Propagation Stability of Rotating Detonation Waves Using Hydrogen/Oxygen-Enriched Air Mixtures

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In this study, tests were performed using a newly developed combustion chamber for a rotating detonation engine to study the effects of reactivity of the mixture as related to the cell width and CJ velocity, and the total mass flow on the stability of rotating detonation wave (RDW) propagation. For the reactant mixtures, \(2H_2+O_2+\beta N_2\) was used, where the dilution ratio \(\beta\) was varied from 0 to 3.76 to change the cell width and CJ velocity. The experimental results showed that stable operation was achieved when the average total mass flow rates \(\dot{m}_{ave}\) were larger than 170, 200, and 350 g/s for \(\beta = 1.36, 2.65,\) and 3.73, respectively, and that the velocity of the RDWs decreased as \(\dot{m}_{ave}\) decreased. Regardless of the mixture composition, a stable mode was obtained when the height of the reactant mixture normalized by the cell width, \(h/\lambda\), was larger than 3. There was a minimum value of \(\dot{m}_{ave}\) that adjusted \(h/\lambda\) to enable the stable propagation of RDWs.

**Key Words:** Detonation Wave, Rotating Detonation Engine, Cell Size, High-Speed Combustion, Operation Mode

**Nomenclature**

- \(A\): cross-sectional area of the channel
- \(d\): diameter of the combustion chamber
- \(D\): detonation wave velocity
- \(f\): operating frequency
- \(h\): height of the reactant mixture ahead of the RDW
- \(\dot{m}\): total mass flow rate
- \(n\): number of rotating detonation waves
- \(p\): pressure
- \(\Delta p\): pressure gain
- \(u\): flow velocity
- \(w\): channel width
- \(\beta\): nitrogen dilution ratio
- \(\lambda\): mixture cell width
- \(\rho\): density
- \(\tau\): time interval

**Subscripts**

- \(\text{ave}\): time-averaged
- \(\text{cj}\): Chapman-Jouguet condition
- \(\text{vsl}\): condition at gas storage tank

1. Introduction

Detonation engines have received increased attention over the past few decades as a new propulsion system for the next generation. The dominant advantage of detonation engines is a higher thermodynamic efficiency than that of conventional engines based on the Brayton cycle, under the same pressure ratio.\(^1\) Rotating detonation engines (RDEs) have an annular combustion chamber in which the detonation waves propagate circumferentially. During the successive propagation of rotating detonation waves (RDWs), a fresh mixture is fed into the combustion chamber after one detonation wave passes. Then, the following detonation wave consumes the newly charged reactant mixture to maintain rotating detonation in the chamber. This propagation process results in higher operating frequency, thrust, and pressure gain than those of pulse detonation engines.\(^2\)

The key factors to sustain stable rotating detonation in the combustion chamber are the mixture cell width, detonation wave velocity, mass flow rate of the reactants, and size of the combustor. To obtain successful rotating detonation wave propagation, Kindracki et al.\(^3\) reported that the combustor size affected the propagation stability of the RDWs. A combustor with a larger diameter had a positive effect on stable propagation when considering the propagation time of the RDWs.

Regarding the effect of the reactant mixture, namely the mixture cell width, George et al.\(^4\) reported that the operation mode of RDEs is determined by the reactant mixture height injected ahead of the detonation wave \(h\), the channel width \(w\), and the mixture cell width \(\lambda\). Tests were performed using RDEs with several channel widths and various mixture compositions, while maintaining a constant total mass flow rate. The detonation front was assumed to be a rectangular shape with length \(h\) and width \(w\). The wave number increased in a predictable manner when the perimeter of the detonation front, which was equal to \(2h+2w\), exceeded \(7.4\lambda\).

In addition, Bykovskii and Zhidan\(^5\) reported that the total mass flow rate of the reactant mixture affected the operation modes of RDEs. Experimental studies using two sizes of RDEs were performed. It was concluded that regardless of the size of the RDE, the number of RDWs increased as the total mass flow rate increased.

In this study, to obtain conditions to maintain stable RDWs, tests were conducted using a newly developed com-
bustion chamber. The total mass flow rate was varied to clarify its effect on the operation mode.

