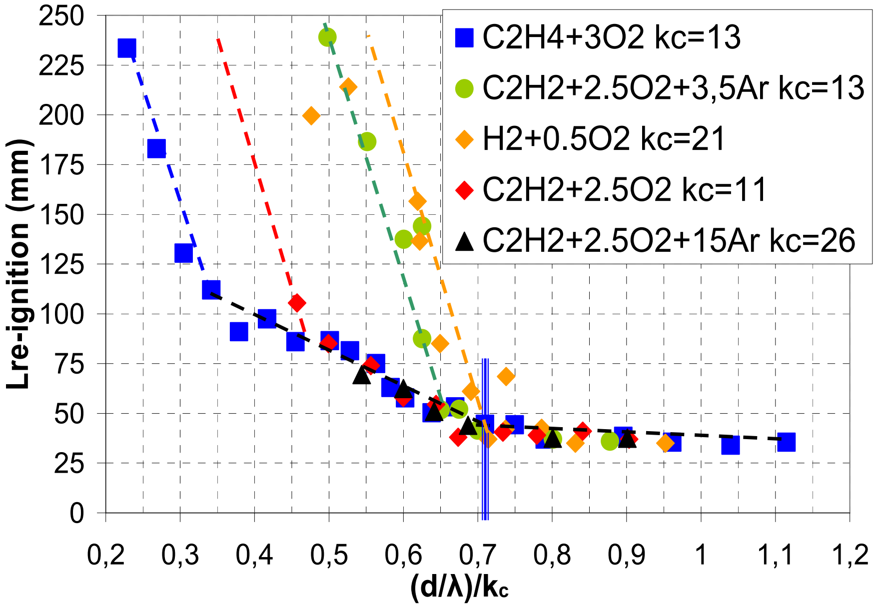

Figure 5 : Variation of $L_{re\text{-}ignition}$ with $(d/\lambda)/k_c$ for D/d=2

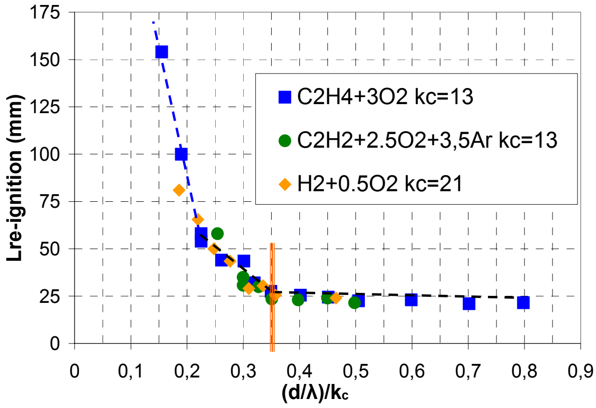

Figure 6 : Variation of $L_{re\text{-}ignition}$ with $(d/\lambda)/k_c$ for D/d=1.5

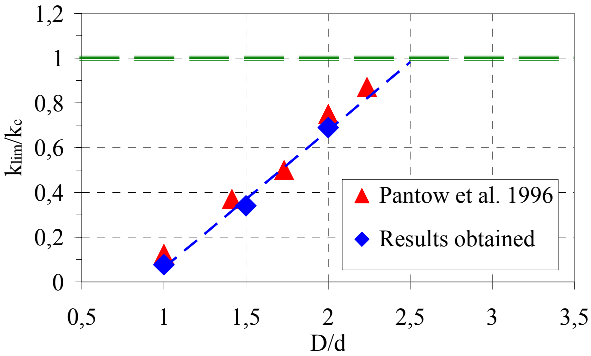

Figure 7: Variation of k_{lim}/k_c with Expansion factor (D/d)

We checked the influence of the expansion ratio (D/d) on the limit value k_{lim}/k_c of re-ignition at the wall (cf. Figure 7). We also report the point for D/d = 1 corresponding to the limit condition of detonation propagation ($d/\lambda \sim 1/\pi$ and 1 respectively for cylindrical and square section) and the results obtained by Pantow et al. (1996). We can notice that our results fit well with those of Pantow. We obtain that k_{lim}/k_c increases as D/d increases. The extrapolation exhibits a ratio $k_{lim}/k_c \sim 1$ for D/d = 2.5, this means that for D/d > 2.5 the transmission of the detonation in the receptor tube is not improved in comparison with the diffraction into half space.

