Effects of Exhaust Dilution in a Disk-shaped Pressure Gain Combustor

Avion Lim, Peng Hwee Chua, Xin Huang, Po-Hsiung Chang, Zhen Wei Teo,
Jiun-Ming Li, Chiang Juay Teo, Boo Cheong Khoo
National University of Singapore
Singapore

1 Introduction

Disk-shaped or radial pressure gain combustors (PGCs) are an alternative combustor geometry to the typical annular-shaped pressure gain combustors. The main difference lies in the direction of flow of the combustion gases, which is illustrated in Fig. 1. One of the main benefits of this design is the reduced axial length of the combustor. The converging flow area of this type of combustor produces backpressure effects on the establishment of rotating detonation in the combustor. The effects of backpressure on ignition characteristics were previously studied for an annular combustor geometry by Fotia et al. [1, 2]. In their experiments, throttle air was added along a converging-diverging nozzle after combustion to control the static pressure of the detonation chamber independent of the ignition and operation of the device. They found that the ratio of air manifold-to-channel pressure rise rate was a key factor influencing the ability of the system to transition to detonative operation. The main differences between their experiment and the current experiment are the geometry of the combustor and the purpose of air addition. Their experiment used an annular combustor and studied the effects of backpressure on ignition. This experiment uses a disk-shaped PGC and studies the thermal management effectiveness of dilution air and its potential impact on operability.
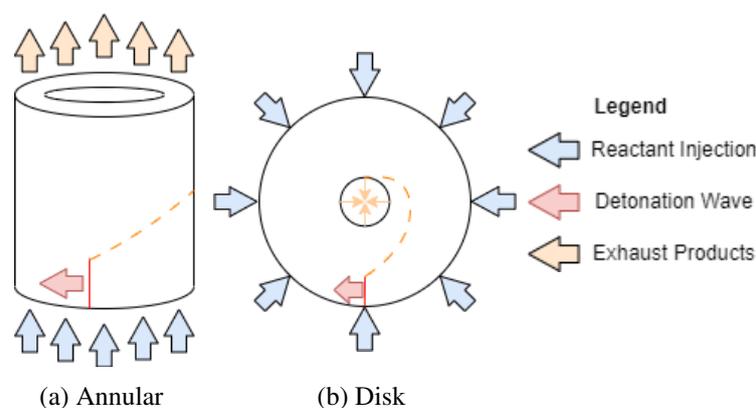

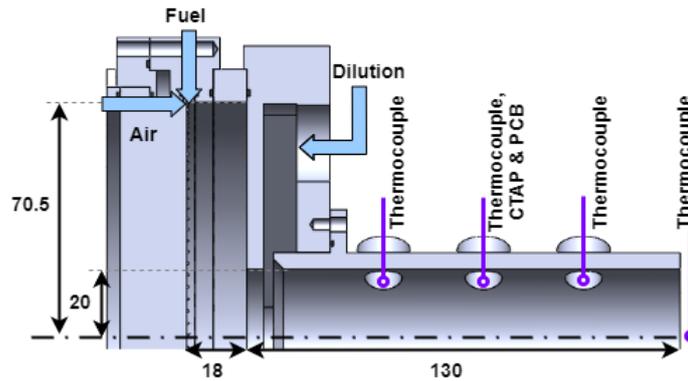Figure 1: Direction of propagation of detonation wave for different PGCs.

Figure 2: Half cross-section disk PGC design.

The objective of dilution of the exhaust of a disk-shaped PGC is to aid in thermal management by cooling the hot combustion exhaust gases. A previous paper focuses on the thermal management aspect, providing information on the total temperature in the combustor and the reduction in temperature after dilution [3]. However, the injection of dilution air also affects the propagation of detonation and the operability of the combustor. This paper focuses on the effects of backpressure and propagation of shock waves. Recent experimental runs use a smaller choking nozzle to control the mass flow rate of combustion air and dilution air into the set-up, fixing the mass flow rates even after ignition, producing more accurate and repeatable runs.

2   Experimental Set-up

A half-cross-section CAD of the disk PGC is shown in Fig. 2. Gaseous air and gaseous ethylene are injected into the combustion chamber along the outer diameter, whereas dilution air enters through the dilution manifold at the start of the nozzle section. The dilution air enters through a slot in a cross-flow configuration.

Along the nozzle, exposed K-type thermocouples were used to measure the temperature in some dilution cases. In most cases, the thermocouple temperature reached equilibrium after about two seconds, while combustion lasted four seconds. Two thermocouples were placed along the outer edge of the nozzle, one thermocouple was placed near the center of the nozzle, and another thermocouple was placed at the center of the nozzle exit. A capillary tube averaged pressure (CTAP) method was used to measure the average static pressure. A dynamic pressure sensor (PCB 113B24) was also installed to record pressure spikes. Two more PCB sensors and a CTAP were also installed in the chamber at a radius of $62.5 \, \text{mm}$ for wave mode evaluation and average static pressure measurements, respectively.

