Symmetric Square Lattice Injector Pattern Design and Testing for a Bi-Propellant Rotating Detonation Engine

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1 Introduction

A rotating detonation engine (RDE) is a simple, compact, engine where a detonation wave propagates in the combustion chamber with a more efficient thermodynamic cycle than deflagration engines [1]. One key feature of an RDE is the injector. Injector geometry and reactant mixing impact detonation phenomenon, wave stability and velocity, as well as RDE efficiency and propulsive performance [2-7].

RDEs typically use a circular injector design and combustion chamber. Although such designs have demonstrated successful detonation operation, other geometry configurations are not widely understood. Although the aforementioned studies exist, there are limited experimental studies varying overall injector geometry from the circular shape or the unwrapped linear channel [8-11]. This study aims to design a two-dimensional injector pattern that injects reactants across the entire injector area for use with a bi-propellant engine, and then test the design at various combustion conditions.

2 Injector Geometry

An injector design for use with a two-reactant system was investigated. The following parameters were used as guidelines: 1: creating a pattern that would be symmetric across the entire cross-sectional area so the design could be scaled up and exhibit similar trends; 2: using basic shapes (triangle or square) that would be repeated; and 3: having interdependent mixing points across the injector face instead of isolated mixing sections. The triangle shape was determined to be unsuitable as it resulted in a hexagon

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becoming the simplest repeated shape for a bi-propellant engine violating guideline 3. Its manufacturing was also challenging because of the number of holes required. The square shape created a lattice pattern that met the guidelines and it was deemed appropriate.

The square lattice pattern in Figure 1 is the result of using the simple square shape. When expanded, the square lattice pattern creates the symmetric, square, lattice injector pattern in Figure 2. In Figure 2, one set of oxidizer injector holes from a single mini oxidizer plenum is equidistant from to another set of oxidizer injector holes, and is also equidistant to fuel sets of injector holes (and vice-versa).

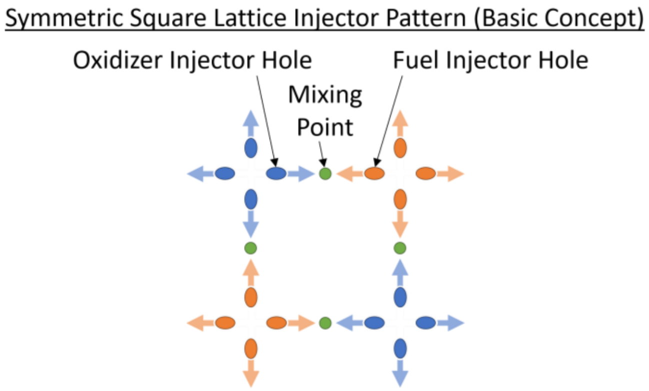

Figure 1: Symmetric square lattice injector pattern's basic concept.

Figure 2 shows the square lattice pattern expanded and adapted for use in a square combustion chamber. It depicts a simple, symmetric, two-dimensional, repeated, square injector pattern arrangement.

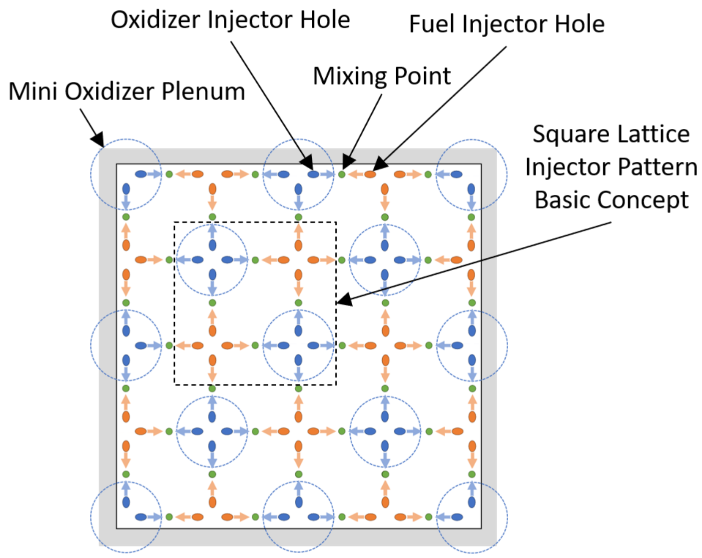

Figure 2: Symmetric square lattice pattern concept extended to a square combustion chamber

3 RDE Design

The engine consists of the following components: the oxidizer plenum, the dual plenum and the combustion chamber. Key features of the design are mainly found within the dual plenum component.