2. Experimental Methods

2.1. Experimental apparatus

Figure 1 shows a detailed configuration of the combustion chamber used in this study. It had an outer diameter of 115 mm and an inner diameter of 95 mm, forming a channel width of 10 mm. This channel width was approximately equal to the cell width\(^2\) of a stoichiometric hydrogen-air mixture at an initial atmospheric pressure and room temperature.

For the reactants, stoichiometric oxyhydrogen mixtures diluted with nitrogen, \(2H_2 + O_2 + \beta N_2\), were used. The reactivity of the mixtures was varied by changing the nitrogen dilution ratio \(\beta\), which was a volumetric ratio of nitrogen to oxygen, to clarify the effects of the cell width and the CJ velocity on the propagation behavior of the RDWs. The values of \(\beta\) were selected to be 0, 1.36, 2.65, and 3.73, where a \(\beta\) of 3.73 corresponded to air.

Nakayama et al.\(^6\) studied the stability of detonation waves propagating in curved channels with curved rectangular cross-section channels for different inner radii of curvature. For an inner radius equivalent to 21–32 times that of the detonation cell width, the detonation wave showed a mode transition from unstable to stable. Meanwhile, stable detonation wave propagation in the RDEs with an inner diameter of approximately 10–30 times that of the mixture cell width was observed in other studies.\(^4\)\(^7\)\(^9\) In this study, the inner diameter was 95 mm based on the findings mentioned in previous research.

The supply section consisted of an adjustable circumferential slit and axial orifice holes, which enabled control of the equivalence ratio and mass flow rate independently, as shown in Fig. 1. An oxidizer was charged through a circumferential slit and axial orifice holes, which enabled control of the equivalence ratio and mass flow rate independently, as shown in Fig. 1. An oxidizer was charged through a circumferential slit and axial orifice holes, which enabled control of the equivalence ratio and mass flow rate independently, as shown in Fig. 1. An oxidizer was charged through a circumferential slit and axial orifice holes, which enabled control of the equivalence ratio and mass flow rate independently, as shown in Fig. 1.

2.2. Propagation mode

It is well known that some propagation modes of RDWs appear when rotating detonation is successfully achieved under various test conditions. In this study, the following cri-
and 2.65, stable propagation was achieved for a mode transition from titude were unstable. When the pressure gain was obtained, the wave velocity was less than 70% of the CJ velocity. An approximately constant frequency was observed.

Duration, and a pressure gain \( \Delta p / C_1 p \) an approximately constant frequency as shown in Fig. 3. The features were as follows.

**Stable:** The RDWs rotated in the combustion chamber at an approximately constant frequency \( f = 1 / \tau \) for a certain duration, and a pressure gain \( \Delta p \) of more than 0.1 MPa was observed.

**Marginal:** When the pressure gain was obtained, the wave velocity was less than 70% of the CJ velocity.

**Unstable:** The operating frequency and the pressure amplitude were unstable.

The number of RDWs \( n \) was determined using high-speed video images and the operating frequency calculated from the pressure history.

### 3. Results

Figure 4 shows the operation modes of the RDE for various average total mass flow rates \( \dot{m}_{ave} \) and nitrogen dilution ratios \( \beta \). For \( \beta = 3.73 \), a stable mode with \( n = 1 \) was observed for \( \dot{m}_{ave} > 350 \text{ g/s} \). Under the condition of \( 300 < \dot{m}_{ave} < 350 \text{ g/s}, n = 2 \) or \( n = 3 \) was observed. For \( \beta = 1.36 \) and 2.65, stable propagation was achieved for \( \dot{m}_{ave} > 200 \text{ and } \dot{m}_{ave} > 160 \text{ g/s}, \) respectively. Moreover, for \( \beta = 2.65 \), a further increase in the average total mass flow rate after RDWs reached a stable propagation mode of \( n = 1 \) caused a mode transition from \( n = 1 \) to \( n = 2 \) at \( \dot{m}_{ave} \approx 450 \text{ g/s} \). The threshold of the mass flow rate between the stable and unstable modes for \( \beta = 2.65 \) was lower than that for \( \beta = 3.73 \), while the wave number did not change. For \( \beta = 1.36 \) and \( n = 3 \), only the stable mode was observed within the range of \( 170 < \dot{m}_{ave} < 300 \text{ g/s} \). However, for \( \beta = 0 \), the stable mode was not observed under the condition of \( \dot{m}_{ave} < 150 \text{ g/s} \). The rotating detonation failure for \( \beta = 0 \) may have been from an insufficient mixture supply owing to lower gas storage pressures for \( \dot{m}_{ave} < 150 \text{ g/s} \) and a potential high operating frequency owing to the high CJ velocity of the \( 2\text{H}_2 + \text{O}_2 \) mixture.

