

An Experimental Investigation of a Detonation Characteristic Length Scale Relevant to Critical Diffraction

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1 Introduction

It is well known that the propagation speed and the propagation mechanism of a steady detonation wave can be well predicted by the Chapmann–Jouguet (CJ) theory and the Zel’dovich–von Neumann–Döring (ZND) theory, respectively. In these theories, the detonation wave is treated as a wave having a one dimensional structure. Nevertheless, in reality, the detonation wave has a three dimensional structure (cellular structure) as numerous observation results indicate. Such the three dimensional structure is of decisive important for prediction of dynamic aspects of detonation, including the detonability limit, the critical energy in the direct initiation of detonation, the critical tube diameter in the detonation diffraction, and the deflagration-to-detonation transition (DDT) distance. This is because initiation and quench characteristics of the detonation wave are mainly determined by the three dimensional structure. Therefore, it is usually difficult for one dimensional theories to predict the dynamic aspect of detonation. Hence, semi-empirical prediction of the dynamic characteristics is attempted based on some known characteristic length scales of detonation, *e.g.* cell width and induction length [1–3]. That is, obtaining a data set of a characteristic length scale is significantly important for quantitative prediction of detonation phenomena.

When a planar detonation wave propagating in a channel emerges into a wider space, the wave front undergoes deformation and diffraction due to expansion of the flow behind the leading shock wave. The transmission of the detonation wave from the narrower channel into the wider space can fail under certain conditions. Based on success or failure in the transmission, the diffraction process is often classified as supercritical or subcritical, respectively [4], and there exists a critical condition for the size of the channel, depending on the chemical composition and thermodynamic state of the detonable gas mixture and the configuration of the channel [2, 4]. For instance, Zel’dovich *et al.* [5] pointed out that a detonation wave in a cylindrical tube will fail in transmission upon diffraction when the diameter of the tube is smaller than a certain value called the critical tube diameter. Here, as described in detail below, a length scale characterizing the detonable mixture can be defined for supercritical diffraction independently of the channel configuration [6, 7]. In the present paper, we refer to that length scale as *reflection point distance*.

In this study, the reflection point distance as a characteristic length scale of detonation, which is relevant to supercritical diffraction, is measured by high-speed schlieren photography for ethylene-oxygen mixtures with different argon dilution ratios and initial pressures; the reflection point distance is elucidated from a viewpoint of characteristic length scale.

2 Experimental Setup

Figure 1 shows a schematic of the experimental apparatus, which mainly consists of a detonation tube with a circular cross section, an observation chamber with a uniform profile in depth, and a dump tank. The detonation tube has a length of 560 mm and a diameter of 25.8 mm. The observation chamber is a gap in between a pair of parallel observation windows and 16 mm deep, and it is connected with the detonation tube through a 90-mm-long inlet channel with a rectangular cross section.

