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Detonation Transition Limit at an Abrupt Area Change Using a Reflecting Board

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To realize quick initiation of detonation in the combustion chamber of a pulse detonation engine operating in the air-breathing mode, in which the combustible gas is a fuel–air mixture, the authors have proposed a new pulse detonation engine initiator using a "reflecting board" near the exit of a predetonator tube. In this study, we clarify the transition limit of this new initiator by examining the detonation cell size at the predetonator exit and the mechanism that gives this transition limit. The combustible mixtures are stoichiometric hydrogen–oxygen mixtures diluted with nitrogen or argon. The main results obtained in this study are as follows. When the incident detonation wave interacts with the reflecting board before it completely disappears due to the rarefaction wave from the predetonator exit, the number of cells between the exit and the board defines the transition limit from the planar to cylindrical detonation waves. Even when the cylindrical detonation does not occur, the reflecting board converts a planar detonation wave into a torus-shape pressure wave. This pressure wave encompasses the combustible gas in the detonation chamber and concentrate on the axis, causing a detonation bubble behind the board. The necessary minimum diameter of the predetonator with a reflecting board is expressed by $D_c = 6.3\lambda$.

Introduction

THE pulse detonation engine (PDE), which induces the compression and combustion processes simultaneously by means of a detonation wave, has recently attracted the attention of researchers from various angles [1,2]. One of the major issues to be resolved to enable the practical use of the PDE is "quick initiation of detonation". The indicator of the ease of detonation initiation of combustible mixtures is detonability. When the PDE operates in the air-breathing mode, the combustible gas is likely to be a fuel–air mixture and its detonability is undoubtedly lower than that of fuel–oxygen mixtures. Another case in which one can encounter a low-detonability condition is that in which the fuel is in the liquid phase. A possible method of overcoming low-detonability conditions is to use high-detonability mixtures as the driver gas in the initial part of the detonation chamber. Adding to this, a predetonator, which is a long narrow duct filled with a highly detonable mixture as a driver gas, is helpful for initiating a detonation wave quickly and reducing the amount of driver gas [3].

Detonation transition through an abrupt area change, such as from a predetonator to the main chamber, is one of the foremost interests in the field of fundamental detonation study, and there have been many investigations concerning this issue [1,2,4,5]. Mitrofanov and Soloukhin have shown that the tube diameter D at which the transition is possible must be at least 13 times the cell size λ ($D \geq 13\lambda$) [6]. Matsui and Lee proposed the critical tube diameter concept that the tube diameter D_c under this marginal condition represents the detonability [7]. Knystautas et al. obtained the D_c values of various combustible mixtures and showed that the relation of $D_c = 13\lambda$ is valid for various mixtures [8]. This relational expression gives the necessary minimum diameter of the predetonator. In an air-breathing PDE that operates in an ambient below atmospheric pressure, the diameter of the predetonator must be 10 cm or more even when the fuel is hydrogen. To reduce the weight of oxygen, which is the major portion of the weight of the driver gas and decreases the total specific impulse of the engine, a predetonator of smaller diameter is preferable. Therefore, a new detonation promotion mechanism that reduces the necessary minimum diameter of the predetonator is required.

Teodorcyzk et al. analyzed a quasi-detonation wave propagating in an obstacle-leaden channel, and showed that Mach reflections at a rigid wall play an important role in detonation propagation [9]. Jones et al. showed a numerical result in which a detonation wave entering a wide channel from a narrow tube decays once and then is reinitiated owing to the Mach reflection at a sidewall of the wide channel [10]. Ohyagi et al. observed this phenomenon experimentally [11]. Murray et al. studied transitions of planar detonation from a circular tube to cylindrical detonation expanding radially outward between a pair of parallel plates and showed that the Mach reflection of the diffracted wave from the wall opposing the tube exit promotes the transition of detonation [12,13]. DeWitt et al. investigated detonation initiation via the interaction of a high-speed shock/flame complex and a disk or a cone obstacle set in the middle of the detonation chamber [14]. In that study, they demonstrated successful detonation initiation in ethylene–air mixtures with comparatively short distances.

The authors have proposed a new PDE initiator using a circular disk called a reflecting board near the exit of a predetonator. The reflecting board promotes the detonation transition owing to Mach reflection on the board. DeWitt et al. achieved detonation initiation by setting up an obstacle such as a disk at the center of the detonation chamber [14]. In their method, the disk obstructs the flow of the