2) Detonation diffraction by 2 successive reflections (device 2)

When the detonation diffracts from the initiator tube, the detonation fails and a quasi spherical shock-flame system propagates in the mixture. When the shock reflects on the front wall RW1 (cf. Figure 2), the head-on reflection becomes oblique as the reflection point moves away from the axis of the system. This reflection becomes irregular (by the same process as described before) and a Mach stem is formed. As the previous case, the detonation may be ignited near the Mach stem. It propagates along the wall in the fresh mixture and backward in the compressed mixture between the leading decaying shock and the associated flame, creating a region of fine cellular structures (cf. Fig 8). If the initial pressure is not high enough the detonation may exist near the wall but does not survive the lateral expansion (cf. Figure 9).

The limit value of head-on re-ignition depends on the distance h/d (cf. Fig 10). We obtain a minimum value of $d_c/\lambda \sim 6{,}5$ (the critical value of transmission of the detonation via head-on collision) for h/d = 1. This configuration shows larger transmission potential than diffraction to free space (k_c=13 for the C_2H_4+$3O_2$ mixture). These results are in agreement with those of Murray et al. (1983) concerning the study of critical transmission of detonation from a tube of diameter d to a cylinder of thickness h. It is the head on collision of the failing detonation that triggers the detonation in the cylinder. Their results of transmission limits with the thickness (h) correspond to those obtained here. They exhibit the same evolution up to a minimum at h/d = 1.1. The extrapolation of the transmission limit shows that the closed end will have no more effect on the detonation transmission for h/d > 2.

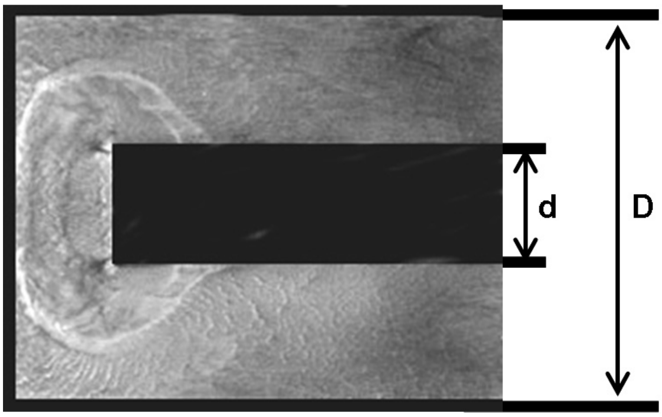

Figure 8 : Head-on re-ignition

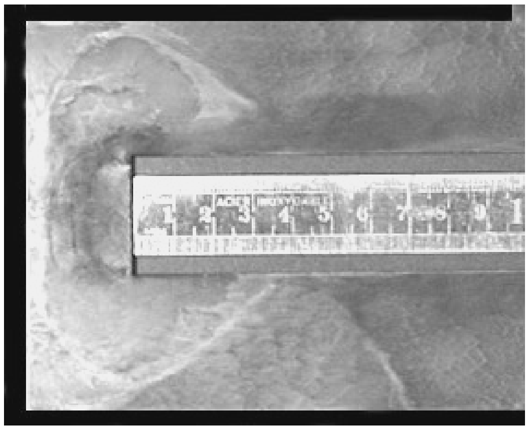

Figure 9: Lateral re-ignition

When the re-ignition does not take place at the front wall, the reflection of the expanding shock on the lateral wall triggers the re-ignition of the detonation for lower value of d/λ. The re-ignition is again the consequence of the onset of a Mach reflection at the wall that creates a triple point which propagates toward the axis (cf. Figure 9). The limit value of lateral re-ignition depends on the diameter ratio of the intermediate tube (D/d) and on the position of the closed end h/d (cf. Fig 11). The optimum transmission condition is obtained for h/d=1. Moreover the re-ignition is favored when the lateral wall is closer the axis, so the transmission limit is smaller when the expansion factor D/d is smaller. When D/d varies from 3.86 to 2, the transmission limit d_c/λ varies from 4.5 to 2.5 for h/d=1 and from 8 to 3.5 for h/d=0.5.

