The Transmission Behavior of the Over-driven Detonation across the Mixture with the Abrupt Area Change

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1 Introduction

Pulse detonation engine (PDE) has attracted many researchers and engineers' eyes due to the very high thermal efficiency brought from the nature of the constant-volume combustion of the detonation. For the practical concern, the oxidizer used by the PDE should be air from the atmosphere but not the pure oxygen from the PDE itself. This is because the burning with pure oxygen will reduce the overall Isp[1]. However, detonation is more like to be generated by burning with the pure oxygen. In view of this, one of the most popular designs of the PDE is proposed with the concept of the 'predetonator'. The pre-detonator has the much smaller size than the PDE combustor and is mounted at the head end of the main combustor. In the smaller chamber, the oxygen and fuel is filled in order to generate the detonation easily and fast until the wave enters the main combustor so that the detonation in the main combustor is 'ignited' at the head in the beginning. This concept can save much more oxygen carried by the PDE. Unfortunately, this size of the pre-detonator can not be reduced to as small as possible. This is due to the diffraction problem.

Many researches had explored the field of the detonation diffraction, and one of the most popular criteria is that the smallest detonation tube diameter where a abrupt area change sited is thirteen times of the detonation cell width [2][3]. An entering over-driven detonation can modify the diffraction situation therefore the limiting tube diameter can be further reduced [4]. And also, the cell sizes will become smaller as the degree of overdriven increase. However, these thumbs of rules can only be applied to the detonation chamber with one kind of mixture because one critical diameter is for one specific mixture. Several researches are also studied for the detonation transmission from high sensitive mixture to low sensitive one [5] or use this kind of technique to generate a detonation wave for a low sensitive mixture [6]. Our previous study also showed the advantages while letting the overdriven detonation transmit to another mixture [7]. Some experiments also use the high sensitive mixture in smaller tube to investigate the ignition of detonation of the less sensitive mixture [8][9]. In the Schultz's work, a propane/oxygen CJ detonation from the small tube (38mm) transmit to propane/oxygen/nitrogen mixture, and they found that in such case, the successful transmission can not be obtained until the oxygen fraction of air excess to 57%. Although the critical condition is sensitive to geometry of the donor, at some conditions, the geometry of the acceptor will influence the diffraction behavior, such as re-ignition and Mach reflection from the wall [10]. In view of this, it is interesting to see what the benefit that it can bring to help the diffraction be successful on the case that the overdriven detonation from a small tube transmits to little larger tubes.

In this study, we would like investigate the propagation behavior of the over-driven detonation transmitting through the interface of the mixture varying and area changing in a small d/d circular tubes system. For mixture varying, the donor section is filled with fuel rich propane/oxygen mixture whereas the propane/oxygen/nitrogen mixture filled in the acceptor. Further, we also find the limiting condition for successful transmission of the detonation.

2 Experiment set-up

In the the experiment, the 25.4mm (i.d.) tube as a donor is connected to the 50.8mm (i.d.) tube as a acceptor. For the considering of changing the degree of overdriven, the donor is assembled by several rings whose length is also the inner diameter in order to make the tube length variable. Propane, oxygen and nitrogen are filling in the tubes separately and controlled by the method of partial pressure. The definition of nitrogen dilution in this paper is the ratio of nitrogen to the sum of the dilution and oxidant (i.e. nitrogen and oxygen). It is convenient to compare with the composition of the air whose dilution of nitrogen is 79%. To ensure the homogeneity of the mixtures, two circulation pumps circulate the mixtures in the donor and acceptor, respectively. An electric spark is installed at the end of the donor. The 30µm thickness Mylar is used to separate the donor from the acceptor. For the reasons of reducing the delay behavior of the Mylar diaphragm when the detonation transmit across it [11], the thickness of the Mylar is prefer as thin as possible. However, the strength problems will occur in the filling process as the Mylar become thinner. Due to the previous works, this thickness is appropriate for the experiment. For the abrupt expansion case, a special geometry near the interface is shown in the Fig.1 and its purpose is to make sure that the interface dimension of the detonation transmission is exactly the size of the donor. According to the author's experience, the broken slice of the Mylar after one shot will entirely the size of the acceptor (i.e. 50.8mm) without this geometry. In other words, the detonation transmission will be influenced by the Mylar even more.

Pressure transducers are used for monitoring the wave velocity and movement. Two pressure transducers and one ion probe is installed at the station near the exit of the acceptor and used to double check the onset of the detonation. Soot foils are also used to investigate the behavior of the detonation transmission and diffraction. The soot foils are made of aluminum plate (590mm×120mm) and scrolled in the acceptor.

