Behavior of Detonations Passing through Reflection Nozzles*

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Interaction between detonation and Prandtl-Meyer expansion is an interesting problem to be solved in connection with the disappearance or continuance of the fish-scale pattern. In this study, seven kinds of reflection nozzles were utilized in order to produce the Prandtl-Meyer expansion effects at various levels. Stability and behavior of a detonation propagating in a reflection nozzle attached to a parallel channel part were experimentally observed with the initial pressure as a parameter using optical measurement methods such as open-shutter and schlieren photographic techniques. It was found that in the case of a nozzle at the half-vertical angle of $A=18$ degrees without the throat length, an initial pressure of at least 5.3 kPa is necessary to sustain detonation configuration during passage through this nozzle.

Key Words: Detonation, Reflection Nozzle, Prandtl-Meyer Expansion, Triple Shock Wave, Shock Diffraction, Quenching, Fish-Scale Pattern, Propagation Velocity

1. Introduction

As a fundamental study to obtain stable converging detonations in a double-disc-type detonation chamber, the behavior of detonations turning corners with various shapes was investigated in the previous work⁽¹⁾. When a detonation propagates in a channel with a right-angle bend, at the vicinity of the inner corner, a region with fish-scale pattern due to radiating trajectories of characteristic triple-shock waves of detonation disappears, a strong band-emission region occurs downstream immediately behind the above region, and in the neighborhood of it, and a fish-scale pattern region, which indicates reestablishment of detonation configuration, was experimentally observed.

The main mechanism behind the disappearance of the detonation configuration near corners such as this

is the interference between the detonation and the strong nonsteady Prandtl-Meyer expansion arising from the inner corner. This interference leads to the collapse of a coupled state of a shock front and a chemical reaction front which originally forms the configuration of a self-sustained detonation. That is, under a strong expansion effect, the temperature behind the shock front in the detonation decreases and as a result, the initiation of the chemical reaction is delayed. These phenomena introduce not only the delay of the chemical energy supply to the shock front but also the decay of the shock strength due to insufficient supply of energy. In addition, the decay of shock strength leads to the temperature decrease in the region behind the shock. As the above processes are repeated, the influence of interference becomes much more marked together with detonation propagation. As a result, space separation between the shock wave front and the chemical reaction front takes place continuously, the triple shock structure existing with transverse waves collapses, and finally disappearance of the fish-scale pattern occurs.

On the other hand, it is considered that the cause of the reestablishment of detonation occurring at

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positions downstream from the corner is local explosion which is induced by satisfying the detonation conditions in the interference processes between a reflected shock wave produced by collision of a part of the detonation front to the outer corner wall and a decaying detonation front diffracting the inner corner.

Today, in buildings under construction and underground shopping malls, various ducts with tubes for gas supply run in all directions. Gas explosion due to leakage of combustible gases into such ducts and spaces which are not in use has often brought about great damage. Therefore, it is considered that the above-mentioned fundamental studies on quenching and reestablishment of detonations are extremely important not only from the phenomenological point of view but also from the viewpoint of safety engineering. There seem to be only a few studies that treat the stability of detonation in connection with the Prandtl-Meyer expansion.

In this study, the stability of detonation under the interference of a nonsteady Prandtl-Meyer expansion generated by means of a reflection nozzle is discussed. Aside from obtaining experimental conditions in which the detonation configuration exists, we aim to clarify by experiment what kinds of disturbances exist and how they behave in a reflection nozzle and a large parallel channel downstream of it. In order to produce the Prandtl-Meyer expansion at various levels, seven kinds of reflection nozzles were used.

2. Experiment

In Fig. 1 is shown a schematic diagram of experimental apparatus and the measurement system utilized in this study. The detonation tube is an iron tube with a rectangular section 20 mm high $\times$ 4 mm wide and about 2 500 mm long. After decreasing pressure

to below 13.3 Pa by means of a vacuum rotary pump, the detonation tube is filled with a premixed equimolar gas of oxygen and acetylene at a given initial pressure from a mixing tank. A driver detonation is produced instantaneously by the spark ignition of a plug which is attached on the tube edge wall, which becomes a test gas detonation after rupture of an aluminum diaphragm 0.1 mm thick. After a pre-run propagation distance of about 1 700 mm, the detonation enters an observation area which is composed of a nozzle with a diverging angle at a half-vertical angle of 18 to 54 degrees and a parallel channel part 50 mm wide $\times$ (80 to 130) mm long. Every channel used in the experiments is 4 mm in depth.