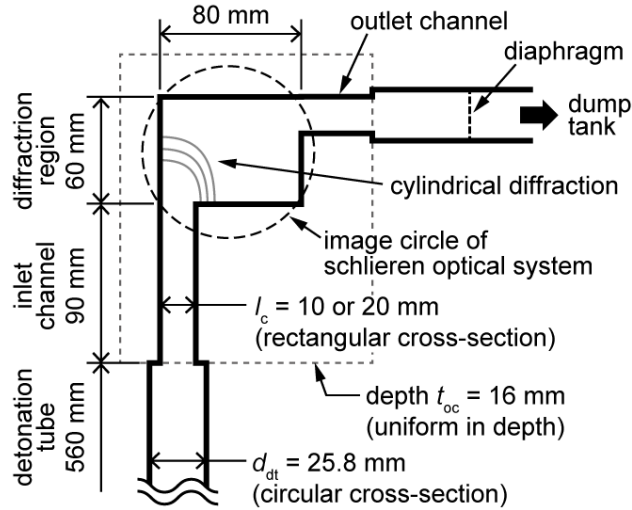


Figure 1. Schematic of the experimental apparatus

Upon an operation, the whole channel, *i.e.*, the detonation tube and the observation chamber, was well evacuated by an oil-sealed rotary pump firstly. Then, the detonation tube and the observation chamber were filled with a premixed fuel-oxidizer gas mixture at a specific initial pressure. After the filling, the mixture was quickly ignited by a spark plug installed at the bottom of the detonation tube. A planar detonation wave was generated in the detonation tube, and it was introduced into the inlet channel of the observation chamber. Then, the planar detonation wave emerged into a wider space (diffraction region) and experienced a diffraction. In synchronization with the diffraction, a pulse laser light source and a high-speed camera were operated, and the sequence of the diffraction event was recorded with the high-speed schlieren photography. After the diffraction, the detonation wave reached the outlet channel of the observation chamber and ruptured a diaphragm. Then, the burned gas was safely released into the dump tank. Note that in the observation chamber, the flow field was macroscopically uniform in depth and thus macroscopically two-dimensional. In this sense, the diffracted wave front was cylindrical but not spherical.

Experimental conditions are listed in Table 1. In the present study, gaseous ethylene, gaseous oxygen, and gaseous argon were selected for the fuel, the oxidizer, and the diluent, respectively. As given in Table 1,

four types of stoichiometric ethylene–oxygen mixtures (E1–E4) were prepared with a variation of argon mole fraction y_{Ar} . For the ethylene–oxygen mixture without argon dilution (E1), the inlet channel width l_c of the observation chamber was varied. The initial pressures (filling pressures) of the mixtures p_0 ranged from 5 to 140 kPa, and the initial temperatures T_0 were at room temperature (22 ± 6 °C). In the present study, we focused particularly on two parameters of the mixture. One was the characteristic length of detonation, and the other was detonation stability. The characteristic length of detonation was varied by controlling the initial pressure of the mixture; the detonation stability was varied by controlling the argon mole fraction of the mixture.

Table 1: Experimental conditions

	Mixture	y_{Ar} (%)	l_c (mm)
E1	$\text{C}_2\text{H}_4 + 3\text{O}_2/\text{Ar}$	0	10, 20
E2		50	10
E3		67	10
E4		75	10

3 Results and Discussion

Figure 2 (a) shows a typical example of sequential schlieren photographs obtained for a supercritical case in the E1 mixture; figure 2 (b) shows corresponding illustrations. Before Figure 2 (a-1), a detonation wave reached to a wider space and partly decoupled in the vicinity of the horizontal wall; then, a transverse detonation was re-initiated at a point apart from the vertical wall in the same manner as described in Reference [5]. In Figure 2 (a-1), the transverse detonation wave approaches to the horizontal wall. In Figure 2 (a-2), the transverse detonation wave just reaches to the horizontal wall. In Figure 2 (a-3), the transverse detonation wave has been reflected by the horizontal wall. In the course of this reflection process, a reflection point distance l_c is defined as shown in Figure 2 (b-2). Namely, the reflection point distance is defined as a distance from the corner of the end of the inlet channel to the intersection point among the transverse detonation wave front, the vertical shock and the horizontal wall.

Here, the reflection point distance should be essentially defined in a system with an infinitely wide donor channel. In such an ideal system, there is no length scale characterizing the geometry, and thus, the features of the flow field are determined based only on physical and chemical properties intrinsic to the mixture [8]. That is, in such a system, the reflection point distance can be a characteristic length manifesting a property of the detonable mixture.

In the present experiment, the channel width is, of course, finite, and thus, the vertical wall of the channel affects the flow field by reflecting transverse waves of the detonation wave and the rarefaction waves generated at the corner of the channel. However, by using a wide enough donor channel compared to the transverse wave spacing of the detonation wave, influence of the physical boundary is expected to be suppressed. In actuality, it has also been known that the reflection point distance well correlates with the detonation cell width [9–11], which is another characteristic length scale of detonation. Hence, at high initial pressures where the transverse wave spacing is small, the reflection point distances obtained in experiments are substantially equivalent to the ideal ones, aside from the inherent variation arising from the stochastic nature of the detonation diffraction problem.