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working fluid and drag is generated. The reflecting board causes virtually no drag because most of the working fluid, i.e., the combustion gas, is free from the drag caused by the reflecting board. In previous research [15], the authors experimentally investigated the effect of reflecting board clearance on the ability of the promotion of detonation transition, in which the combustible gases used were stoichiometric hydrogen–oxygen mixtures diluted with nitrogen. The results showed that the effectiveness of the reflecting board on the transition of detonation is a strong function of the clearance of the reflecting board. The appropriate clearance for detonation transition corresponds to the distance at which the head of the rarefaction wave reaches the axis of the predetonator and the incident planar detonation wave disappears. When the clearance of the reflecting board is within this distance, strong Mach reflection occurs on the board, resulting in the promotion of detonation transition. The results of a series of experiments, in which the pressure and the nitrogen concentration of the mixture were varied, suggested that the critical cell size of the incident detonation wave gives the detonation transition limit at a certain clearance of the reflecting board. Although in the previous study the effect of the cell size on the detonation transition limit was investigated by varying two independent parameters, i.e., the pressure and the nitrogen concentration of the mixture, the diluent was limited to nitrogen only and the relationship between the clearance of the reflecting board and the critical cell size was not sufficiently clarified. The mechanism, if it exists, by which the critical cell size governs the detonation transition limit at a certain clearance of the reflecting board also remains unclear.

In the present study, whether the cell size of the mixture can be a comprehensive criterion for the detonation transition limit at a certain clearance of the reflecting board, even when the diluent is changed, is determined. In addition to nitrogen, argon was employed as the diluent in this study. The main purpose was to clarify how the critical cell size governs the detonation transition limit at a certain clearance of the reflecting board, which is strongly related to the mechanism of detonation promotion brought about by the reflecting board.

Experimental Details

Figure 1a shows a schematic of the experimental apparatus. Although the experimental apparatus and the experiment method are the same as those in our previous study [15], we would like to explain the details again for the convenience of the readers because the previous paper was written in Japanese. The apparatus mainly consists of a main detonation chamber and a predetonator. The main detonation chamber is 220 mm long with a 100 mm internal diameter. The predetonator upstream of the main chamber is 2936 mm long with a 20.4 mm internal diameter. A ball valve divides the predetonator into two sections and it opens 0.5 s before ignition. A stoichiometric hydrogen–oxygen mixture fills the upstream section of the predetonator as a driver gas. Because the downstream section of the predetonator is connected to the main detonation chamber, the same mixture fills the main detonation chamber and the downstream section. Preliminary experiments showed that the detonation wave at the exit of the predetonator is in the Chapman–Jouguet (CJ) state of the target gas filling the main chamber. Four shafts support the reflecting board of 70 mm diameter and 5 mm thickness, as shown in Figs. 1b and 1c. The shafts are M6 screws and the reflecting board clearance w can be arbitrarily chosen in the range of 5–40 mm by adjusting the position of the nut. A standard automotive spark plug at the front end of the predetonator ignites the driver gas. Five sensor ports, S, A, B, C, and D in Fig. 1, are each for a pair of an ionization probe and a pressure transducer (PCB 113A26, Piezotronics Co., Ltd.). The ionization probe and pressure transducer detect the combustion and pressure waves, respectively. If both the combustion wave and the pressure wave reach a sensor port simultaneously, a detonation wave can be identified. Soot tracks are collected at the following four locations in Fig. 1: the downstream section of the predetonator (point A*), the surfaces of the front flange (point B*) and the reflecting board (point C*), and the sidewall of the detonation chamber (point D*). A scanner converts the soot track images into digital data. The cell size λ of the incident detonation wave represents the mean size of 30 cells at the downstream section of the predetonator.

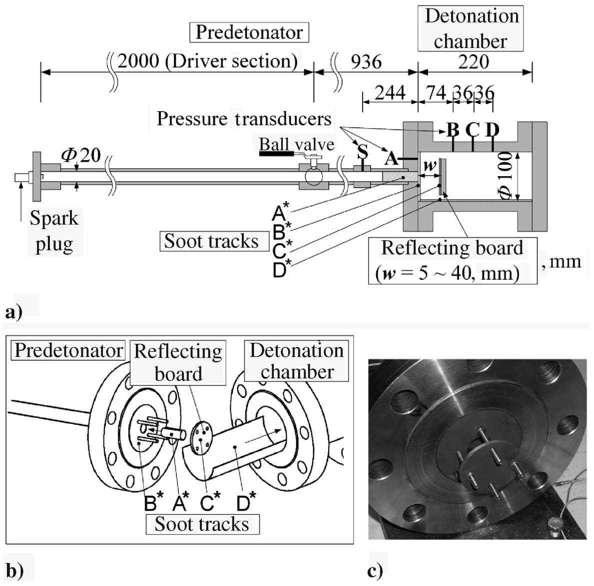


Fig. 1 Experimental apparatus and positions of smoke records.

Target gas mixtures filling the main detonation chamber are stoichiometric hydrogen–oxygen mixtures diluted with nitrogen or argon. The mixtures are prepared and completely mixed in a gas handling apparatus beforehand. Common to all experiments, the initial pressures of the predetonator and the main detonation chamber were 1 atm. Because the cell size of the stoichiometric hydrogen–oxygen mixture at 1 atm is approximately 1 mm, the predetonator diameter of 20 mm is near the transition limit, according to the relation $D_c = 13\lambda$. Therefore, the scale of the experimental apparatus is appropriate in exhibiting the transition promotion effect of the reflecting board.