Optical observation of the propagation behavior of disturbances in the observation area was made by instantaneous schlieren photography with a pulse laser as a light source and open-shutter photography⁽²⁾. A trigger signal to induce the pulse laser (NEC-SLG 2018: light emission period of 20 ns at half-width) was detected from the ignition controller through the delay pulse generator. The propagation velocity of detonation in the detonation tube immediately before incidence into the observation area was measured using a digital memory scope (IWATSU-DMS-6430), universal counters (IWATSU-UC-7641) and photodetectors (HTV-S874-18K: rise time of 0.4 μ s) attached on the tube walls.

3. Experimental Results and Discussions

The properties of detonation configuration are characterized by (1) existence of a triple shock wave in which a shock wave front and a chemical reaction front are coupled in the wave front and (2) occurrence of a regular cell pattern due to radiating trajectories in stable propagation. It has been clarified from

Fig. 1 Schematic diagram of experimental apparatus and measurement system

previous works⁽¹⁾⁻⁽³⁾ that judgement of whether disturbances form detonation configuration can be made by measurement of radiating trajectories, and that the disappearance of detonation configuration is caused by interference with the strong nonsteady Prandtl-Meyer expansion.

In this study, in order to extract the nonsteady Prandtl-Meyer expansion effect, reflection nozzles were used. Figure 2 shows the shape and dimensions of the observation areas including the reflection nozzles utilized in the experiments. A denotes the half-vertical angle of a reflection nozzle, d the height of the cross section of the detonation tube and D the height of the cross section in the parallel channel of the observation area. H and L are the height and the length of the throat part of the nozzle, respectively. A detonation propagates in the detonation tube of which cross section is 20 mm high $\times$ 4 mm wide and reaches the entrance of a reflection nozzle. At this stage, only the central part (3 mm high $\times$ 4 mm wide or 5 mm high $\times$ 4 mm wide) of the detonation front enters the reflection nozzle, and the remainder of the wave front returns upstream as a reflected shock wave after collision with the entrance wall of the nozzle. On the other hand, some triple shock waves are included in the cut-off detonation front and the detonation will propagate in a combustible mixture without changing the number of triple shock waves if the cross section remains uniform.

However, the objective of this study is to clarify experimentally how a detonation behaves due to interference with the nonsteady Prandtl-Meyer expansion which is generated by enlargement of the cross section after passing through a throat part of a nozzle. Actual sizes of reflection nozzles used to realize this objective are, as shown in Fig. 2, as follows: Half-vertical angles of nozzles are 18, 30 and 54 degrees, the throat lengths are 0 and 3 mm, and the heights are 3 and 5 mm. Experiments were conducted in the initial pressure range of 4.0 kPa to 13.3 kPa using the above-mentioned nozzles.

L	0						3
H	3			5			3
A	18	30	54	18	30	18	30

$d = 20 \text{ mm}$, $D = 50 \text{ mm}$

Fig. 2 Shape of reflection nozzle used in experiment (L, H : mm, A : degree)

Figures 3(a) through (d) show typical open-shutter photographs of experimental results obtained for a combination of two different initial pressures (6.7 kPa and 12.0 kPa or 4.0 kPa and 6.7 kPa) and using two kinds of reflection nozzles. The propagation direction of detonations is from right to left. Therefore, information of disturbances propagating from the detonation tube to the observation area edge is contained in these photographs. Common observations from the two nozzles are as follows: in Figs. 3(a) and 3(c), at lower initial pressures, regular cell patterns similar to those observed in the detonation tube were not seen. These cell patterns are different from the cases at higher initial pressures. In other words, at lower initial pressures, detonations decay due to the effect of the nonsteady Prandtl-Meyer expansion and collapse as a result of difficulty of sustaining the detonation configuration.

