Transition to detonation due to shock focusing in C_2H_6-air mixtures

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Abstract

The phenomenon of transition to detonation due to shock focusing in C_2H_6-air mixtures (φ = 0.85 – 1.2) initially at 1 bar has been experimentally investigated. The limiting leading shock wave velocities have been measured for two reflectors with orthogonal walls: a wedge reflector and a 3-wall corner reflector. The results showed that in a stoichiometric C_2H_6-air mixture, direct transition to detonation can occur when a shock wave approaches the reflector at a minimum of 752 m/s (M = 2.19) or 620 m/s (M = 1.81) for wedge and corner reflectors, respectively. Ignition delay time (IDT) is strongly dependent on the leading shock wave velocity, and for all tests with a successful transition to detonation, it was less than 10 µs. Tests also proved the high shock-focusing ability of both reflectors by comparing the maximum pressures recorded in the reflector tip with the corresponding post-normal reflection pressure. For tests with a wedge reflector, the pressure was 6.5 – 7.5 times higher, while for a 3-wall corner reflector, the ratio was 18 – 19.4. The results also showed that the ratio between transition to detonation limiting velocities for both reflectors is close to 0.82 - 0.83 throughout the investigated mixtures. A similar ratio obtained for hydrogen-air mixtures was close to 0.84 [1] which suggests the existence of a scaling factor between both reflectors, potentially independent of the fuel.

1 Introduction

Detonation is the most dangerous combustion process, driven by a supersonic (~2 km/s) shock wave that self-ignites the flammable mixture behind it. Simultaneously, the detonation is considered to drive future propulsion systems like Pulse Detonation Engines or Rotating Detonation Engines [2]. Quantifying critical conditions necessary for transition to detonation for accelerating flame is still one of the unresolved problems in combustion. Transition to detonation mechanisms might be divided into two main groups: shock reflection and/or focusing, and instabilities at the turbulent flame [3]. It has already been proven, [1,4,5] due to the high temperature and pressure in the focal point, shock focusing is a very effective way to trigger detonation, and recorded pressures can be as high as 17-fold the normal post-reflection pressure. In previous work, transition to detonation in stoichiometric H_2-air has been observed due to shock focusing in a 3-wall corner reflector (with orthogonal walls) at shock velocity as low as 605 m/s (M=1.45) [1] or 715 m/s (M=1.7) when the reflector was a 90-deg wedge [4]. These relatively low velocities, obtained for commonly occurring geometries, threaten the safety of the processing units and installations.

To the best of the authors' knowledge, similar critical shock velocities for a successful transition to detonation in hydrocarbon-air mixtures initially at 1 bar have not been investigated yet. As ethane is an important gas in LNG processing units and a good feedstock for chemical synthesis, it has been selected to explore the transition to detonation in ethane-air mixtures due to shock focusing in two focusing reflectors: a 90-deg wedge and 3-wall corner.

2 Experimental setup and procedure

The experimental setups used in this research include two detonation tubes, of which one was a rectangular cross-section 0.11 x 0.11 x 1.5 m (H x W x L) equipped with a 90-deg wedge reflector at the tube end. The second tube was 0.14 m in diameter and 2 m long and equipped with a 3-wall corner reflector. Both tubes were equipped with piezoelectric pressure sensors (PCB Piezotronics) and ion probes (in-house developed) placed along the tube's upper wall to measure the shock wave and flame velocities propagating towards the tube end. Each reflector had a single pressure sensor in its tip and an ion probe close to it. Each tube had an acceleration section placed close to the ignition point, opposite the reflector's position. The sensors were sampled with a 2 MHz frequency. The acceleration section aimed to accelerate the flame to the fast deflagration regime, where the shock wave preceded the flame. Modifying the acceleration section configuration (number of obstacles/mesh layers) allowed control of the flame acceleration level and the leading shock wave velocity V_S. The leading shock wave approached the reflector, and after focusing ignition, the following deflagration or detonation initiation was recorded. The schematic cross-sections of the tubes and 3D view of the reflectors are presented in Figure 1. The mixtures were prepared by the partial pressures method with a digital manometer with 1 mbar accuracy in a gas cylinder and stored horizontally for a minimum of 24 hours to enhance mixing. Initial conditions for all tests were 1 bar and 295 ± 3 K. A more detailed description of the experimental setups and procedure can be found in [4] and [1].