Results and Discussion

Promotion of Detonation Transition by Reflecting Board

To investigate the variation of the detonation transition limits upon changing the reflecting board clearance, a series of experiments with various concentrations of nitrogen and argon was performed. The histories of the ionization probe and the pressure transducer at port C and the soot track on the sidewall of the detonation chamber provided information to determine successful transition of the detonation wave. Figures 2a and 2b show results with mixtures of 35 and 40% nitrogen dilution, respectively. The reflecting board clearance w was 20 mm in both cases. The size of the tracks was 100 × 220 mm and the predetonator exit was on the left side. Figure 2a shows the failure region of detonation transition behind the reflecting board. At 50 mm from the left, a local explosion occurred and the fanlike detonation wave spread downstream. Around 100 mm from the left, a planar detonation wave appeared and a regular cellular pattern of detonation existed in the downstream region. The pressure sensor and the ionization probe at port C, 110 mm from the left, respectively, detected sudden pressure and voltage increases simultaneously, showing the passage of a detonation wave. These results prove the successful transition of the detonation wave. On the contrary, the soot film record in Fig. 2b exhibits no cellular pattern of detonation waves, and the pressure increase does not coincide with the voltage increase of the ionization probe at port C. These results indicate that the transition of detonation was not successful in this case. Accordingly, the detonation transition limit with the reflecting board clearance of 20 mm is between 35 and 40% nitrogen dilution.

Figure 3 shows the variation of the detonation transition limits with the reflecting board clearance of 5 to 40 mm. The upper and lower graphs show the results for nitrogen and argon dilutions, respectively. The longitudinal and horizontal axes show the dilution rate and reflecting board clearance, respectively. On the horizontal