However, it is found that in spite of the change of the tube cross section, the disturbance wave maintaining propagation without extinction of the regular cell pattern is a detonation wave, and the minimum initial pressure of a gas mixture for maintaining the detonation configuration depends upon the nozzle shape. Figures 3(b) and 3(d) show typical experimental results of propagation where the detonation

Fig. 3 Open-shutter photographs taken at various initial pressures ($P=30$: 4.0 kPa, $P=50$: 6.7 kPa, $P=90$: 12.0 kPa)

configuration is maintained regardless of interference of the nonsteady Prandtl-Meyer expansion. Except in the region near the throat part of the reflection nozzle which is connected with the edge of the detonation tube, regular cell patterns are observed entirely in the downstream for both cases, and these patterns are almost the same as those in the detonation tube.

In Table 1, experimental results showing whether detonations continue to sustain the detonation wave structure after passage through reflection nozzles are summarized for various combinations of the initial pressure and channel shape used in the experiment. The initial pressure P in the Table is expressed in Torr. Marks $\circ$ and $\bullet$ denote continuance and extinction of the detonation configuration, respectively.

On the basis of Table 1, Fig. 4 presents a plot of

Table 1 Shape of reflection nozzle and disturbance configuration in relation to initial pressure

			P							
L	A	H	30	40	50	60	70	80	90	100
0	5.4	3	$\bullet$	$\bullet$	$\bullet$	$\bullet$	$\bullet$	$\bullet$	$\bullet$	$\circ$
			$\bullet$	$\bullet$	$\bullet$	$\bullet$	$\bullet$	$\bullet$	$\bullet$	$\circ$
	3.0	5	$\bullet$	$\bullet$	$\bullet$	$\bullet$	$\bullet$	$\bullet$	$\bullet$	$\circ$
			$\bullet$	$\bullet$	$\bullet$	$\bullet$	$\bullet$	$\bullet$	$\bullet$	$\circ$
	1.8	3	$\bullet$	$\bullet$	$\bullet$	$\bullet$	$\bullet$	$\bullet$	$\bullet$	$\circ$
			$\bullet$	$\bullet$	$\bullet$	$\bullet$	$\bullet$	$\bullet$	$\bullet$	$\circ$
3	3.0	3	$\bullet$	$\bullet$	$\bullet$	$\bullet$	$\bullet$	$\bullet$	$\bullet$	$\circ$
	1.8		$\bullet$	$\bullet$	$\bullet$	$\bullet$	$\bullet$	$\bullet$	$\bullet$	$\circ$

L, H: mm, A: degree, P: (x 0.133) kPa

$\circ$: continuance of detonation configuration
 $\bullet$: extinction of detonation configuration

Fig. 4 Minimum initial pressure for maintenance of detonation configuration vs. divergent angle of nozzle ($P=40\sim 100$: 5.3~13.3 kPa)

the minimum initial pressure for maintenance of the detonation configuration versus the half-vertical angle of the nozzle. From this graph, we find that the detonation configuration is always maintained after passage through a nozzle at an initial pressure above that of the curve, but collapses at initial pressures lower than that of the curve at a given A .

It is found from these experimental results that in order to maintain the detonation configuration after passing through a reflection nozzle, the initial pressure must increase with increasing half-vertical angle of the nozzle, and at the same half-vertical angle, the initial pressure must increase with decreasing H if the length of the throat part is also taken into consideration. As the initial pressure becomes higher, the number of triple shock waves included in a detonation front increases; thus even if a half-vertical angle of a nozzle is the same, a higher initial pressure is required in order to maintain the detonation configuration. Therefore, it is suggested from these experimental findings that there is a limit in the number of triple shock waves entering a nozzle for maintenance of the detonation configuration. For example, if the height H of the throat part increases, maintenance of the detonation configuration can be achieved even at a low initial pressure. In our experiments, at least 4 triple shock waves were included at $A=18$ degrees. In the case of propagation with the detonation configuration, the propagation velocity in a parallel channel part after passage through a reflection nozzle is nearly equal to the value in a detonation tube, as can be easily assumed from the regular cell pattern obtained by an open-shutter photograph. The propagation velocity is of the order of about 2800 m/s, though being slightly different depending on the initial pressure of a gas mixture used in the experiment.