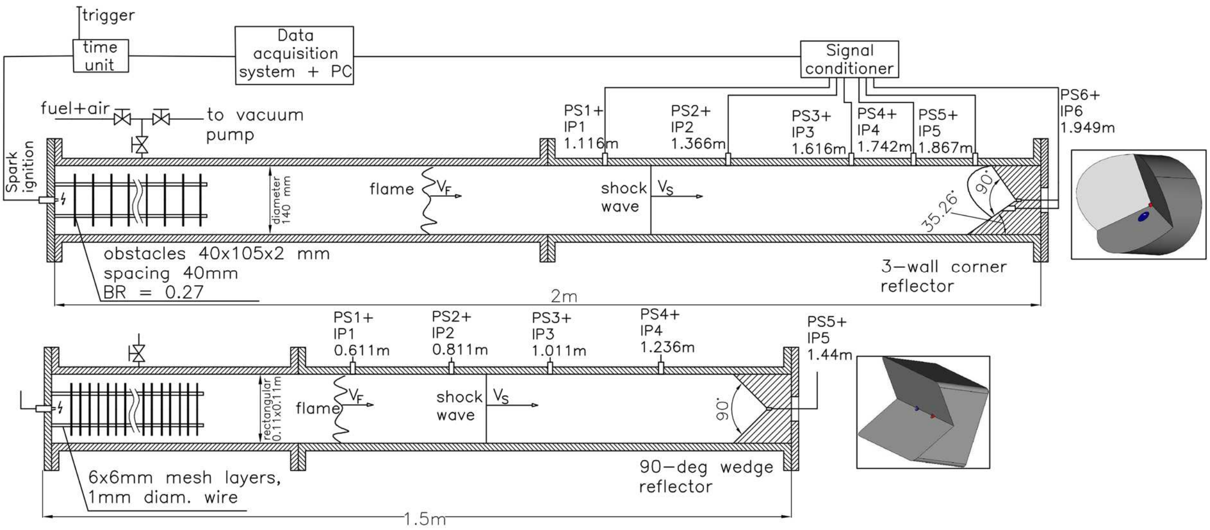

Figure 1. Scheme of the experimental setups used in research.

3 Results

In total, 187 tests were conducted, 90 for the wedge and 97 for the 3-wall reflector. The mixtures tested included C_2H_6-air mixture in equivalence ratio in the range of 0.85 – 1.2, which corresponds to a concentration range of 4.8% to 6.7% C_2H_6 in air, respectively. Example pressure sensors are presented in Figure 2. The pressure sensors and ion probes readings following shock wave focusing let to categorize tests into three main groups: first, with ignition and following deflagration, second, with the direct transition to detonation, and third, with deflagrative ignition and delayed transition to detonation. A similar intermediate ignition regime has already been reported in [5–8]. In this research, this third type had two characteristic pressure peaks recorded in the reflector tip, with a second peak higher (wedge reflector) or close to the first value peak (corner reflector), and was delayed 15 - 58 µs and 15-22 µs for wedge and corner reflector, respectively. Each test was post-processed using the time-of-arrival method for shock and flame position. Shock wave velocity at the time of focusing was linearly extrapolated based on the last 3 pressure sensor readings. This procedure is similar to that previously used in [1,4]. As each reflector was equipped with an ion probe, it was possible to record ignition delay time (IDT) in the corner tip as the time difference between the pressure sensor and the ion probe signal. One needs to remember that in the case of a wedge reflector, the ion probe and pressure sensor are placed in the reflector tip, while in the case of a corner reflector, the ion probe is placed at the reflector wall 24 mm away from the pressure sensor. This will cause an ion probe reaction time delay, which in the case of transition to detonation has been recognized to be in the range of 15-18 µs. Example ignition delay time measurements are presented in Figure 3 for both reflectors and lean and stoichiometric mixtures. As one can see in Figure 3, IDT is strongly dependent on the leading shock wave velocity and can increase 10 - 20 times when the shock wave velocity decreases by ~50 m/s. For transition to detonation events, the IDT is at the order of 1 - 9 microseconds. Similar IDT ranges for transition to detonation and strong IDT dependence on shock velocity have also been recorded for hydrogen-air mixtures [1,4]. Figure 4 shows the dependence between ethane concentration and leading shock wave velocity (Figure 4, left), shock velocity related to the speed of sound in combustion products (Figure 4, center), and maximum pressure recorded in the reflector tips (Figure 4, right). Limit lines in Figure 4 connect the points with the lowest recorded velocities/pressures for direct transition to detonation. In general, the limiting velocity lines have a U-shape with a minimum value for a stoichiometric C_2H_6-air mixture close to 752 m/s (M = 2.19, V_S/a_P = 0.819) and 620 m/s (M = 1.81, V_S/a_P = 0.675) for the wedge and 3-wall corner reflector, respectively.