Schematics of the RDE are in Figure 3, and Figure 4 shows real engine photos. The dual plenum consists of the fuel plenum, 13 walled mini oxidizer plenums inside the fuel plenum section, and injector holes.

The engine is 135mm in length and 85 mm in diameter. The 13 mini oxidizer plenums have an internal diameter of 3 mm. They were critical for achieving the symmetric, square, lattice injector pattern in Figures 1 and 2: oxidizer travels from the oxidizer plenum, through the dual plenum via the mini oxidizer plenums, to the injector holes and into the combustion chamber below. The mini plenums are arranged in a diamond lattice pattern so injector holes could be arranged in the square lattice pattern. Since the square lattice injector pattern was used, to meet design guideline 1, the inside of the combustion chamber was also square (23 mm wide by 23 mm high to compare with [12], and 85 mm long) and uniformly spaced 1 mm from the injector holes. As for the injector holes, Figures 2 & 3 show 40 oxidizer holes of Ø0.6 mm and 40 fuel holes of Ø0.6 mm designed to create 40 impending jets and 40 mixing points. All the injector holes are placed at 45° angles from the injector exit face and injector holes are 2.2 mm apart. Pressure sensor holes are located on the combustion chamber on the top surface in the middle, and in the top corner (tangential to the wall) (Figure 3 Left).

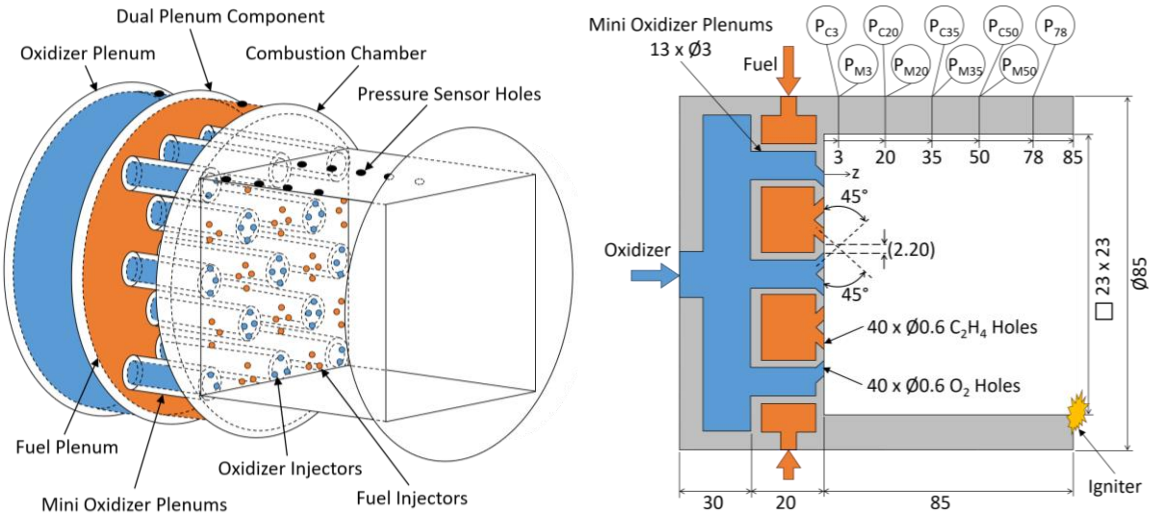

Figure 3: RDE Structure. Left: 3D engine model (outer walls removed). Right: Engine schematic with dimensions (in mm).

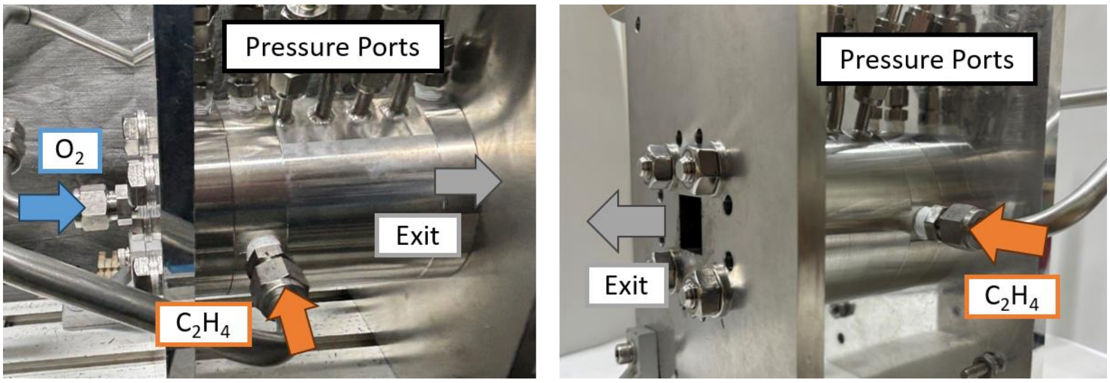

Figure 4: RDE Engine Set Up. Left: View from the side. Right: View from the exit.

