Effect of Vortex Flow on Characteristics of Deflagration-to-Detonation Transition

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1. Introduction

The pulse detonation engines (PDEs) do not require a sophisticated and expansive compressor and turbo pump machinery, and have a simple, compact design in contrast to many existing jet engine concepts. PDEs also have a high pressure ratio and burning velocity of the detonation wave, thus, their thermal efficiency considerably exceeds that of a Brayton cycle gas turbine [1-3]. Therefore, the pulse detonation engine (PDE) is expected to be a new type of power sources for aerospace vehicles and electric generators.

A problem for application of PDEs is the need to shorten the distance of the deflagration-to-detonation transition (the DDT distance) which is very important for realizing high PDE performance. In general, a predetonator was used to control the characteristics of DDT [1,2]. However, advantages of PDEs, such as their simplicity and low weight, are lost if devices such as a predetonator and an igniter are added. To control the DDT distance without additional ignition energy and sophisticated, heavy structures such as predetonators, we attempted to apply the vortex flow (VF) injection concept to the injection part of a PDE, because the flame can propagate very fast in a VF depending on the rotating velocity [4,5]. In this study, a very strong vortex flow field of the mixture was established in the detonation tube, and the effects of the characteristics of rapid flame propagation and rotating velocity in the VF on the characteristics of DDT were examined.

2. Experimental apparatus

Figure 1 shows a schematic of the experimental setup, including the gas supply and exhaust systems, ignition system, and measurement system. The mixture supplied into the detonation tube is ignited by the igniter installed at the closed end of the tube. Detonation propagates in the tube, and the burned gas is exhausted into the dump tank. The detonation propagation process was observed using ten pressure transducers and ion probes located at 200-mm intervals. The burned gas was swept by air supplied from the compressor after each detonation had propagated.

Figures 2 shows the schematic structure of the VF injector. In the VF injector, fuel and oxidizer are supplied from the circumferential direction of the mixer tube, where they are mixed. Many protuberances are placed inside the mixer tube to promote mixing of the fuel and oxidizer. The mixture is injected into the detonation tube from the circumferential direction of the detonation tube. Then, a VF field is established in the detonation tube. On the other hand, in the CF injector, which

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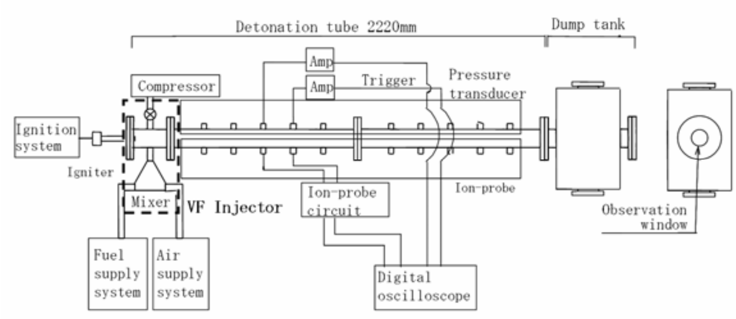

Figure 1 Schematic of experimental setup

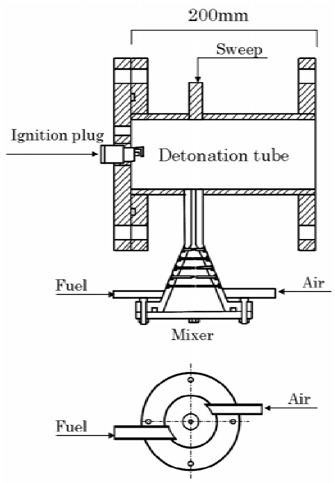

Figure 2 Vortex-flow-type injector

has no mixer part, the fuel and oxidizer are supplied directly into the detonation tube from the counter direction of the tube and mixed in the detonation tube. Hydrogen and air are used as fuel and oxidizer, respectively.

3. Experimental results and discussion

Figure 3 shows the Neumann spike pressure ratio p_N/p_0 when the vortex flow-type (VF) and counterflow-type (CF) of injection and the rotating velocity V_θ are varied. Here, p_N and p_0 are the Neumann spike pressure and the initial pressure. The ordinate and the abscissa describe the pressure ratio p_N/p_0 and the distance x from the closed end of the detonation tube, respectively. The values of p_N/p_0 at x = 330 mm vary widely due to the Shchelkin wire which is inserted in the position between x = 0 and 420 mm. The influence of the Shchelkin wire is particularly evident in the results for the VF injector. We assume that the turbulence produced by the Shchelkin wire is promoted in VF, and large scattering appears in the pressure values. Clearly, the pressure in VF reaches the theoretical Neumann spike pressure $p_{NC\text{-}J}$ early compared with that in CF, and reaches it earlier as V_θ increases. However, the pressure fluctuations appear again in the process of DDT as V_θ is further increased (V_θ › 131 m/s). Then, the DDT distance becomes again longer. It seems that the turbulence generally promotes acceleration of flame propagation, but local extinction may occur in the very strong turbulence so that DDT is deterred by the very strong turbulence in a high rotating velocity. The distances for reaching $p_{NC\text{-}J}$ are 1130-1350 mm (V_θ=318 m/s), 1130-1350 mm (V_θ=255 m/s), 530-930 mm (V_θ=131 m/s), 930-1130 mm (V_θ=92 m/s), 1130-1550 mm (V_θ=23 m/s), and 1350-1550 mm (CF).