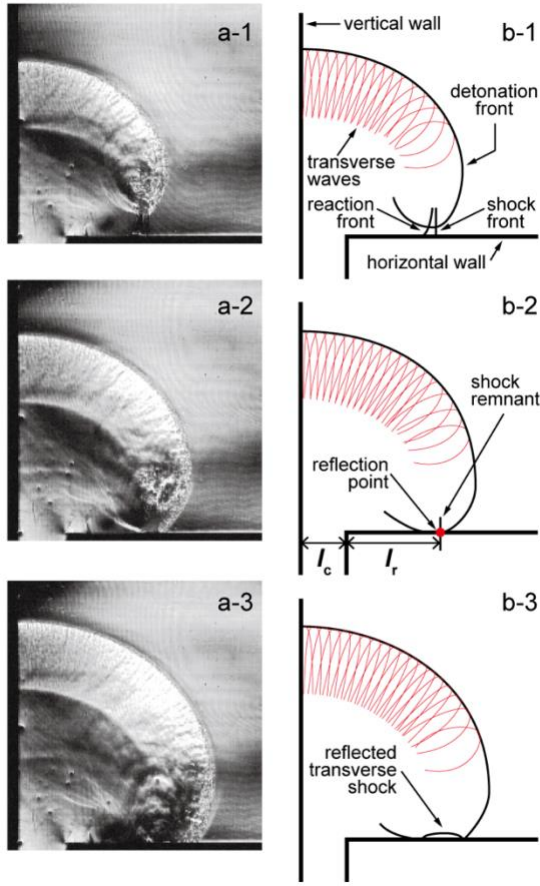
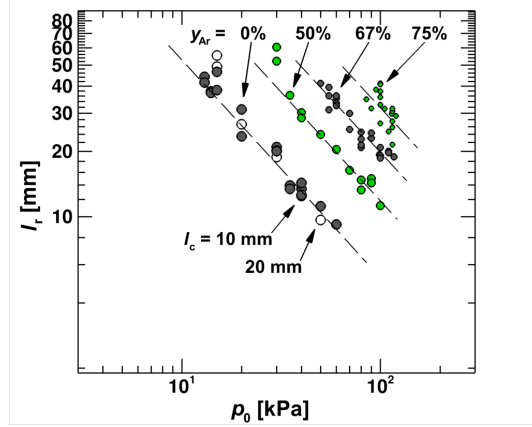
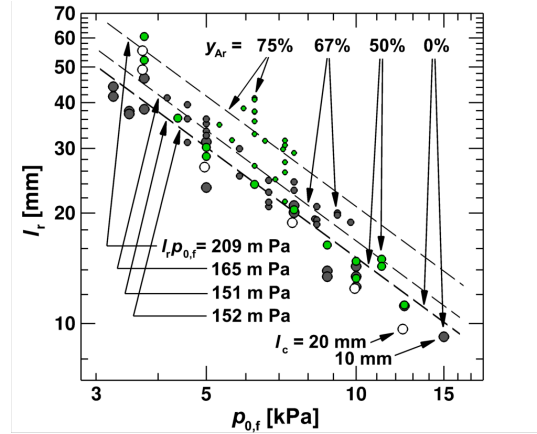


Figure 2. Typical sequences of detonation diffraction processes for $C_2H_4 + 3O_2$. (a) Schlieren photographs at frame interval = $2 \mu s$. (b) Schematic illustrations.



(a) Reflection point distance l_r versus initial pressure p_0



(b) Reflection point distance l_r versus initial fuel pressure $p_{0,f}$

Figure 3. Characteristics of reflection point distance [7]. Solid and open symbols are for 10 mm and 20 mm wide channel, respectively. Smaller symbols are for more diluted mixtures.

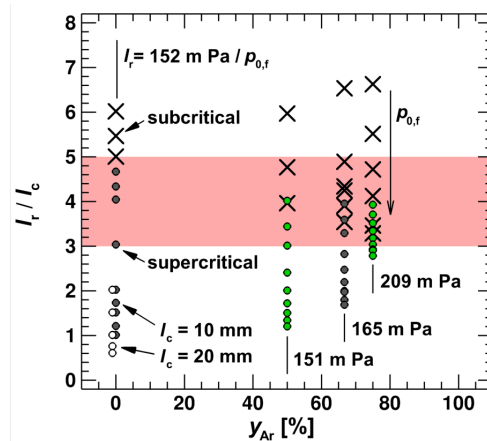


Figure 4. Length ratio l_r/l_c versus argon mole fraction y_{Ar} . [7].