Except for \( \beta = 0 \), a marginal or stable mode appeared as the total mass flow rate increased.

To examine the behavior of RDWs in terms of the average total mass flow rate, the wave velocity normalized by CJ velocity is shown in Fig. 5. For all of the mixture compositions, the normalized wave velocity increased as the total mass flow rate increased under the same wave number. Although the unstable mode appeared for \( \beta = 1.36 \), the wave number increased at approximately \( \dot{m}_{ave} = 150 \text{ g/s} \), and the wave velocity decreased as the wave number increased from \( n = 2 \) to \( n = 3 \). For \( \beta = 2.65 \), the wave number increased from \( n = 1 \) to \( n = 2 \) at \( \dot{m}_{ave} \approx 450 \text{ g/s} \) as the wave velocity decreased, and the RDWs showed an unstable mode in this region. Therefore, these average total mass flow rates were in the transition condition, in which the RDWs showed unstable behavior accompanied by a changing wave number. Moreover, comparing the number and stability of the waves for the same average total mass flow rate, the wave number or wave velocity increased as \( \beta \) decreased.
for providing the same average mass flow rate. For $\beta = 2.65$ and $n = 1$, a stable mode was obtained for different supply pressures at approximately $m_{\text{ave}} = 350 \text{ g/s}$. This was also the case for $\beta = 3.73$ and $m_{\text{ave}} \approx 400 \text{ g/s}$. In addition, a stable mode with $n = 2$ appeared for $\beta = 2.65$ and $m_{\text{ave}} > 425 \text{ g/s}$. These results suggest that the operation mode of the RDE is governed by the average total mass flow rate within a certain range of supply pressure.

4. Discussion

In the previous section, although the operation mode was determined by $m_{\text{ave}}$, the total mass flow rate was dependent on the combustion chamber size from the results of other studies. In this study, the operation mode was analyzed using the height of the mixture injected ahead of the RDW $h$ and mixture cell width $\lambda$.

The height of the reactant mixture $h$ was estimated as follows. The average total mass flow rate was calculated from the initial and final pressures in the gas storage tank. The density of the reactant mixture injected into the combustion chamber was estimated by assuming isentropic expansion to the atmospheric pressure in the combustion chamber. From a combination of the mass conservation equation, Eq. (1), and the total mass flow rate calculated, the velocity of the reactant mixtures provided in the combustion chamber was deduced as Eq. (2). Using the operating frequency observed, the time interval between two successive waves was calculated using Eq. (3). Finally, the height of the mixture ahead of the RDW $h$ was formulated as Eq. (4).

$$m = \rho u A$$

$$u = \frac{m}{\rho A}$$

$$\tau = \frac{1}{f} = \frac{\pi d}{D}$$

$$h = u \cdot \tau$$

The detonation cell width was obtained using an exponential fitting of the available experimental data for the stoichiometric H$_2$-O$_2$-N$_2$ mixtures at an initial condition, as shown in Fig. 7. The cell widths used $\lambda$ were 3.3 mm, 6.8 mm, and 12.3 mm for $\beta = 1.36, 2.65, \text{ and } 3.73$, respectively.

