Experiments of the Tri-arc Non-Circular Rotating Detonation Engine (RDE)

Eun Sung Lee, Hyung-Seok Han, Jung-Min Kim, Jae-Hyuk Lee, and Jeong-Yeol Choi*
Department of Aerospace Engineering, Pusan National University
Busan, Republic of Korea, 46241

1 Introduction

RDE is a combustor where the compression effect by the detonation wave provides the thermodynamic cycle efficiency to generate enough useful work to be called an "engine". However, no rotating parts such as compressor and turbine are required in a 'rotating' detonation engine, but only the detonation wave is moving around a closed channel. Thus, no geometrical constraint of circular configuration is imposed except the closed channel. Non-circular geometrical flexibility would be useful for the design of a propulsion system that could be installed into the airframe designed for optimum stealth characteristics or aerodynamic performance. Such a non-circular cross section concept has been suggested and tested by means of numerical simulation as shown in Fig. 1 [1].

Fig. 1 Numerical smoked-foil records of detonation wave propagations in various cross-sections.

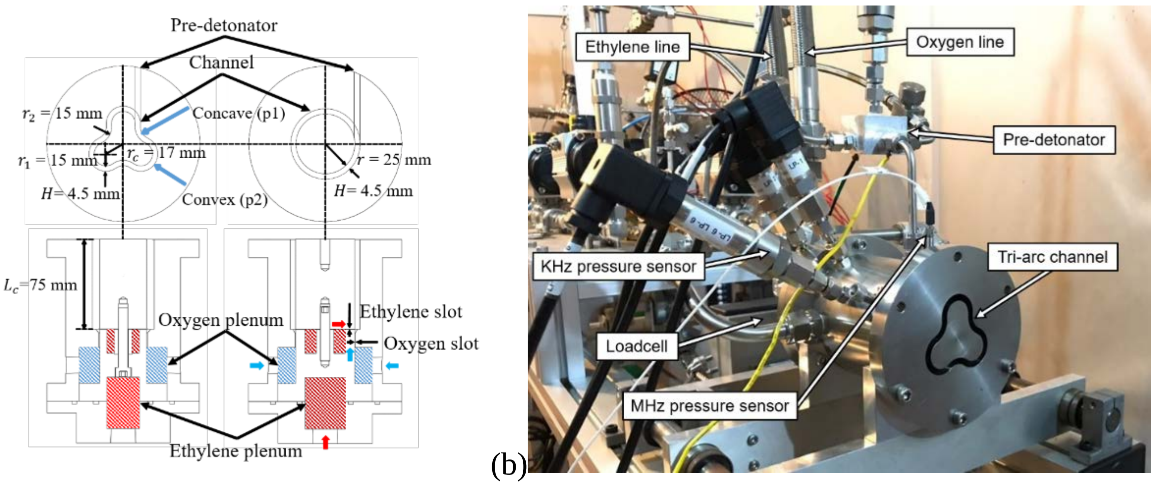
Since there is neither an experimental study nor a realistic numerical study for the non-circular arbitrary cross section RDE, tri-arc shaped cross section is designed and tested in comparison with a circular shaped RDE as an example of general shaped cross section. It is called as 'tri-arc RDE' in this paper since it looks like a tri-lobed fidget spinner toy. Its scale is almost identical to the circular RDE conducted previously [2], excepts some unavoidable mechanical discrepancies for the difference shapes. Primary goal of present study is to investigate the basic characteristics and performance of the tri-arc RDE and to compare with those of circular RDE.

Since there is neither an experimental study nor a realistic numerical study for the non-circular arbitrary cross section RDE, tri-arc shaped cross section is designed and tested in comparison with a circular shaped RDE as an example of general shaped cross section. It is called as 'tri-arc RDE' in this paper since it looks like a tri-lobed fidget spinner toy. Its scale is almost identical to the circular RDE conducted previously [2], excepts some unavoidable mechanical discrepancies for the difference shapes.

Primary result of tri-arc RDE has been presented previously [3] but the goal of present study is to investigate the characteristics and performance of the tri-arc RDE compared with those of circular RDE.