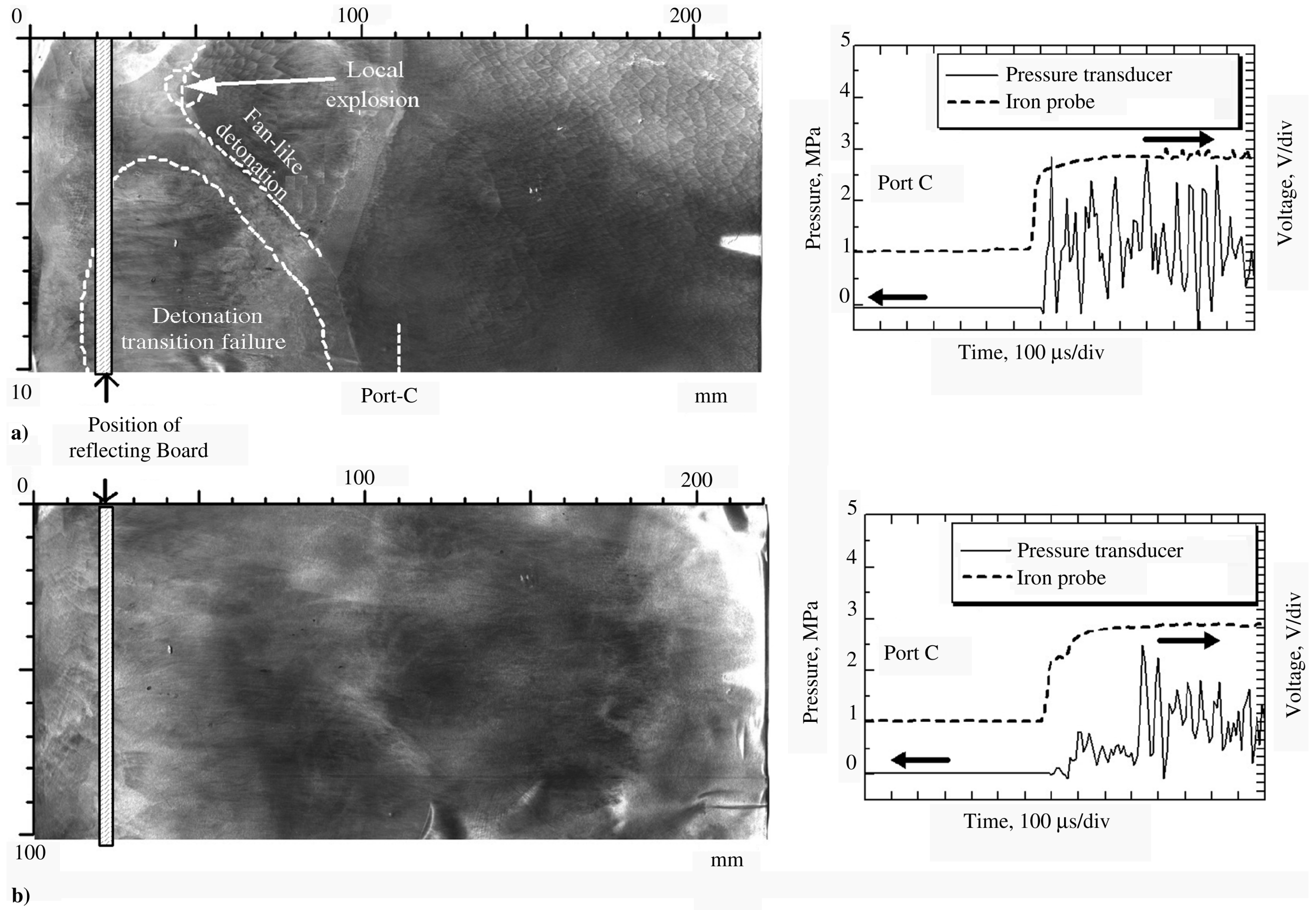


Fig. 2 Soot tracks (Fig. 1, D*) and histories of ionization probe and pressure transducer.

axis, ∞ represents the condition without the reflecting board. In addition to the case of using the reflecting board, successful transition of the detonation wave without the reflecting board is judged from the histories at port C and the soot track on the sidewall. The results for nitrogen dilution show a considerable positive impact of the reflecting board on the detonation transition limit, improving from 0 to 10% up to 35% dilution. The most appropriate clearance was 15–20 mm. Before the appropriate clearance, the benefit of the reflecting board gradually increases with clearance. After the appropriate value, it rapidly becomes less effective. With argon dilution, the significant positive impact of the reflecting board on the detonation transition limit appeared again, improving from 50 up to 70% dilution. Although the transition limits on the argon dilution ratio are high compared with those on the nitrogen dilution ratio, there are some similarities between them: the most appropriate clearance of the reflecting board is 15–20 mm and the reflecting board rapidly becomes less effective when the clearance exceeds 20 mm.

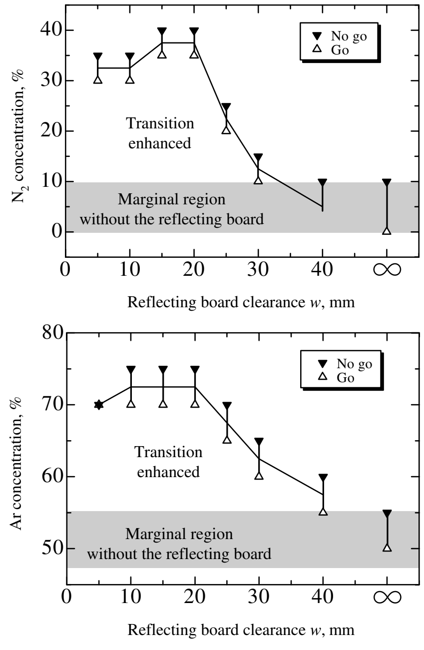


Fig. 3 Transition limit as function of reflecting board clearance *w*.

Interaction Between Incident Planar Detonation Wave and Reflecting Board

Figure 4a shows the soot tracks at the surfaces of the front flange and Fig. 4b shows the reflecting board with a clearance of 10 mm and the nitrogen dilution of 10%. The figure also shows the conceptual diagrams of the detonation reinitiation mechanism in this case. This is a typical mechanism of detonation reinitiation on the surface of the reflecting board. Rarefaction waves from the corner of the exit chip away at the circumference of the incident planar detonation wave, as Fig. 4c shows. The diffracted detonation wave divides into the pressure wave and the combustion wave, spreading radially between the reflecting board and the front flange. The detonation reinitiation could occur on the outer edge of the black area at the center of the reflecting board, as Fig. 4b shows. This black area is the imprint of the front collision of the incident planar detonation wave. The Mach reflection of the shock wave on the reflecting board causes a local region of high-temperature and high-pressure at the outer edge of this area, resulting in the detonation reinitiation. Figure 4a shows a soot track on the front flange surface of the detonation chamber, in which the most dominant feature is an annular ring. This ring represents the boundary between the traces of the diffracted shock wave from the predetonator and the returning detonation wave reinitiated on the reflecting board. With increasing reflecting board separation, the ring diameter tends to increase.