Figure 8 shows the operation mode of the RDE analyzed using the normalized height of the mixture and nitrogen dilution ratio. The stable mode appeared under the condition of $h/\lambda > 3$ for $\beta = 1.36$ and 2.65 and $h/\lambda > 2.8$ for $\beta = 3.73$. In addition, transition of the wave number from $n = 1$ to $n = 2$ was achieved at $h/\lambda \approx 4$ for $\beta = 2.65$. The transition occurred at $h/\lambda \approx 3-5$ for $\beta = 1.36$. Although only a marginal mode was observed for $\beta = 3.73$, the transition from $n = 1$ to $n = 2$ occurred at $h/\lambda \approx 3$. From these results, it was deduced that the number of RDWs increases as $h/\lambda$ increases. In addition, there was a lower threshold value of $h/\lambda$ for stable propagation, namely $h/\lambda \approx 3$ in this study. Comparing the results shown in Fig. 5 and Fig. 8, the RDWs showed different operation modes that were dependent on the mixture composition and total mass flow rate for the following reason. For the same mixture condition, the RDWs

Figure 6 shows the effects of the average total mass flow rate and nitrogen dilution ratio on the normalized wave velocity and wave number.

Figure 7 shows the effects of the average total mass flow rate and normalized pressure at the gas storage tank on the propagation mode of RDWs.
changed operation mode because \( h/\lambda \) increased together with the total mass flow rate, which was deduced from Eqs. (1)–(4). For different mixtures, the mixture cell widths varied, and thus \( h/\lambda \) differed even though the total mass flow rate was constant, leading to different operation modes. For example, for \( \beta = 3.73 \), because the mixture cell width was the largest among the present mixtures, \( h/\lambda \) was the smallest at the same average total mass flow rate. Therefore, this suggests that a relatively high total mass flow rate is required for mixtures with large cell widths to obtain stable RDW propagation.

To examine the effect of the total mass flow rate on the operation mode, tests in which the operation mode changed during the test period were analyzed. Figure 9 shows a pressure history demonstrating transition of the operation mode for \( \beta = 2.65 \) and \( \dot{m}_{\text{ave}} = 460 \text{ g/s} \). The operating frequency was different after transition at approximately 115 ms.

To analyze operating frequency transition, a short-term FFT was applied to the pressure history, as shown in Fig. 10. From Eq. (2), the maximum operating frequency was achieved when RDWs propagated at the CJ velocity. For the mixture of \( \beta = 2.65 \), the operating frequencies \( f_{\text{CJ}} \) were 6.0 kHz and 12.0 kHz for \( n = 1 \) and \( n = 2 \), respectively. Comparing \( f_{\text{CJ}} \) and the frequency shown in Fig. 10, it was confirmed that the wave number changed from \( n = 2 \) to \( n = 1 \) during operation.

Figure 11 shows the temporal history of the total mass flow rate in the same test which the results are shown in Figs. 9 and 10. Time “zero” is the timing of the spark ignition at the initiator tube. The total mass flow rate was approximately 450 g/s at the transition time of 115 ms. This result agrees well with the mode transition for \( \beta = 2.65 \) shown in Fig. 4. Consequently, it was deduced that the total mass flow rate strongly affects the operation mode of RDEs. The transition scenario was that a decrease in total mass flow rate
leads to a decrease in the fresh mixture height ahead of a RDW, triggering mode transition when \( h/\lambda \) reaches the critical value.

When the combustion chamber size changes, the critical value of \( h/\lambda \) may differ owing to the curvature effect of the annular chamber on the propagation of RDWs. Further studies are needed to clarify the chamber size effect on the operation modes of the RDEs.

5. Conclusion

In this study, the operation modes of RDEs were experimentally studied by varying the total mass flow rate and composition of the reactant mixture independently under a stoichiometric condition.

Stable propagation of RDWs was observed under the condition of \( \bar{m}_{\text{ave}} > 350 \text{ g/s} \) for nitrogen dilution ratio mixture of \( \beta = 3.73 \), \( \bar{m}_{\text{ave}} > 200 \text{ g/s} \) for \( \beta = 2.65 \), and \( \bar{m}_{\text{ave}} > 160 \text{ g/s} \) for \( \beta = 1.36 \). For \( \beta = 2.65 \), RDWs showed a stable mode at a lower average total mass flow rate than that of \( \beta = 3.73 \) with the same wave number. Moreover, a further increase in average total mass flow rate after RDWs reached a stable propagation mode caused a mode transition from \( n = 1 \) to \( n = 2 \) at \( \bar{m}_{\text{ave}} \approx 450 \text{ g/s} \). For \( \beta = 1.36 \), within the range of \( 170 < \bar{m}_{\text{ave}} < 300 \text{ g/s} \), only the operation mode with three waves was observed. Furthermore, with the same average total mass flow rate, the wave number increased and velocity of the RDWs decreased as \( \beta \) decreased.