2 Experimental Setup

The tri-arc RDE is designed as uncooled device and fabricated with stainless steel for short time hot-fire test. Except for the cross-sectional shape, size and structure are similar to the circular RDE, which is a reference model of tri-arc RDE. The cross-section shape of tri-arc RDE consists of tri-lobed-rounded plane of 120 degrees. The dimensions of the tri-arc RDE are also similar to those of the circular RDE like channel width and combustor length. The length and width of the combustion channel are 75.0 and 4.5 mm, respectively. Each size of injection slots for the fuel and oxidizer is 0.34 and 0.4 mm. The cross-sectional areas for each injection slot and combustion channel are 46.8, 63.4 and 771.4 mm2, respectively. The fuel and oxidizer are used gaseous ethylene (GC_2H_4) and oxygen (GO_2), these are injected from each plenum into the combustion channel through each injection slot.



(a) (b)

Fig. 2 a) schematic of two RDE model and b) A picture of the experimental setup.

For detonation initiation in combustion channel, a micro-scale pre-detonator is used, and its fuel and oxidizer is same as the RDE. The inner diameter and length for pre-detonator are about 4.2 and 150.0 mm, respectively. In this pre-detonator, Shchelkin spiral is unnecessary since the DDT distance is sufficient for the present oxygen-based mixture. The pre-detonator is combined with the RDE in the tangential direction.

3 Experimental Results

Figure 3 is the experimental pictures of the tri-arc non-circular RDE. The mass flow rate measured and calculated within range of 0.2 to 0.8 MPa. The theoretical mass flow rate $\dot{m} = \frac{A_t P}{\sqrt{T}} \sqrt{\frac{\gamma}{R}\left(\frac{2}{\gamma+1}\right)^{\gamma+1/\gamma-1}}$ is used to verify the measured results. he maximum difference from the calculated values in tri-arc RDE showed 2.6 g/s (2.5%) for the fuel and 1.7 g/s (1.1%) for the oxidizer. For the circular RDE, the maximum difference is 2.0 g/s (14.0%) and 3.5 g/s (9.9%), respectively. In this study, burning time is about 0.4 sec at the mass flow rate of 150.0 g/s or less and 1 equivalent ratio. FFT and STFT were used to investigate the detonation behavior, and the images captured at 256 x 256 resolution and 200,000 fps for optical observation.

(a) (b) (c)

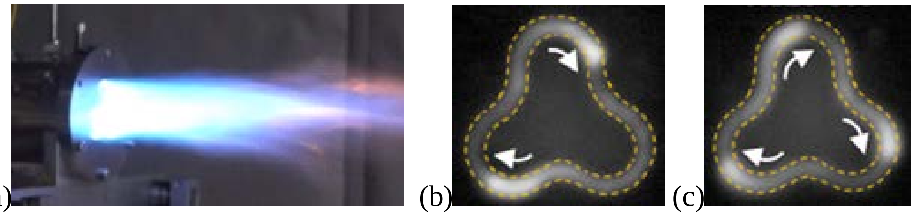


Fig. 3 Expexperimental pictures of the tri-arc non-circular RDE, (a) direct picture of tri-arc RDE plume, (b) two-wave motion captured at the exit, (c) three-wave motion captured at the exit

Fig. 4 shows the STFT results of tri-arc RDE at $\dot{m} = 80.06$g/s, $\Phi = 1.04$. At low mass flow rate, In the case of tri-arc RDE, rotation direction and number of waves are continuously changed from ignition to approximately 28 ms showing unstable state. However, after 28 ms, two detonation waves were rotate stably until the end of operation. Circular RDE observed stable rotation of the detonation wave only for a short period of time during operation. In relatively high mass flow rate conditions, unlike in low mass flow rate conditions, three waves temporarily rotate over a short period in tri-arc RDE, whereas in circular RDE, continuously unstable detonation waves were propagated over the entire period. The deficit of the detonation speed tended to decrease as the mass flow rate increased. Tri-arc RDE is superior to the circular RDE in terms of stability. It is considered that shape of the channel affected the detonation propagation behavior. Actually, detonation waves which rotates the RDE inside the channel, is propagate by the interaction between the strong and weak waves. For circular RDE, the strength of the detonation waves maintained and propagated according to the channel's shape but for tri-arc RDE the process of weakening the strong waves and strengthening weak waves is repeatedly propagated.