Figure 5 shows an X - T diagram that denotes the propagation behavior of flame in an observation area for the case of extinction of the detonation configuration. Measurement error for time fits into the size of the circles shown in Fig. 5. It is found from this figure that the mean propagation velocity of the flame changes from 900 m/s in the vicinity of the throat exit to 700 m/s in the parallel channel part.

Theoretical and experimental studies on transition from slow combustion to detonation were made by Oppenheim and Soloukhin⁽⁵⁾ and Soloukhin⁽⁶⁾. As an example, Oppenheim and Soloukhin have reported the initial flame velocity of 300 m/s to 400 m/s in their experiment using a gas mixture of acetylene and oxygen at the initial pressure range of 6.7 kPa to 26.7 kPa and an experimental apparatus with a rectangular cross section of 25 mm $\times$ 4 mm and length of 400 mm. Even the lowest value of 700 m/s obtained in

Fig. 5 X - T diagram denoting propagation behavior of disturbance. The initial pressure is $P_0=6.7$ kPa

Fig. 6 Instantaneous schlieren photographs ($P=50 : 6.7$ kPa)

the parallel channel part of the nozzle used in this study is much larger than their values. This is a reason why in our study (refer to Fig. 6), the flame follows a precursor wave front separated from a detonation front, and that turbulence in a flow field of flame propagation is more highly developed than that in Oppenheim and Soloukhin's flow field.

Figures 6(a) through (d) denote a series of instantaneous schlieren photographs at the initial pressure of $P_0=6.7$ kPa. The propagation configuration of Fig. 6 corresponds to that of the open-shutter photograph shown in Fig. 3(a). Although cell pattern characteristic of the propagation configuration of a detonation has not been obtained in the open-shutter photograph of Fig. 3(a), wave fronts with marked density change existing as disturbance waves, instead of a detonation front causing cell pattern and propagating in a channel, are seen in the instantaneous schlieren photographs.

Detailed observation of Fig. 6 indicates that a detonation has already separated into two arc-shaped disturbance waves in the vicinity of the nozzle entrance immediately after the reflection nozzle. This precursor wave is a shock wave front and is arc-shaped. It was reported in previous studies⁽¹⁾⁻⁽⁴⁾ that the shape of a detonation front turning a corner was similar to the case of a shock wave. The studies on diffraction of a shock wave by Skews^{(7),(8)} and the shock kinetic theory by Whitham⁽⁹⁾ are applied here. Figure 7 is a schematic which shows the shape change of a shock wave front propagating in a channel with a divergent cross section. We determine the distance l in which the entire shock wave front becomes arc-shaped under the influence of nonsteady Prandtl-

Fig. 7 Shape change of a shock wave front propagating in a divergent channel.

S_1, S_2 : starting point of curved-wave front
 M : Mach number of incident shock wave

Meyer expansion. In Fig. 7 are shown shock wave fronts at different times t_1 and t_2 , and S_1 and S_2 on wave fronts denote points at which the shock wave fronts become out-of-plumb to the channel axis. That is, these are points at which the wave fronts begin to be bent by the influence of an expansion wave arising from a corner. A line with gradient m_0 through the origin O is the trajectory of such points. A chain line at $y = H/2$ denotes the center axis of the divergent nozzle. M_w is the Mach number of shock front propagating on the nozzle wall. At time t_1 , a part of the shock wave front maintains the Mach number at the entrance of the nozzle, but at time t_2 , the segment of the wave front normal to the channel axis disappears. According to Skews' theory, m_0 of the line is a function of the incident shock Mach number M and the specific heat ratio of gas γ . Assuming $M=8.5$ and $\gamma=1.3$, $m_0=20.5$ degrees and l which the wave front moves at t_2 in the case of $H=3$ mm is about 4 mm. That is, at 4 mm from the throat exit, the shock wave front no longer has the segment normal to the channel center axis and becomes an arc-shaped wave front. It can be considered that Fig. 6(a) shows a propagation state at more advanced time than at $t=t_2$ in Fig. 7. Characteristic features shown in Figs. 6(b) through (d) are that the distance between the two wave fronts increases as they propagate downstream and that the precursor wave front has rather a surface with diffraction points than an arc-shaped surface with an almost smooth curvature after incidence onto the parallel part of the channel. The explanation for these is given below.