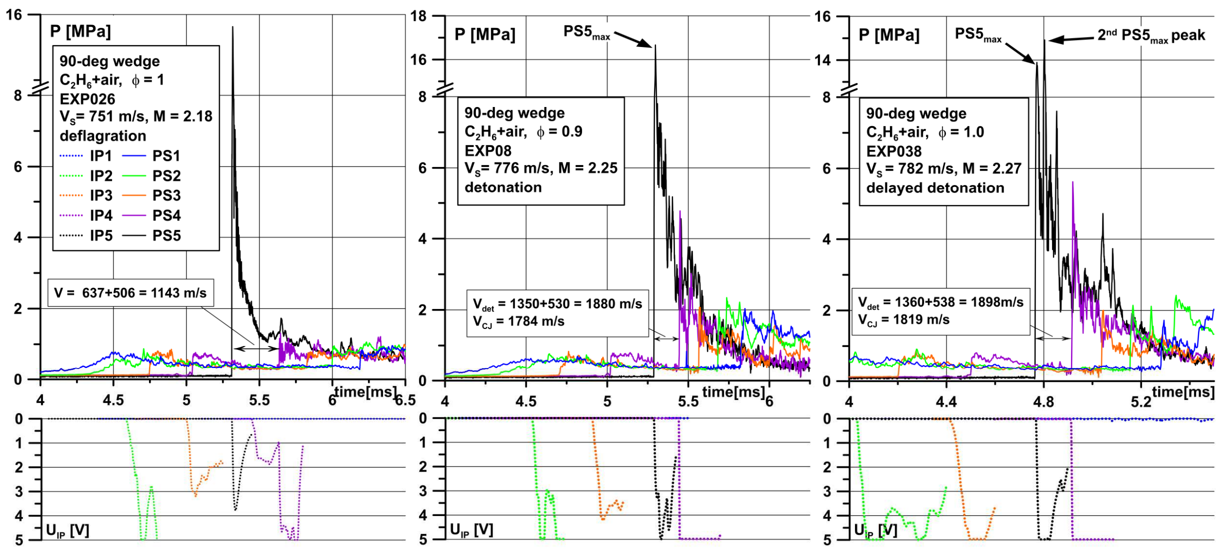

Figure 2 The example pressure and ion probe indications with three types of ignition events after focusing: ignition with following deflagration (left), direct transition to detonation (centre), and ignition with delayed transition to detonation (right).