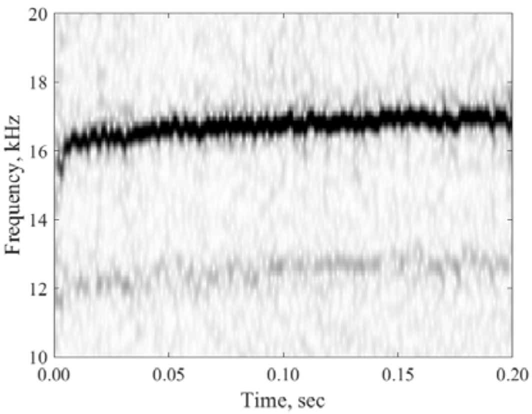


Fig. 4 STFT result of tri-arc RDE

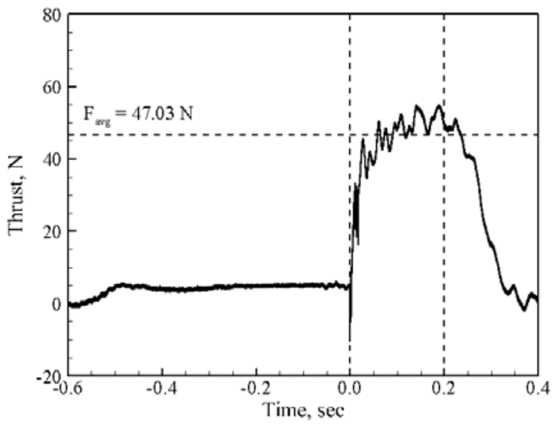


Fig. 5 Thrust of tri-arc RDE

Fig. 5 shows thrust of tri-arc RDE at reference mass flow rate. The specific thrust shown is expressed as the ratio of thrust to mass flow rate, and is the pure force generated by combustion except for the force of propellant injection. The test for each condition was conducted two or more times. The performance of tri-arc RDE tends to be greater than that of circular RDE. In addition, the performance difference is too large to be attributed to the combustion channel area or volume. Therefore, the quantitative decision is not possible in this work, but this trend is considered to be due to the difference in the combustion channel area and the effect of backflow into the plenum as the detonation propagates.

4 Conclusions

The non-circular tri-arc RDE was tested in comparison with a circular RDE. The detonation propagation of concave and convex corner of tri-arc RDE was observed under the stoichiometric condition. The detonation pressures at concave corner were greater than the those at convex corner, which means the strong and weak detonation propagate at the concave and convex corner, respectively. In terms of stability, tri-arc RDE was superior to the circular RDE. The unstable detonation waves propagate frequently in the circular RDE, but the detonation waves rotate stably and consistently in the same direction in the tri-arc RDE. It is considered that repeated changes in curvature enhance the detonation stability. In both RDEs, one to three waves were observed, and deficit of detonation speed reduced as the mass flow rate increased. In performance-wise, the tri-arc RDE is shown better than circular RDE and it is considered to be affected by the difference in the combustion channel shape. Therefore, the non-circular tri-arc RDE performs better than circular RDE both in performance and detonation stability. Further investigation using numerical simulations would be necessary to confirm the detailed characteristics

Acknowledgments

This work was supported by the National Research Foundation (NRF) of Korea grants (NRF-2018M1A3A3A02065563, NRF-2019R1A2C1004505) funded by the Ministry of Science and ICT (MSIT) of the Republic of Korea Government.

References

[1] Kim TY, Choi JY (2014) Numerical Study of detonation Wave Propagation in 2-D Channels of Arbitrary Radius of Curvature. AIAA 2014-3903, See also, Niyasdeen M, Kim TY, Pradeep PK, Ryu J, Choi JY, Effect of the Dimensionless Radius of Annulus on the Detonation Propagation Characteristics in Circular and Non-Circular RDEs, Shock Waves, in final review.

[2] Han HS, Lee ES, Choi JY. (2021) Experimental Investigation of Detonation Propagation Modes and Thrust Performance in a Small Rotating Detonation Engine Using C_2H_4/O_2 Propellant. Energies. 14(5): 1381.

[3] Lee ES, Han HS, Kim JM, Lee JH, Choi JY. (2021) Operating Characteristics of Non-Circular Tri-arc Rotating Detonation Engine(RDE). AIAA2021-3667.