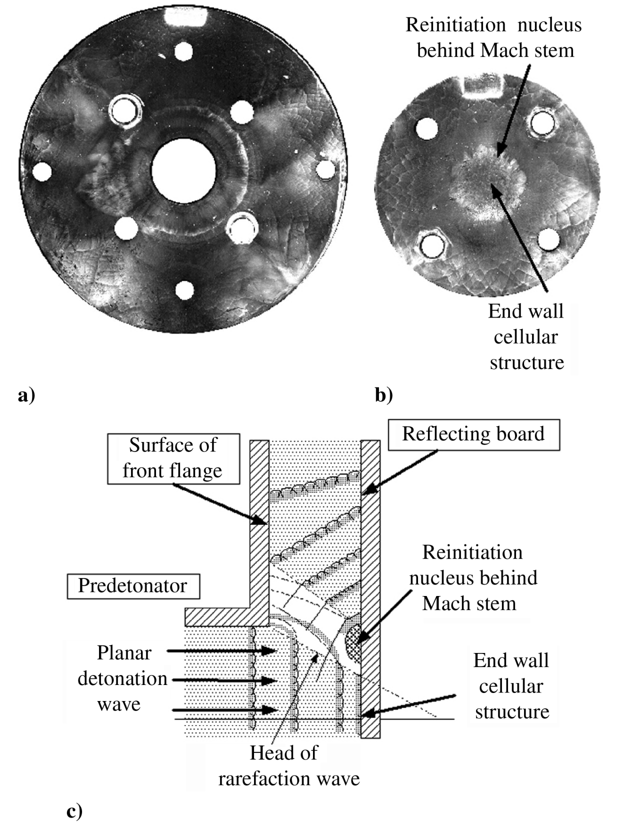


Fig. 4 Typical mechanism of reinitiation in relatively sensitive mixtures (10 ∼ 20% of N_2).

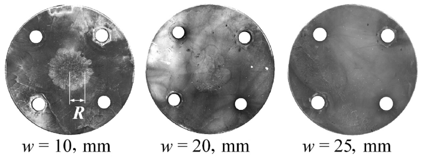


Fig. 5 Soot tracks on reflecting board (Fig. 1, C*) with 20% N_2 dilution.

Figure 5 shows the variation of the soot track on the surface of the reflecting board, in which the degree of nitrogen dilution is 20%. The black area in Fig. 4 becomes evident with the reflecting board clearance of 10 mm. In contrast, the black area completely disappears with the reflecting board clearance of 20 mm. A further increase of the reflecting board clearance to 25 mm causes the disappearance of the annular reinitiation ring, and there is no apparent trace of detonation reinitiation. Accordingly, the incident planar detonation wave from the predetonator disappears at a distance of 20 mm or less under this condition. When the predetonator diameter is above the transition limit and the detonation wave can survive the abrupt area change, a spherical detonation commences from an explosion nucleus before the planar detonation wave disappears completely. In the present research, however, the predetonator diameter is under the transition limit in most cases, and spontaneous reinitiation from an explosion nucleus does not occur. Therefore, the incident planar detonation wave disappears completely due to the rarefaction wave without the contribution of the reflecting board.

Figure 6 shows the variation of the black area radius R with the reflecting board clearance. The ranges of nitrogen and argon dilutions are 10–30% and 60–65%, respectively. The solid line in the figure corresponds to the theoretical R representing the location of the rarefaction wave when the incident detonation wave propagating at the CJ speed collides with the reflecting board. The speed of the expansion wave in this calculation is the speed of sound of the combustion gas behind the detonation wave. The length at which R becomes zero is known to be approximately 0.9 times the predetonator diameter D, and independent of the mixture condition. This is because the ratio of the CJ speed to the speed of the rarefaction wave is virtually constant [12]. Therefore, the distance at which the incident planar detonation wave completely disappears is approximately 18 mm in this experimental apparatus. This value agrees well with the experimental result that the plane detonation wave disappears at a distance of 20 mm or less. Because the planar detonation wave disappears at approximately 18 mm from the predetonator exit regardless of the mixture condition, there is no strong effect of Mach reflection when the reflecting board clearance exceeds 20 mm. Therefore, the promoting effect of the detonation transition decreases rapidly as the reflecting board clearance exceeds 20 mm. In conclusion, the reflecting board clearance must be within 0.9 times the predetonator inside diameter to obtain the promotion effect of detonation transition.

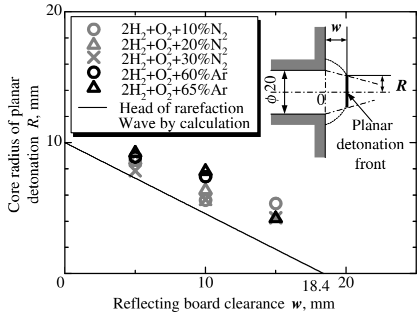


Fig. 6 Core radius of incident planar detonation wave as function of w.

Comprehensive Discussion Based on Cell Size

Up to this point, the dilution ratio with nitrogen or argon has defined the transition limit of a detonation wave. At the same time, it may be possible to perform a comprehensive evaluation in terms of the cell size of the incident detonation wave. This idea is related to the expression $D_c = 13\lambda$ giving the detonation transition limit at the abrupt area change. In this section, we reexamine the transition limit with argon dilution on the basis of the cell size, which may allow a comprehensive evaluation of the transition limit for both nitrogen and argon dilutions.