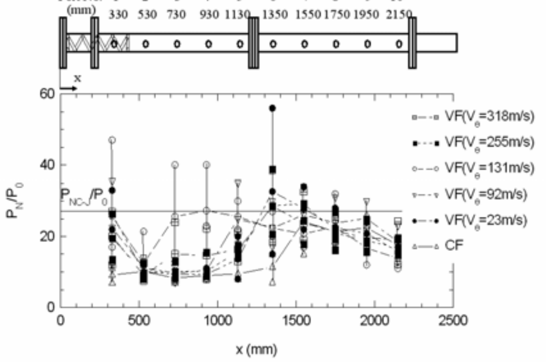

Figure 3 Neumann spike pressure

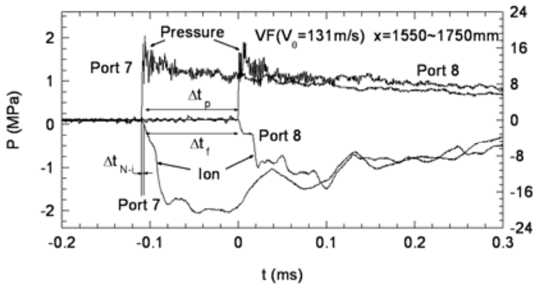

Figure 4 Pressure and ionization current signals at two ports adjacent to each other

Figure 4 shows the pressure and ionization current signals at two ports adjacent to each other. Δt_p, Δt_f and $\Delta t_{N\text{-}i}$ give the time lags between the arrival times of the shock wave, the flame and between the arrival times of the shock wave and the flame at the two ports adjacent to each other. The propagation velocity V_p of the shock wave was calculated from the distance between the two adjacent ports and the time lag Δt_p between the arrival times of the shock wave at the two ports.

Figure 5 shows the propagation velocity V_p of the shock wave. After ignition, the shock wave propagates at about V_p = 1000 m/s in both VF and CF injectors, after which the propagation velocity rapidly reaches the theoretical propagation velocity $V_{pC\text{-}J}$, which is calculated using the program presented by Tanaka [6]. From these results, we can estimate the distances for DDT to be 1130-1350 mm (V_θ=318 m/s), 1130-1350 mm (V_θ=255 m/s), 730-930 mm (V_θ= 131 m/s), 930-1350 mm (V_θ= 92 m/s), 1130-1350 mm (V_θ= 23 m/s), and 1350-1750 mm (CF). The distances for DDT shown in Fig. 5 are nearly the same as those shown in Fig.3. We can estimate the DDT distance from the results of the pressure and propagation velocity of the shock wave, as shown in Figs. 3 and 5. However, to determine the actual DDT distance, we need to consider whether the shock wave and the flame are unified, namely whether a fully developed detonation forms.

Figure 6 shows the flame velocity V_f calculated from the distance between two ports and the time lag Δt_f between the arrival times of the flame at the two ports adjacent to each other. From this figure, we can estimate the distances for DDT to be 1130-1350 mm (V_θ=318 m/s), 1130-1350 mm (V_θ=255 m/s), 730-930 mm (V_θ= 131 m/s), 930-1130 mm (V_θ= 92 m/s), 1130-1350 mm (V_θ= 23 m/s), and 1350-1550 mm (CF).

The time lag $\Delta t_{N\text{-}i}$ between the arrival times of the shock wave and the flame in each port is also shown in Fig. 7. We can also observe that the flame first propagates far a short distance from the shock wave and is established just behind the shock wave. Then, the flame propagates with the shock wave, again separating from the shock wave near the open end of the tube. Therefore, we can estimate