4 Experimental Set Up

Experiments were conducted at Nagoya University using the 30 m^3 vacuum chamber. The supply system, thrust measurement system, and camera set up are shown in Figure 5.

The mass flowrate was controlled upstream of the engine using choked orifices of various diameters. Pressure data was collected using PAA-23SY 1 KHz sampling rate KELLER pressure transducers located according to Figure 3. A Phantom v.2011 high-speed camera, an SA5 FAST CAM, and a Samsung Galaxy S10 were used to capture combustion footage. The camera settings are generally around 430,000 fps and 1.01 us of exposure for the Phantom, while the SA5 settings varied. Gunpower was used as the igniter and attached at the rear of the engine. The load cell shown in Figure 5 was calibrated by comparing the results with measurements obtained when applying a load of known weight.

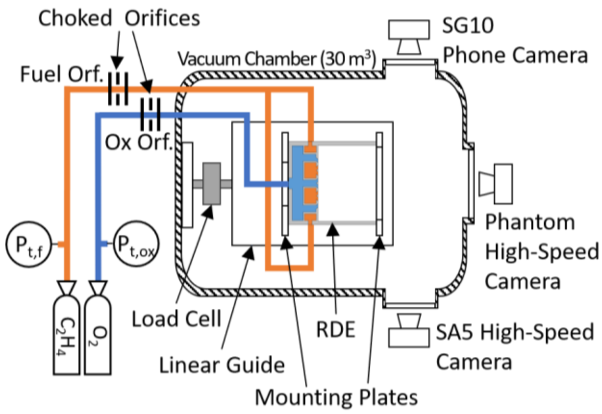

Figure 5: Test facilities experimental set up (top view).

5 Results and Discussion

Experiments were conducted within a range of total mass flowrate $\dot{m}_{tot}$ = 30 to 38 g/s, equivalence ratio $\Phi =$ 1.0 to 1.6, and from an initial back pressure p_b =5 kPa. Test conditions are summarized in Table 1. Performance parameters were obtained using time-averaged data from the combustion plateau (between t = 0.24 sec and 0.40 sec for shot 6, see Figure 6).

Table 1: Experimental Conditions and Summary of Results

Shot #	$\dot{m}_f$ [g/s]	$\dot{m}_{ox}$ [g/s]	$\dot{m}_{tot}$ [g/s]	Φ [-]	p_{M3} [kPa]	p_{78} [kPa]	p_b [kPa]	F [N]	I_{sp} [s]	D_w [m/s]	$\%D_{CJ}$ [%]	c^* [m/s]	$\%c^*_{theo}$ [%]
1	8.0	23.0	31.0	1.2	76.2	45.4	5	51.6	169	--[1]	--[1]	1300	78
2	7.6	22.8	30.4	1.1	75.0	46.7	5	50.5	169	2358	98	1305	79
3	7.9	27.0	35.0	1.0	79.4	48.8	5	51.9	151	--[1]	--[1]	1200	74
4	11.1	27.0	38.1	1.4	95.2	58.1	5	64.0	171	2358	93	1321	77
5	11.2	23.6	34.8	1.6	90.5	51.3	5	59.6	175	2224	86	1375	79
6	9.6	23.5	33.1	1.4	83.8	49.1	5	53.5	165	2310	91	1339	78

[1]Due to poor weather conditions, etc., it was not possible to acquire data to calculate this.

Figure 6 shows the time history data for shot 6 ($\dot{m}_{tot}$ = 33.1 g/s, Φ = 1.4, and p_b = 5kPa). The ignition trigger was at time t =0 s. The p_{Mi} and p_{Ci} vary by approx. 20% at 3 mm into the combustion chamber near the detonation wave front, however, the difference is 4%, 2.5%, and 5% at 20 mm, 35 mm, and 50 mm respectively. It is believed that as the combustion products move downstream in the engine mixing makes them homogenous and reduces the pressure difference between the middle and corner locations.

The theoretical maximum detonation wave velocity is known as the Chapman-Jouget wave velocity and it is denoted by D_{CJ}. Numerical studies have specifically indicated that a lower detonation wave velocity D_w effects engine efficiency [1, 6], and lower velocity is due to non-ideal reactant mixing [1, 5-7]. Although some experimental RDE studies have shown D_w of around 80% for cross flow jets and pintle injectors [10], using this injector geometry, D_w was 92% of D_{CJ} obtained using [13] on average (98%

maximum). The increased wave velocity from this RDE compared to Yokoo et al.'s hollow RDE in [12] indicates there may be improved mixing inside this RDE. This may be due to the two-dimensional nature of the injector pattern, or a reflected wave that occurred under stable operation when the detonation wave collided with a wall. Wave propagation was mostly only clockwise or counter-clockwise (only one variation was observed after unstable combustion), and decomposing the wave motion into horizontal and vertical phases, its horizontal velocity was 15% higher than its vertical velocity.