Figure 7 shows the transition status for various nitrogen and argon dilutions. The longitudinal and horizontal axes are the cell size of the incident detonation wave and the reflecting board clearance, respectively. Gray symbols and black symbols represent cases of nitrogen and argon dilution, respectively. Both the circular and triangular symbols indicate that the detonation transition was successful. Circular symbols indicate that the detonation wave reinitiated on the surface of the reflecting board, as Fig. 4 shows. Triangular symbols indicate that the detonation transition was successful, but the trace of reinitiation did not exist on the surface of the reflecting board. Crosses indicate that the detonation transition was not successful. The standard deviations of the boundary conditions for each symbol are shown in Fig. 8. Results for nitrogen and argon dilution cases are in good agreement with each other for the reflecting board clearance of 5–20 mm. It is common to both cases that the critical cell size is approximately 2.5 mm in this range

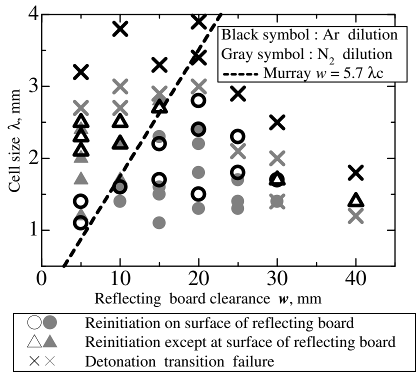
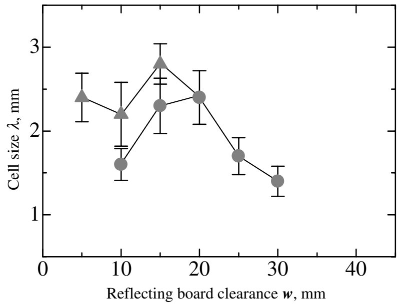
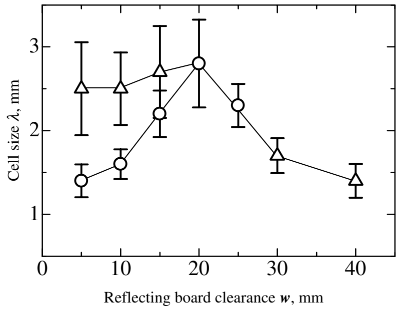


Fig. 7 Transition status for various nitrogen and argon dilutions.



a) N_2 dilution



b) Ar dilution

Fig. 8 Cell size and standard deviation of boundary condition for Fig. 7 symbols.

of board clearances. Accordingly, a critical cell size can reasonably represent the transition limit that is common to both nitrogen and argon dilution cases.

Murray and Lee observed the transformation of planar detonation to cylindrical detonation experimentally and showed that there are two reinitiation mechanisms, i.e., spontaneous reinitiation and reinitiation by reflection from a wall [12]. According to them, the spontaneous reinitiation starts with the formation of reignition nuclei before the incident shock interacts with the wall opposite the tube exit. Because under the supercritical condition of $D \leq 13\lambda$ the incident detonation wave decays before the formation of a reignition nucleus, spontaneous reinitiation did not occur in this study. Another meaningful result obtained by Murray and Lee is that the clearance from the tube exit to the wall must be greater than 5.7λ for a successful transition to cylindrical detonation. The broken line in Fig. 7 represents the relation $w = 5.7\lambda$. On the right side of the line, the transition to a cylindrical detonation occurs, whereas on the left side of the line, the transition does not occur. With the reflecting board clearance in the range of 5–20 mm, the boundary between circular plots and triangular plots agrees well with the broken line of $w = 5.7\lambda$ in both nitrogen and argon dilution cases. However, when the reflecting board clearance exceeds 20 mm, this agreement does not hold and the cell size at the transition limit begins decreasing rapidly.

Matsui and Lee investigated the limit of cylindrical detonation initiation experimentally and showed that it is difficult to initiate cylindrical detonation using flanged electrodes when the electrode spacing is reduced to below approximately five cell sizes [7]. This means that an incident detonation wave that has less than five cells between the tube exit and the reflecting board cannot withstand the cylindrical expansion. The result obtained by Murray and Lee of the critical condition being $w = 5.7\lambda$ is consistent with the result that Matsui and Lee obtained, indicating that the critical wall separation for the transition from planar detonation to cylindrical detonation is equivalent to the critical length of the ignition source for the initiation of cylindrical detonation [12]. The difference in the research of Murray and Lee from ours is that the incident detonation wave reaches the opposite wall before it disappears completely in all of their experiments. The planar detonation wave disappears in approximately 18 mm regardless of the mixture condition in our study, as the foregoing section shows. Therefore, it is inappropriate to apply the detonation transition condition $w \geq 5.7\lambda$ to the clearance of the reflecting board exceeding 20 mm because the cell structure does not exist beyond 20 mm from the tube exit. When the board clearance is greater than 20 mm, the increase in the clearance does not result in an increase in the number of cells along the axis, but causes a severe restriction on the detonation initiation because the pressure wave must expand in the axial direction as well as the radial direction. As a result, the detonation transition limit decreases rapidly when the board clearance exceeds 20 mm.