Figure 3 (a) shows the reflection point distance as a function of the initial pressure for the ethylene–oxygen mixtures (E1–E4) with different argon dilution ratio. The dashed auxiliary lines indicate inversely proportional relations as an aid in visualization. As shown in the figure, the reflection point distance is inversely proportional to the initial pressure particularly at high pressures where transverse wave spacings are well smaller than the channel width. For higher argon dilution ratio, the reflection point distance is greater. Figure 3 (b) shows reflection point distance as a function of the partial pressure of the fuel. As shown in the figure, the correlations between the reflection point distance and the initial partial pressure of fuel are very similar regardless of the argon mole fraction. In the figure, inversely proportional curves fitted to the experimental results by the least mean square method are also shown with dashed lines. Note that the fitting was performed selectively for data at high initial pressures ($l_r/l_c < 4$).

In Figure 4, the ratios of re-evaluated reflection point distance to the channel width, l_r/l_c , are plotted against the argon mole fraction y_{Ar} for the ethylene mixtures (E1–E4). The circles correspond to supercritical diffraction. The reflection point distance l_r was re-evaluated by using the fitted curves shown in Figure 3 (b). That is, for a given initial partial pressure of fuel, each data point is given through a calculation using the corresponding fitted curve. Note that data points were given also for the subcritical cases at relatively low initial pressures, where re-initiation does not occur in reality, by extrapolation from data at high initial pressures, because ideally, the reflection point distance is suggested to be roughly inversely proportional to the initial pressure as described above. In Figure 4, the data points extrapolated for subcritical cases are indicated by $\times$ -mark symbols. When the channel width is decreased gradually under certain mixture conditions, detonation transmission from the channel to unconfined space will fail at some point. Then, that channel width is the critical width for those mixture conditions. Here, by analogy from the cell width, the critical channel width is expected to be generalized by making it a dimensionless quantity with the use of the ideal reflection point distance, which can serve as a characteristic length of the mixture as described above. Thus, in this study, critical condition is given by the ratio of ideal reflection point distance to the channel width, l_r/l_c . If we assume that the critical conditions $(l_r/l_c)_{crit}$ lie in a range of 3–5, which is shown by a shaded band in Figure 5, for all the ethylene mixtures with different argon mole fractions, the results shown in Figure 4 are consistent with the assumption because the critical value of the ratio l_r/l_c is thought to exist between the largest value of the ratio l_r/l_c in the supercritical cases and the smallest value of the ratio l_r/l_c in the subcritical cases, whether the outcome overlaps or not. The critical condition may also vary $(l_r/l_c)_{crit}$ with the argon mole fraction. However, the dependence of the critical condition on the stability cannot be deduced clearly only from the results obtained in this study, although the dependence is potentially small. Note that above discussion is also applicable for the results in the acetylene–oxygen mixtures.

4 Conclusions

For stoichiometric $C_2H_4-O_2$ mixtures with or without Ar dilution, the processes of detonation diffraction have been investigated in a two-dimensional setup through high-speed schlieren imaging with variations of characteristic length and detonation stability by regulating the initial pressure and argon mole fraction of the mixture. In supercritical cases, reflection point distances of the transverse detonation on the end face of the donor channel were particularly deduced from the obtained sequential schlieren images and analyzed. The reflection point distance can be idealized for the infinitely wide donor channel because of the absence of a length scale characterizing the geometric setup of this problem, and thus, it can be a parameter in which properties intrinsic to each detonable mixture are manifested. We draw the following conclusions.

The reflection point distance was roughly inversely proportional to the initial pressure for identical mixtures and independent of the width of the donor channel at high initial pressures. For a certain combination of the fuel and oxidizer, correlations between the reflection point distance and the initial partial pressure of fuel

were very similar regardless of the argon mole fraction. Critical conditions of the diffraction problem could be given for the ratio of the reflection point distance to the channel width, and it was suggested that the critical value lies in a range of 3–5 and does not significantly depend on the stability of the mixture.

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