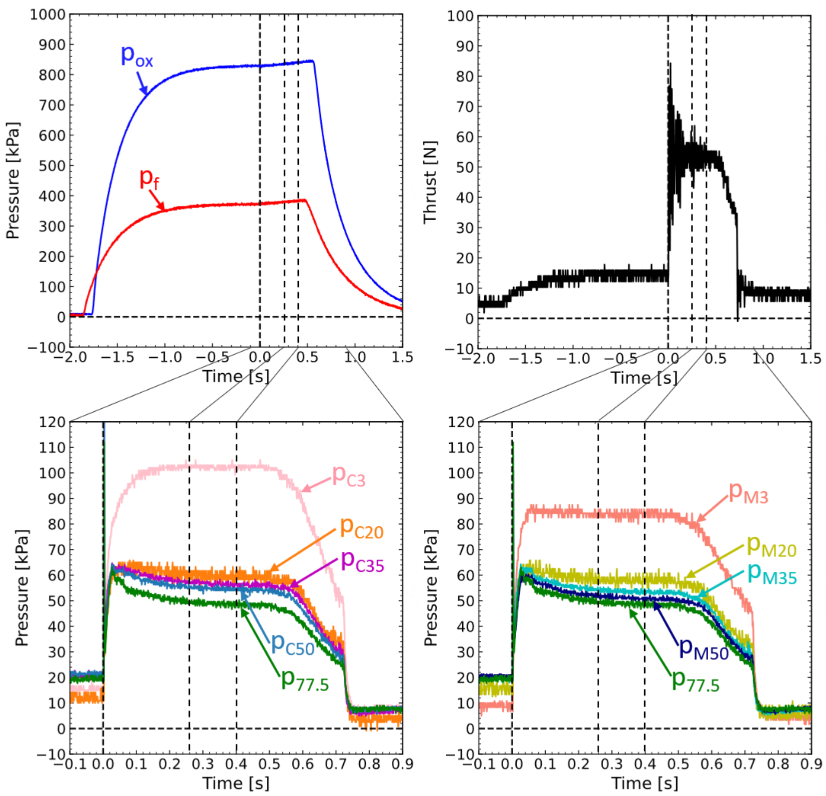

Figure 6: Pressure and thrust time history (shot 6: $\dot{m}_{tot}$ = 33.1 g/s, Φ = 1.4, p_b = 5 kPa) Top Left: Plenum pressures; Top Right: Thrust curve; Bottom Left: Corner pressures; Bottom Right: Middle pressures.

Evaluating the propulsion performance of the engine, this engine had a maximum thrust, $F_{max} = 64\ N$ and $I_{sp,max} = 175\ s$. These are both 70% of the thrust and specific impulse generated by Yokoo et al.'s hollow RDE [12], however, the increased wave velocity indicates this engine may still have other benefits. The average c* of the engine is 1307 m/s, approx. 77% of its theoretical maximum calculated using NASA-CEA [13]. Some calibrations still need to be completed.

6 Conclusion

In summary, this study found that to design a symmetric injector for a bi-propellant engine using a simple repeated shape, a square lattice pattern can be used. Expanding the square lattice pattern created a symmetric, two-dimensional, repeated, injector flow field across the entire cross-sectional area, and that injector was then fitted with a square combustion chamber and tested.

The symmetric, square, two-dimensional flow RDE was tested at mass flowrates between 30 – 38 g/s and equivalence ration between 1.0 – 1.6 at a back pressure of 5 kPa. The results showed an increased D_W of approx. 94%, a reflected wave occurring during stable detonation propagation, and a transitional reflective shuttling wave before and after stable operation.

These results show that the symmetric, square, lattice pattern created by the dual plenum component may exhibit improved mixing and thereby improve engine efficiency. Further studies are necessary to confirm if the two-dimensional injector pattern or the reflected wave is most responsible for the increased wave velocity, and to confirm about engine efficiency.

Acknowledgements

The authors would like to thank NETS Co., Ltd. for their critical support and with whom this study was conducted as joint research. One of the authors (K. Higashino) is thankful to the Asian Office of Aerospace Research and Development for their partial support by the project number of FA2386-23-1-4061.

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