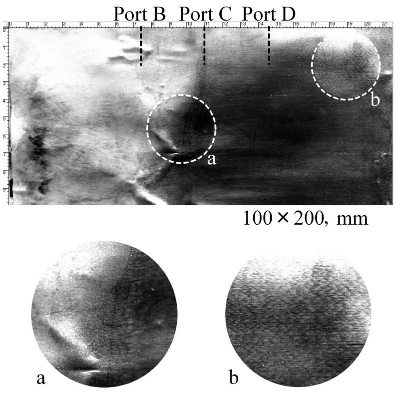


Fig. 9 Soot track on detonation chamber sidewall with $w = 20$ mm and N_2 dilution of 35%.

When the board clearance is less than 20 mm, the boundary between circles and triangles represents the limit of the transition of planar detonation to cylindrical detonation. More specifically, in triangular cases, reignition on the surface of the reflecting board does not occur despite the successful detonation transition. Accordingly, the detonation initiation occurs in places other than the surface of the reflecting board in triangular cases, showing that reinitiation mechanisms downstream of the reflecting board also play an important role in detonation transition to the detonation chamber.

Reinitiation Mechanism Under Marginal Conditions

Figure 9 shows the soot track on the detonation chamber sidewall with the board clearance of 20 mm and nitrogen dilution of 35%. Figure 10 shows the pressure histories at ports B–D for the same experiment. The experimental conditions are the same as those in the case of Fig. 2a and correspond to the triangle group in Fig. 7. Similar to that in Fig. 2a, the cell structure of the detonation wave appears in the downstream half of the chamber sidewall. This feature is common to the cases represented by the triangles, with the board clearance of 5–20 mm, as Fig. 7 shows. (The experimental results of Figs. 9 and 10 are based on the data of an additional test to examine the transition limit shown in Fig. 3. Because the soot tracks at the predetonator exit were not gathered in these experiments, we could not include this data in Fig. 7. From the nitrogen concentration, the cell size is estimated to be around 3 mm.) There is no cell structure in the soot track near port B. The pressure history at port B shows a small oscillation continuing for 32 μs before the rapid pressure increase. These results show that a deflagration wave passed port B. The cell pattern near the boundary of the cell structure (region a) is

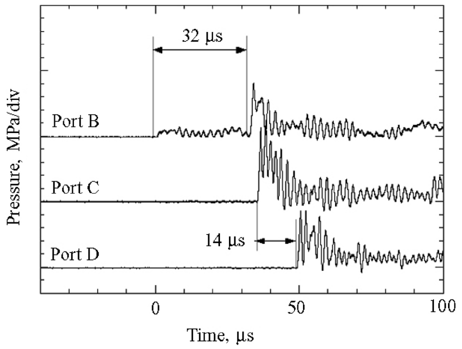


Fig. 10 Pressure histories at ports B–D with $w = 20$ mm and N_2 dilution of 35%.

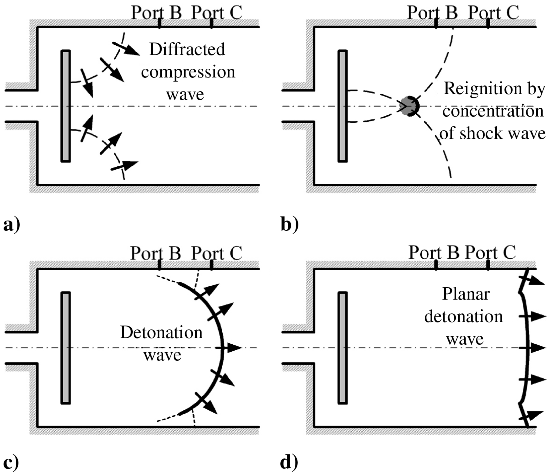


Fig. 11 Detonation reinitiation mechanism under marginal conditions.

irregular, which is the characteristic appearance of a soot track when a detonation wave collides vertically with a soot film. Unlike in the case of port B, the pressure history at port C does not show any oscillation before the rapid pressure increase. The rapid pressure increases at ports B and C are virtually simultaneous and the velocity of the pressure wave derived from the time difference between ports C and D is approximately 2.6 km/s, which is faster than the CJ speed under this condition of 2.2 km/s.

The soot track and pressure histories in Figs. 9 and 10 lead to the detonation reinitiation mechanism shown in Fig. 11. The detonation reinitiation does not occur upstream of the reflecting board, and a torus-shaped compression wave encompasses the combustible gas in the detonation chamber (Fig. 11a). The torus-shaped pressure wave concentrates at the axis of the detonation chamber behind the reflecting board, generating an area of high-temperature and high-pressure sufficient for detonation reinitiation (Fig. 11b). A hemispherical detonation wave evolving from such a spot propagates and reaches port B and port C virtually simultaneously (Fig. 11c). Owing to this mechanism, it is possible to induce a successful detonation transition even under the condition that detonation reinitiation by Mach reflection on the reflecting board does not occur. Jackson et al. [16,17] designed an initiator for creating a collapsing toroidal detonation wave front and showed chemiluminescent images of the collapsing toroidal wave front concentrating at the central axis of the initiator. These images clearly show that the concentrating toroidal wave creates a high-temperature spot at the focal point, resulting in detonation reinitiation. Murray et al. [13] succeeded in inducing the transition of the detonation wave by using an annular orifice. The annular orifice produces an exploding toroidal wave that eventually implodes along the axis of symmetry. The high pressures and temperatures at the focus of the imploding toroidal wave create a hot spot capable of evolving into a self-sustained detonation wave. The addition of the annular orifice allowed successful detonation transition for tubes 2.2 times smaller in diameter than tubes having simple circular orifices. The detonation reinitiation phenomena described in those studies agree well with our observations reported in this paper and support the transition mechanism illustrated in Fig. 11. This detonation reinitiation mechanism was also observed in the argon dilution cases.