Figure 8 shows a typical result of numerical simulation of a detonation wave passing through a reflection nozzle⁽¹¹⁾. This example treats the case in which a detonation front of $2H_2+O_2$ gas mixture separates into a shock wave front and a chemical reaction front and the detonation wave structure collapses as it propagates downstream from the nozzle. Although the mixture assumed in the computa-

Fig. 8 Numerical simulation result due to finite difference method

tion is different from that used in the experiment, qualitative comparison with experiment is possible. The precursor shock front has diffraction points as in the experiment. From the analogy of both cases, we can consider that the precursor wave front obtained in the experiment is a shock wave, and that the diffraction points have formed triple points of shock waves decoupled with chemical reaction. Figure 9 is a plot of the behavior of such triple points obtained from instantaneous schlieren photographs of the experimental results at the initial pressure of $P_0=10.7$ kPa using the same channel as that in Fig. 6. As seen from the trajectories of the two triple points, collision angle and scattering angle before and after collision of the triple points differ from each other and are asymmetric. That is, it is found that as the angle after their collision is smaller than the angle before collision, the shock front segment existing between triple points can be accelerated forward after their interaction. Such a result shows qualitatively good agreement with the calculation results on the collision of triple points by Hayashi and Fujiwara⁽¹⁰⁾. Thus it is found that a shock wave front decoupled with chemical reaction exhibits an inherent property of a shock wave. The increase in distance between the two wave fronts observed in Figs. 6(b) through (d) is due not only to the velocity difference between the two waves but also to acceleration of the shock wave front due to the collision of triple points.

Figure 10 shows an instantaneous schlieren photograph corresponding to Fig. 3(b). That is, this photograph shows the case in which cell pattern peculiar to the detonation wave structure is maintained over the observation area although the detonation front shows

Fig. 9 Movement trajectories of triple points in precursor shock front ($L=3$, $H=3$, $A=30$; $P_0=10.7$ kPa)

Fig. 10 Instantaneous schlieren photograph of detonation ($L=3$, $H=3$, $A=30$; $P_0=12.0$ kPa)

turbulence extremely near the nozzle entrance in the above-mentioned open-shutter photograph. Although the entire wave front exhibits a convex curve along its propagation direction, the curve appears to be smooth and does not have diffraction points on the wave front as shown in Figs. 6(b) through (d). However, careful observation of the wave front shows that there are many triple shock waves on it. Therefore, it is only the existence of these triple shock waves coupled with chemical reaction that enables the production of the cell pattern due to the radiating trajectories characteristic of the detonation observed in Fig. 3(b), and guarantees the propagation configuration of detonation.

4. Conclusions

In this study, seven kinds of reflection nozzles were utilized to produce the Prandtl-Meyer expansion effects at various levels. Behavior of detonations during passage through reflection nozzles was experimentally observed. Obtained results can be summarized as follows:

(1) As the half-vertical angle of a nozzle becomes large and height H of the throat part becomes small, maintenance of detonation wave structure requires higher initial pressure.

(2) In order to maintain the detonation configuration, the smallest number of triple shock waves propagating into a nozzle is necessary.

(3) In the case that the cell pattern disappears in an open-shutter photograph, a shock wave front and a flame front can be observed to exist separately in an instantaneous schlieren photograph.

(4) Even in the case that the detonation wave structure is not maintained, a shock wave front with nonreactive triple points exists in a parallel channel section.

(5) From the relationship between the change of

angles immediately before and after collision obtained from movement trajectories of triple points, the acceleration of the shock wave front can be observed.

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