The normalized height of the fresh mixture ahead of the RDWs, \( h/\lambda \) was evaluated using the mixture cell width \( \lambda \). The stable mode appeared at \( h/\lambda > 3 \), regardless of the mixture composition.

By measuring the supply pressure and estimating the temporal history of the total mass flow rate during operation, it was found that mode transition is accompanied by a change in the total mass flow rate, and the propagation mode of the RDWs is governed by the total mass flow rate within a certain range of supply pressure.

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References

1) Wolatński, P.: Detonative Propulsion, *Proc. Combust. Inst.*, 34 (2013), pp. 125–158.
2) Kindracki, J., Kobiera, A., Wolatński, P., Gut, Z., Folusiak, M., and Swiderski, K.: Experimental and Numerical Study of the Rotating Detonation Engine in Hydrogen-Air Mixtures, *Progr. Propul. Phys.*, 2 (2011), pp. 555–582.
3) St. George, A., Driscoll, R., Anand, V., and Gutmark, E.: On the Existence and Multiplicity of Rotating Detonations, *Proc. Combust. Inst.*, 36 (2017), pp. 2691–2698.
4) Bykovskii, F. A. and Zhdan, S. A.: Current Status of Research of Continuous Detonation in Fuel-Air Mixtures, *Combust. Explosion Shock Waves*, 51 (2015), pp. 21–35.
5) Kaneshige, M. and Shepherd, J. E.: Detonation Database, Technical Report FM 97-8, California Institute of Technology, 1997.
6) Nakayama, H., Moriya, T., Kasahara, J., Matsu, A., Sasamoto, Y., and Funaki, I.: Stable Detonation Wave Propagation in Rectangular-Cross-Section Curved Channels, *Combust. Flame*, 159 (2012), pp. 859–869.
7) Bykovskii, F. A., Zhdan, S. A., and Vedernikov, E. F.: Initiation of Detonation of Fuel-Air Mixtures in a Flow-Type Annular Combustor, *Combust. Explosion Shock Waves*, 50 (2014), pp. 214–222.
8) Rankin, B. A., Richardson, D. R., Caswell, A. W., Naples, A. G., Hoke, J. L., and Schauer, F. R.: Chemiluminescence Imaging of an Optically Accessible Non-Premixed Rotating Detonation Engine, *Combust. Flame*, 176 (2017), pp. 12–22.
9) Liu, W., Zhou, J., Liu, S., Lin, Z., and Zhuang, F.: Experimental Study on Propagation Mode of H\(_2\)-Air continuously Rotating Detonation Wave, *Int. J. Hydrogen Energy*, 40 (2015), pp. 1980–1993.
10) Shank, J. C.: Development and Testing of a Rotating Detonation Engine Run on Hydrogen and Air, Dissertation, Air Force Institute of Technology, 2012.
11) Anand, V., St. George, A., Driscoll, R., and Gutmark, E.: Investigation of Rotating Detonation Combustor Operation with H\(_2\)-Air Mixtures, *Int. J. Hydrogen Energy*, 41 (2016), pp. 1281–1292.
12) Lu, F. K. and Braun, E. M.: Rotating Detonation Wave Propulsion: Experimental Challenges, Modeling, and Engine Concepts, *J. Propul. Power*, 30 (2014), pp. 1125–1142.
13) Frolov, S. M., Aksenov, V. S., and Ivanov, V. S.: Experimental Proof of Zel’dovich Cycle Efficiency Gain over Cycle with Constant Pressure Combustion for Hydrogen-Oxygen Fuel Mixture, *Int. J. Hydrogen Energy*, 40 (2015), pp. 6970–6975.

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