3 Results and discussion

The equivalence ratio of the donor in this study is ranging from 1.4~1.8 because the minimum DDT induction distance is observed in the fuel-rich range in the previous study [12]. The selection of the acceptor mixture is slightly fuel-rich because the critical energy is also near the valley of the Vshape critical energy curve around the slight fuel-rich [13]. In Fig.2, two velocity determined by the three pressure transducers indicate the process before the development of the overdriven. When the overdriven detonation enters the diaphragm, the wave velocity decreases about two factors and then accelerates to the CJ state. It is noticed here that the non-dimensional velocity at the diaphragm is defined by the average of the two CJ velocities. Also, due to the delay time while wave passing through the diaphragm, this value is not analyzed in the present study. In the case of 60% dilution of the nitrogen, the detonation transmission is successful in all runs. However, there are three mainly modes of detonation transmission. The first is the rapidly onset of the over-driven detonation measured by two pressure transducer behind the diaphragm. The second mode is that the incident wave accelerates to slight overdriven detonation wave. The third mode indicate the incident wave propagate for a while and then transit to CJ detonation by a possible local explosion. This process can be observed by the pressure time trace plot shown in the Fig.3. The pressure trace of A3 in the C mode is found with a overshooting behind the incident shock wave. After the A3 signal, the wave velocity

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climbs to CJ state. When the dilution is increasing to 67.5%, the detonation transmission seems to be unstable, and the failure of detonation occurs. From the experiment results, we can know that the successful detonation transmission never occurs when the dilution increases to 70%. Fig.4 shows the variation of degree of overdriven at different length of donors in the range from 50% to 30% nitrogen dilution. It can be seen that the longer donor create lower degree of over-driven whereas the short donor create wide range of overdriven degree. This is possibly that the shorter length is much close to the induction distance of DDT. Generally, the degree of overdriven in the acceptor increase with the increasing of degree in the donor. Some data apart from the trend are the cases of lower dilution. In the lower dilution case, the low overdriven degree even create very high overdriven.

The detonation diffraction through the mixture interface is not a common problem comparison to the continuous mixture. This is possibly due to the delay problem coming from the material of the diaphragm and the interface of the two mixtures of different sensitivity. A typical super-critical diffraction is a continuous transmission of detonation. In the other way, the critical case describes the decoupling of shock wave and reaction front. That is, a temporal break-down of the detonation transmission will occur before the re-ignition happens somewhere. A temporal situation also occurs in the case of having diaphragm and mixture interface. In this study, although the Mylar thickness is chosen as thin as possible, the delay problem still plays some roles on the transmission. In the results of the soot foil, we observe by the soot foil that continuous propagation does not occur even the dilution of nitrogen is 26%. The soot foil is shown in the Fig.5, the saw-toothed wave front explains the highly multi-dimensional structure of detonation diffraction especially in a highly confine space. (i.e. the acceptor dimension is twice about the donor dimension). This wave front is composed of reflected shock wave and trace of triple point. The similar results are also shown in the paper [9]. The study discovers that the overdriven detonation almost start from the point of two triple point line. The phenomena can be explained by the similarly of the re-ignition process at the end of a detonation cell. In the highly oxygen-rich case, the starting points seem to be many but not only one. So there are several overdriven detonation strips and they can be seen by the very small detonation cells in these strips. The characteristic feature of nose shape is found at the highly dilution case. This can be seen in the Fig.5 and the nose shape become flat as the dilution is increasing. Although the nose becomes flat, the smallest cells are still located in the apex of the nose. Because the re-ignition point can be identified so the length of the pre-detonation can be defined. Besides, the length of the pre-detonation is also an important parameter of designing the PDE. The shorter the pre-detonation length, the volume of the combustor wasted less. In the Fig.6, the pre-detonation length increase with the nitrogen dilution and the higher overdriven degree has shorter pre-length than the lower overdriven degree.

4 Concluding remark

This work performs the experimental study of the detonation transmission across the mixture and the interface of the abrupt area change in a highly confined acceptor. Results show that the overdriven detonation can induce higher transmitted overdriven detonation. The limiting nitrogen dilution is about 67.5%. Three transmission modes are mainly discussed. The first mode is that the transmission detonation via a highly overdriven detonation. The second mode is that the overdriven degree is much slight and accelerates to CJ state and the overdriven delay to occur in the third mode. The soot foils show good structures of the detonation transmission and the pre-detonation length is also defined to plot with the dilution of nitrogen.







Figure 2. Non-dimensional wave velocity to the location from the diaphragm



Figure 3. Pressure trace at three different transmission modes



Figure 4. Variation of degree of overdriven in acceptor with different length of donors



(c) Figure 5. Soot foil results: (a) 25% dilution of nitrogen, ER=1.2 (b) 50% dilution of nitrogen, ER=1.2 (c) 60% dilution of nitrogen, ER=1.2



Figure 6. The relations between pre-detonation length and dilution of nitrogen

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