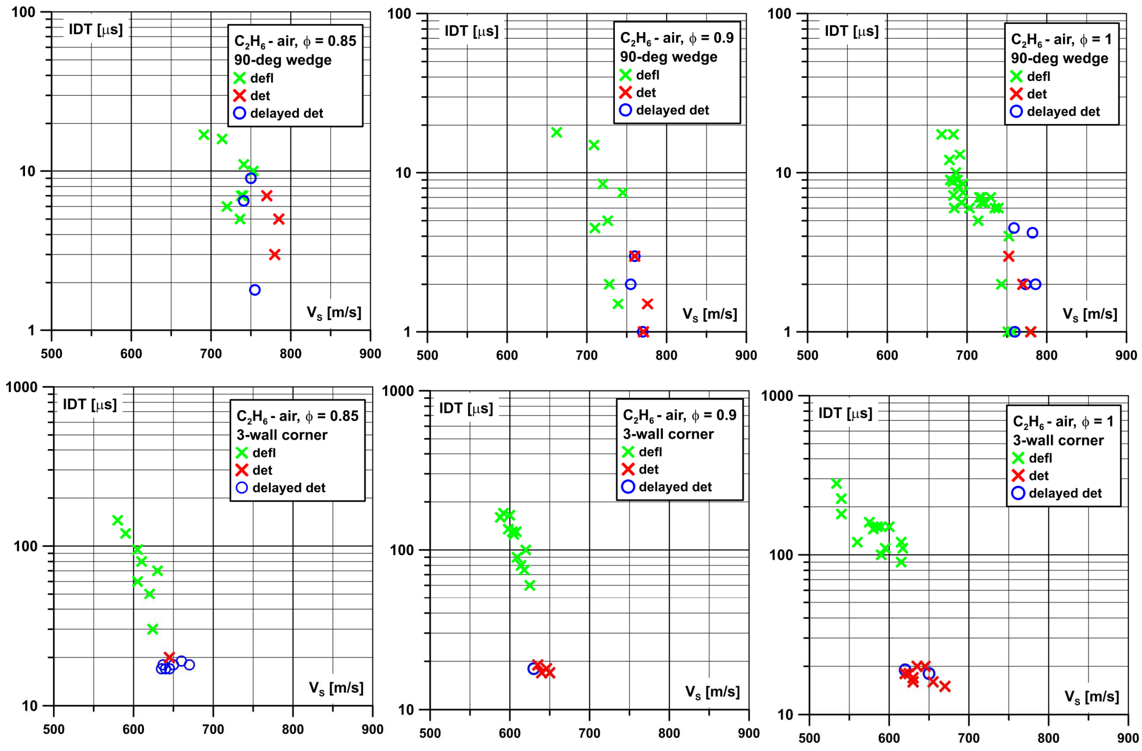

Figure 3 Example ignition delay time graphs measured in the reflectors tip for various C_2H_6-air mixtures.