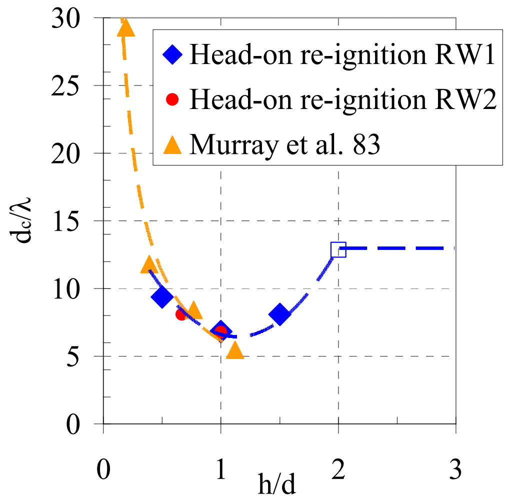

Figure 10: Head-on re-ignition limits

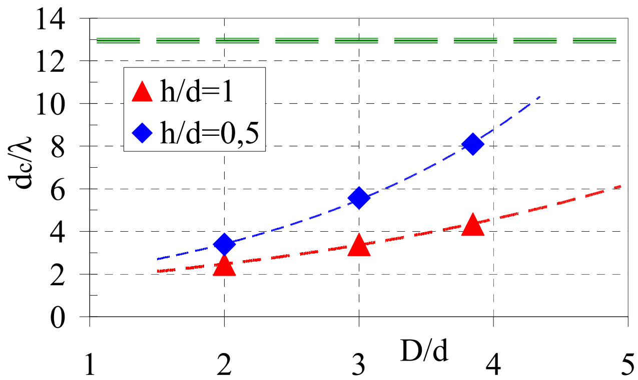

Figure 11: Lateral re-ignition limits

The second normal reflection (on RW2 cf. Figure 2) of the detonation or shock wave proceeds by similar mechanisms than those underlined in the first reflection. The significant result is that the detonation can re-ignite in the second reflection even if it does not take place in the first one (cf. Fig 12). The detonation can be transmitted to the combustion chamber for lower d/λ value i.e. $d_c=2.2*\lambda$ quasi-independently of the ratio D/d. In the limit case of transmission from the tube of d=26mm to the chamber of D_{ch}=200mm the re-ignition happen after shock focalization behind the reversed tube.

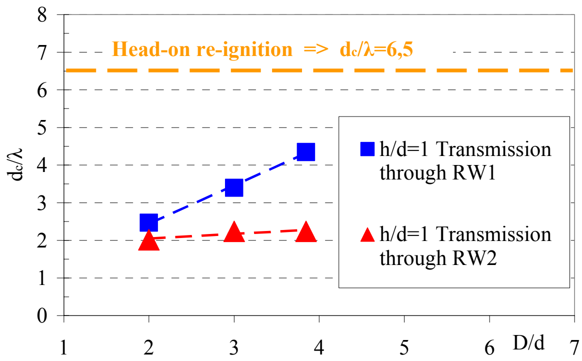

Figure 12: limits of transmission of detonation with the intermediate tube for h/d=1, $C_2H_4+3O_2$

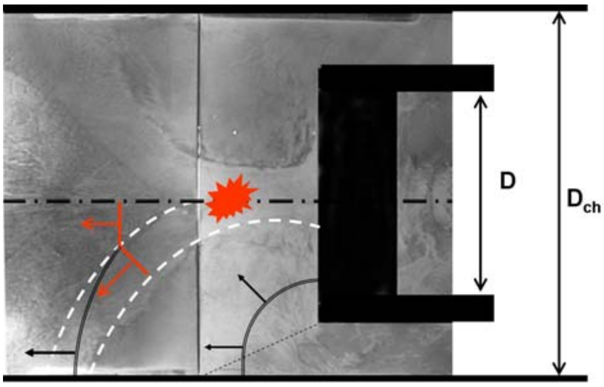

Figure 13: Smoked foil in the limit case of re-ignition

In conclusion, the above situation corresponds globally to the condition of transmission of a self-sustained detonation from a tube of i.d. d = 26 mm to a tube of much larger i.d. D_{ch} = 200 mm. Without the two successive reflections the critical diameter is classically $d_c = 13\lambda$. With the mean of double reflection, we obtain $d_c = 2.2\lambda$ which represents a significant improvement in the detonation transmission.

Conclusion

The study of the diffraction of a self-sustained detonation through different geometries (brutal increase of diameter and double reflection insured by a reversed intermediate tube) was performed. The results for the brutal increase of diameter geometry show that when $1 < D/d < 2,5$ the limit value of d/λ to have a wall re-ignition varies from $1/\pi < d/\lambda < k_c$ (= 13). For an expansion ratio larger than 2.5, the wall reflection is no more efficient to re-ignite the detonation compared with the transmission to free space. The results obtained with a reversed intermediate tube show that for the first reflection (i) the normal reflection of the diffracted shock allows re-ignition up to $d/\lambda \sim k_c/2$ for an optimized gap h ~ d, (ii) the lateral reflection allows wall re-ignition up to $d/\lambda \sim k_c/3$ to $k_c/5$ (for D/d varying from 3.86 to 2). The transmission through the 2 successive reflections is obtained up to $d/\lambda \sim k_c/6$ from the initiator tube of d = 26mm to the chamber of D_{ch} = 200mm, i.e. that the detonation is transmitted with a $d_c = 2.2\lambda$ law.

References

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