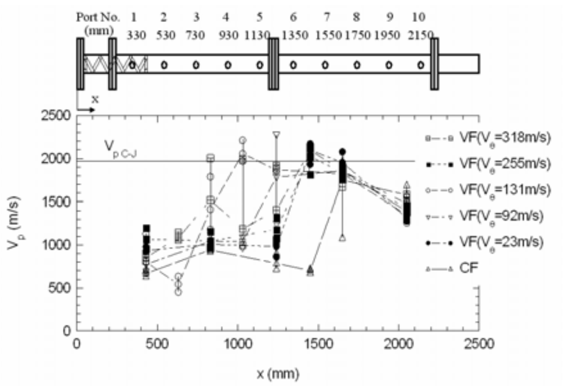

Figure 5 Propagation velocity of shock wave

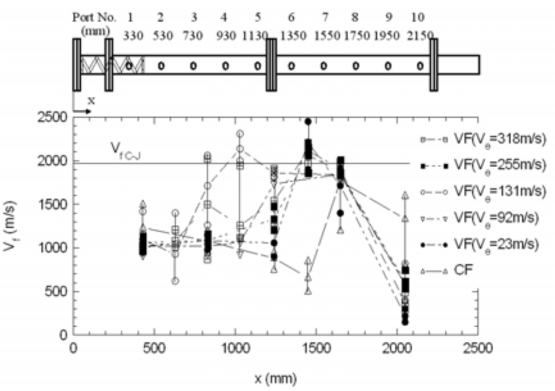

Figure 6 Flame velocity

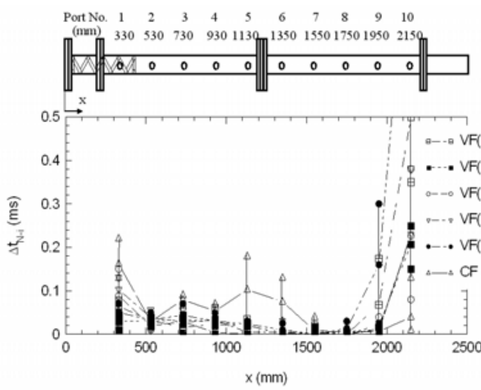

Figure 7 Time lags between arrival times of shock wave and flame

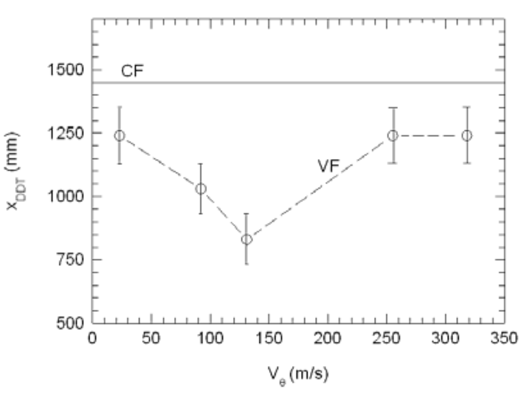

Figure 8 DDT distances based on Figs. 3-6

the DDT distances from these results to be 1130-1350 mm (V_θ=318 m/s), 1130-1350 mm (V_θ=255 m/s), 730-930 mm (V_θ= 131 m/s), 930-1130 mm (V_θ= 92 m/s), 1130-1350 mm (V_θ= 23 m/s), and 1350 -1550 mm (CF).

Figure 8 shows the DDT distance x_{DDT} obtained from the results shown in Figs. 3 – 6. x_{DDT} is the distance till the shock wave with the flame transits to C-J detonation, which is considered to be the steadily propagated detonation. The distances for DDT in a VF-type injector are decreased by 15-56 % compared with that in the CF-type injector. The degree of mixing between fuel and oxidizer, energy supplied by the igniter, and turbulence produced by the Shchelkin wire generally affect the DDT distance in a PDE, if fuel/oxidizer and equivalence ratio are the same. The fuel and air are premixed before supplying into the detonation tube in the VF injector but not in the CF injector. Thus, we can estimate the effect of premixing on x_{DDT} from extrapolating the value of x_{DDT} by approaching V_θ to 0 m/s. The effect of premixing on x_{DDT} is limited to a decrease of only about 10 % in the DDT distance of the CF-type injector. On the other hand, x_{DDT} in V_θ = 131 m/s is decreased by about 46 % of x_{DDT} in V_θ = 23 m/s. The shortening of the DDT distance becomes remarkable as the rotating velocity induced by the VF increases. The degree of premixing in the VF injectors with V_θ= 131 m/s and with V_θ= 23 m/s is similar, so difference in the rotating velocity must substantially shorten the DDT distance. The expected effects in the VF injector were obtained when the rotating velocity was increased. Thus, it is possible to realize a simple PDE without additional ignition energy or sophisticated, heavy structures such as predetonators, if a VF injector is used. In the cases of V_θ=318 and 255 m/s, however, the effect of the rotating velocity on shortening of DDT is deterred. It seems that the local extinction in the detonation tube may be occurred by the very strong turbulence in a high rotating velocity so that the DDT distance becomes again long.

4. Conclusions

(1) When the VF-type injector is used, the DDT distance is shortened by 15-56 % compared with that of the CF-type injector. The shortening effect becomes remarkable as the rotating velocity induced by the VF injector is increased.

(2) The effect of the rotating velocity on shortening of DDT is deterred in the very strong turbulence due to the local extinction.

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