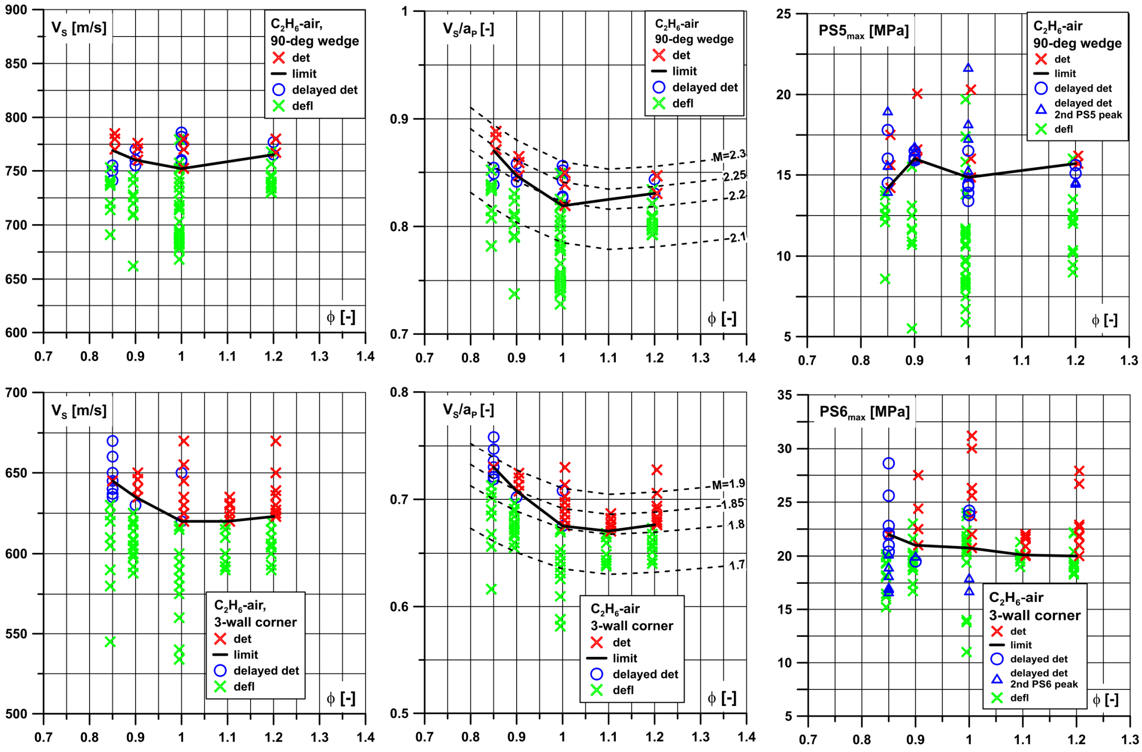

Figure 4. Cumulative diagrams of shock velocity influence (left), relative shock velocity (center), and maximum pressure recorded in the reflector tip (right); det – direct transition to detonation, defl – ignition with following deflagration, delayed det – delayed detonation, a_P – isobaric speed of sound in combustion products.

4 Summary and Conclusions

The phenomenon of transition to detonation due to shock focusing in C_2H_6-air mixtures initially at 1 bar has been experimentally investigated. The limiting leading shock wave velocities have been quantified for two reflectors with orthogonal walls: a wedge reflector and a 3-wall corner reflector. The results proved that in a stoichiometric C_2H_6-air mixture, direct transition to detonation can occur when a shock wave approaches the reflector at a minimum velocity of 752 m/s or 620 m/s for wedge and 3-wall corner reflectors, respectively. IDT is strongly dependent on the leading shock wave velocity, and for tests with successful transition to detonation, IDT was less than 10 µs. Tests also proved the high focusing ability of both reflectors by comparing the maximum pressures recorded in the reflector tip with the corresponding post-normal reflection pressure (see Table 1). The pressure was 6.5 – 7.5 times higher for tests with a wedge reflector, while for a 3-wall corner reflector, the ratio was 18 – 19.4. Another important feature of the obtained results is the ratio between limiting velocities for both reflectors, which is close to 0.82 - 0.83. A similar ratio obtained for hydrogen-air mixtures was close to 0.84 [1]. These close numbers suggest the existence of a scaling factor between both reflectors and a potentially important feature if confirmed for more fuel-air mixtures. Another value of the current results worth comparison with hydrogen-air mixtures is the pressure gain ratio defined in the last column in Table 1 as the ratio between maximum limiting pressures related to corresponding post-normal reflection conditions. In the case of C_2H_6-air, this ratio is in the range of 2.4 – 2.8, while for hydrogen-air is close to 2 for near stoichiometric mixtures and approaches a value of 2.5 for extremely lean and rich mixtures [1]. It is also worth noting that the 3-wall corner can act as the 90-degree wedge reflector by rotating it by 35 degrees around the corner tip to reduce the number of walls taking part in the shock focusing phenomenon. Therefore, a change in reported critical shock wave velocity (620 -752 m/s), maximum pressures (207.5 - 148 bar), and a change in IDTs for both reflectors are covered within a 35-degree shock wave approach direction only. This proves that the transition to detonation is highly sensitive to local geometrical conditions of the reflecting/focusing walls, which seems to be one of the factors responsible for the stochastic nature of the transition to detonation.

Table 1. Comparison between limiting conditions for transition to detonation in the 3-wall reflector and wedge reflector. Subscript *n.refl.* refers to the post-normal reflection pressure, calculated with Gaseq software [9] for specific V_S.

φ	3-wall reflector				90-deg wedge				V_S ratio	Pressure gain ratio
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)		
	V_S [m/s]	$P_{n.refl.}$ [bar]	$PS6_{max}$ [bar]	$PS6_{max}/P_{n.refl}$ [-]	V_S [m/s]	$P_{n.refl.}$ [bar]	$PS5_{max}$ [bar]	$PS5_{max}/P_{n.refl}$ [-]	(1) / (5)	(4) / (8)
0.85	645	12.2	220	18.0	769	21.97	142	6.46	**0.838**	**2.78**
0.9	635	11.6	210	18.1	760	21.20	160	7.55	**0.835**	**2.40**
1	620	10.7	207.5	19.37	752	20.56	148	7.22	**0.824**	**2.68**
1.1	620	10.75	201	18.70	-	-	-	-	**-**	**-**
1.2	623	10.97	200	18.23	765	21.92	157	7.16	**0.814**	**2.54**

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