Performance of System with Reflecting Board

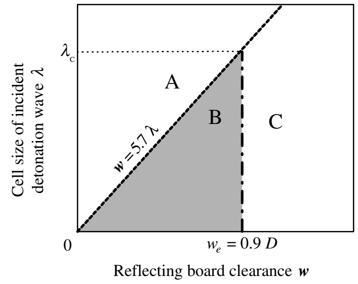


Fig. 12 Simplified transition status.

Figure 12 shows a simplified transition status derived from the foregoing discussions. The longitudinal and horizontal axes are the cell size of the incident detonation wave and the reflecting board clearance, respectively. The detonation transition phenomena with the reflecting board consist of three areas being divided by the two relational expressions $w = 5.7\lambda$ and $w = 0.9D$. Under the condition that the transition of the detonation wave to the combustor fails (crosses in Fig. 7), no evidence of reinitiation at the reflecting board was observed. The present study confirmed that the transition from planar incident detonation to cylindrical detonation between the chamber front wall and the reflecting board is a sufficient condition for successful detonation propagation in the main chamber. The reflecting board clearance w_e must be within 0.9 times the predetonator diameter D to achieve the promotion effect because the incident planar detonation wave does not survive beyond this distance. By substituting the conditional expression $w = 5.7\lambda_c$ presented by Murray et al. [13], which states that the critical cell size λ_c for successful transition from a planar to cylindrical detonation is the wall clearance w divided by 5.7, into the restriction of $w < 0.9D$, the critical cell size λ_c in the present study is given by $\lambda_c < (0.9/5.7)D$. When the relation is reexpressed in terms of the critical tube diameter D_c, the necessary minimum diameter of a predetonator with the reflecting board is expressed as $D_c = 6.3\lambda$. This relational expression holds when the gap between the reflecting board and side wall is comparable in magnitude to the reflecting board clearance or the diameter of the predetonator. The minimum diameter of the predetonator without the reflecting board is expressed by the well-known relation $D_c = 13\lambda$. Therefore, the reflecting board reduces the predetonator diameter to one-half and reduces the amount of driver gas to at least one-quarter. However, when the detonation chamber is too small for the successful transformation to the cylindrical detonation wave, or the gap is too large and the cylindrical detonation wave cannot survive the diffraction around the board, or the gap is too small and the toroidal detonation wave cannot survive the expansion, this assumption may not be hold. These conditions are beyond the scope of this study.

Conclusions

The authors have proposed a new PDE initiator with a reflecting board near the exit of the predetonator to promote detonation transition. The results of the present study confirmed that the cell size of the mixture serves as a comprehensive criterion for the detonation transition limit at a certain clearance of the reflecting board. Specifically, a critical cell size governs the detonation transition limit at a certain board clearance even when the diluent is changed from nitrogen to argon. One important mechanism behind the enhancement of the detonation transition is that the Mach reflection of a shock wave on the surface of the reflecting board causes a local region of high-temperature and high-pressure, resulting in detonation reinitiation. A transformation of planar detonation to cylindrical detonation occurs by this mechanism. When the board clearance is less than $0.9D$, where D is the predetonator diameter, the limit of successful transition of planar detonation to cylindrical detonation agrees well with that obtained in the previous research by Murray et al. [13], $w = 5.7\lambda$, where λ is the cell size of the mixture. Because the incident planar detonation wave disappears completely due to the rarefaction waves at the distance $0.9D$ from the exit, the promoting effect of detonation transition decreases rapidly as the board clearance exceeds $0.9D$.

Even when the transformation of planar detonation to cylindrical detonation is unsuccessful, detonation transition may be possible by another mechanism: the reflecting board converts a planar detonation wave into a torus-shaped pressure wave. This pressure wave encompasses the combustible gas in the detonation chamber and concentrates at the axis, causing a detonation bubble behind the board. Owing to these promoting effects, the reflecting board improves the cell size of the transition limit by more than 2.5–3 times.

The necessary minimum diameter of the predetonator with the reflecting board is expressed by $D_c = 6.3\lambda$. Therefore, the reflecting board reduces the predetonator diameter to one-half and reduces the amount of driver gas to at least one-quarter of those for the conventional system.

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