Propagation of Detonation in a Combustible Supersonic Flow

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1 Introduction

Recently propulsion systems using detonation have been intensively studied because of their simple construction and high thermal efficiency. From their working principles they can be classified into two groups. One is a pulse detonation engine (PDE) in which detonation is initiated repeatedly in a combustor. The other is a standing detonation engine (SDE) in which detonation is stabilized toward a supersonic flow in a combustor. SDE is expected to be operated in hypersonic flight [1] and its performance, which is compared to that of PDE and scramjet engines, has been analyzed [2].

There are two tasks to realize SDE on the ground experiment. The first one is generation of a combustible supersonic flow that balances a propagation velocity of detonation. The second one is initiation of detonation in a supersonic flow. As for the first task, Terao et al. [1] used a shock tube for acceleration of a combustible gas and it was confirmed detonation decelerates in an opposed supersonic flow. Vasil'ev et al [3] reported that the apparent propagation velocity of detonation in a combustible supersonic flow is different from the CJ velocity. On the second task, a few studies have been made using a supersonic flow [4], although detonation initiation in a quiescent mixture has been investigated by many researchers.

2 Experimental apparatus

Experiments were performed in a detonation tube combined with a shock tube as shown in Fig. 1. The whole tube consists of a 3030 mm high pressure section, a 3030 mm low pressure section, a 620 mm test section, a 3030 mm dumping section, and an 530 mm initiation tube. The high pressure section is a circular tube of an inner diameter of 50 mm and the rest sections except the initiation tube have a 40 mm \times 20 mm rectangular cross section. The initiation tube, which was connected to the test section, has an inner diameter of 16 mm. Schematic of test section is shown in Fig. 2. The test section has 5 mounting holes on the upper-wall for pressure transducers of P1~P5 and one of them is replaced by the initiation tube according to the test condition. The high pressure section and the low pressure section were separated by a diagraph of aluminum and a thin diagraph made of PET is inserted between the test section and the initiation tube. Soot was coated on the test section sidewall.

Properties of the supersonic flow in the present experiment is shown in table 1, where. P,T, M denote static pressure, static temperature, and Mach number, respectively. Test time is 0.5 ms, which is half of the calculated value by KASIMIR [5]. A stoichiometric oxyhydrogen was charged in the low pressure section, the test section, the dumping section and the initiation tube at desired pressure. Helium was introduced in the high pressure section for a driver gas. The initial pressure in the initiation tube was 100 kPa.

In operation, an incident shock wave is generated by rupture of the diaphragm between the high and low pressure section so that a flow of combustible mixture can be obtained behind the incident shock wave. The flow

becomes supersonic with Mach number of 1.2 in the coordinate fixed to the tube, when Mach number of the incident shock wave is 2.4. Then spark discharge, which is synchronous with generation of the incident shock wave, was made at the end of the initiation tube to ignite a mixture inside it. After DDT process, detonation is initiated and travels in the initiation tube. It breaks the diaphragm set between the test section and the initiation tube and intrudes into the test section. Although a part of the detonation front decays due to rarefaction waves, it diffracts and reflects at the wall of the test section. Finally the detonation front is re-initiated, propagating in both upstream and downstream directions.

Arrival of the incident shock wave and propagation behavior of detonation are monitored by conventional pressure transducers (PCB 113A24 and 113A26). Variation of cellular structure near the exit of the initiation tube was recorded by coating soot on the surface of a side wall of the test section.



Fig. 2 Schematic of test section. Dimension in mm.

3 Detonation velocity

Figure 3 shows measured velocity of the combustible supersonic flow U, detonation propagating upstream V_{UP} and downstream V_{DOWN} . U was calculated from velocity of the incident shock wave and CJ velocity V_{CJ} was calculated by AISTJAN [6]. From Fig. 3 it is confirmed that apparent velocity of detonation in a supersonic flow is faster or slower than V_{CJ} by the velocity of combustible supersonic flow. Figure 3 indicates that V_{CJ} - U of 1790 m/s agrees well with V_{UP} of 1800 m/s. This is also the case with the detonation propagating downstream, since V_{UP} of 3700 m/s coincides with $V_{\text{UP}} + U$ of 3710 m/s.

4 Cellular structure

Figure 4 shows smoked records of the test section 320 mm upstream and downstream from the initiation tube. Apparently cellular structure is deformed by existence of the supersonic flow. While the cell seems to shrink for detonation propagating upstream in Fig. 4 (a), it is stretched along the flow direction for detonation propagating downstream Fig. 4 (b). From Fig.4 cell width W and cell length L are obtained as shown in Table 2. Aspect ratio of cellular structure L/W was larger in the downstream area from the initiation tube than in the upstream. It was assumed that the velocity of triple point moving downstream what is parallel with a combustible supersonic flow was faster than upstream that. It showed the same trend of detonation's velocity in Fig. 3.



Fig. 3 Measured speed of detonation and combustible flow. *U*: speed of conbustible supersonic flow; V_{UP} : speed of detonation propagating upstream; V_{CJ} : speed of the CJ-detonation; V_{DOWN} : speed of detonation propagating downstream.

Table 2 Measured cell size and aspect

W

[mm]

2.4

2.1

Upstream

Downstream

L

[mm]

3.0

4.8

L/W

1.3

2.3

ratio. W: cell width ; L: cell length.





(b) 320mm downstream from the initiation tube

Fig. 4 Smoked records of upstream and downstream.



Fig. 5 Comparison between calculated aspect ratio L/W and experimental one.

Such the deformation of cellular structure can be explained by movement of triple points. Generally shape of detonation cell is determined by velocities of a detonation front and of a transverse wave [6]. It was appeared as follows in a combustible supersonic flow what is parallel with the direction of detonation propagation. From

the fact that W shows almost the same value in the upstream and downstream area, the following assumptions can be made.

1. A velocity of transverse wave is not affected by the supersonic flow and is kept constant.

2. A propagation velocity of detonation relative to the supersonic flow is V_{CJ} .

Since cellular structure is a record on the coordinate fixed to the test section, L/W can be estimated by the following equation.

$$\frac{L}{W} = \frac{V_{\rm CJ} \pm U}{U_{\rm T}},\tag{1}$$

where $U_{\rm T}$ is a velocity of transverse wave ($U_{\rm T} = M_{\rm T} \times c_1$), $M_{\rm T}$ is a Mach number of transverse wave, and c_1 is a speed of sound just behind the shock wave consisting of detonation front. Assuming that $M_{\rm T}$ is 1.4 [7], relationship between L/W and $V_{\rm CJ} \pm U$ is obtained as shown in Fig. 5. Comparison of calculated values with experimental one indicates good agreement.

5 Conclusions

- 1. Apparent velocity of detonation in a supersonic flow is faster in the upstream area and slower in the downstream than V_{CJ} by speed of the supersonic flow.
- 2. Calculated values of L/W agrees well with experimental one on the assumption that velocity of the transverse wave is not affected by the supersonic flow.

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