The air for combustion and the air for dilution were controlled separately through two different lines with a choking nozzle in each to adjust and measure the mass flow rates of air. The choking nozzles remained choked throughout combustion. The fuel line has a flow meter to help adjust the fuel flow rate. This setup enables independent control of the dilution air mass flow rate ($\dot{m}_d$), combustion air mass flow rate ($\dot{m}_a$), and fuel mass flow rate ($\dot{m}_f$) in the disk PGC. These independent variables are non-dimensionalised and represented as dilution ratio ($\lambda = \frac{\dot{m}_d}{\dot{m}_a}$), and chamber equivalence ratio ($\phi_c = \frac{\dot{m}_f / \dot{m}_a}{(\dot{m}_f / \dot{m}_a)_{stoich}}$), with $\dot{m}_a$ held constant at $132 \pm 3 \, \text{g/s}$.

3 Results and discussion

3.1 Overview of wave modes

Wave modes were determined using a combination of three different sources: (1) short-time Fourier analysis of PCB data; (2) visual inspection of high-speed camera video; and (3) a modified form of the circuit wave analysis by Chacon and Gamba [4]. This reduced the subjectivity or bias of any one method. Figure 3 shows the short-time Fourier transform for the different wave modes. Single-wave modes have a dominant frequency of $3,200 - 3,500$ Hz, while multi-wave modes represent two pairs of counter-rotating wave modes with a dominant frequency of $5,100 - 6,250$ Hz. The transition shown in Fig. 3c shows the transition mode alternating between two pairs of counter-rotating wave modes and a single-wave mode. The wave speeds for single-wave modes were calculated to be in the range of 66 to 84% of CJ velocity.
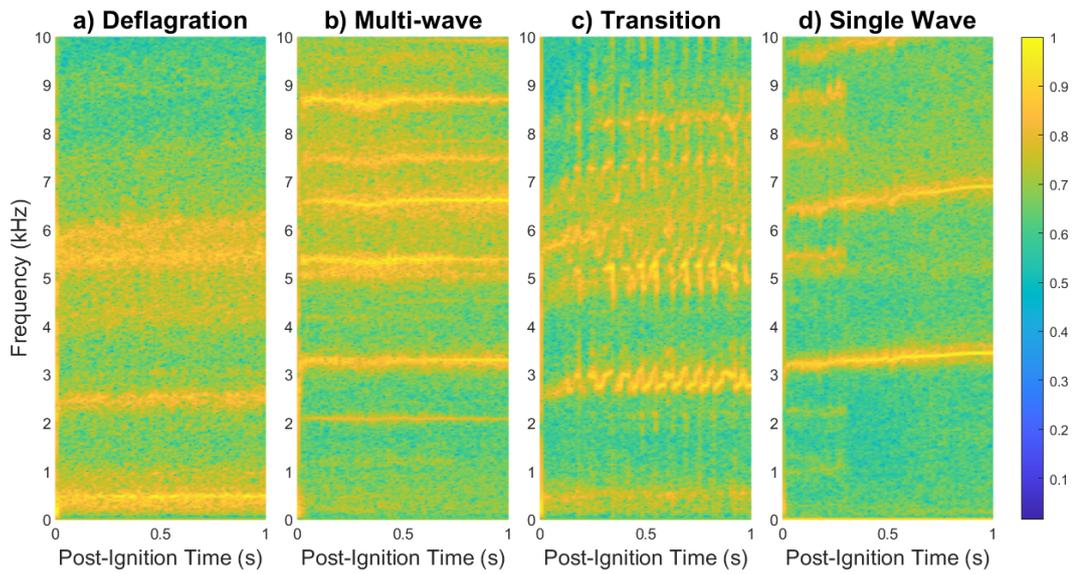

Figure 3: Short-time Fourier transform for different wave modes.

Figure 4 shows the wave modes observed in the 60 cases run. The error bars were obtained by propagating the 95% confidence interval of variations in mass flow rates throughout the duration of firing. Multi-wave modes represent two pairs of counter-rotating waves, while transition modes represent transitions either between single-wave and multi-wave, or between single-wave and deflagration modes. In general, the addition of dilution air after the exhaust of the disk-shaped PGC did not significantly impact the operating range of single-wave modes, except for dilution ratios of $\lambda \approx 0.4$, where the lean limit of single-wave detonation increased to 0.95. Two pairs of counter-rotating wave modes were generally observed under richer chamber equivalence ratio conditions. The high pressures caused by the passing detonation wave likely stopped the flow of fuel through the orifices more significantly than the flow of air through the slot. Hence, multiple wave modes can only be sustained at higher fuel flow rates when the recovery time of the fuel flow into the chamber is reduced.

The operation of a single-wave mode PGC is also observed with high dilution ratios of $0.8 < \lambda < 1.6$, indicating the possibility of using dilution as a cooling method to reduce the temperatures of detonation combustion exhaust gases in disk-shaped PGCs.
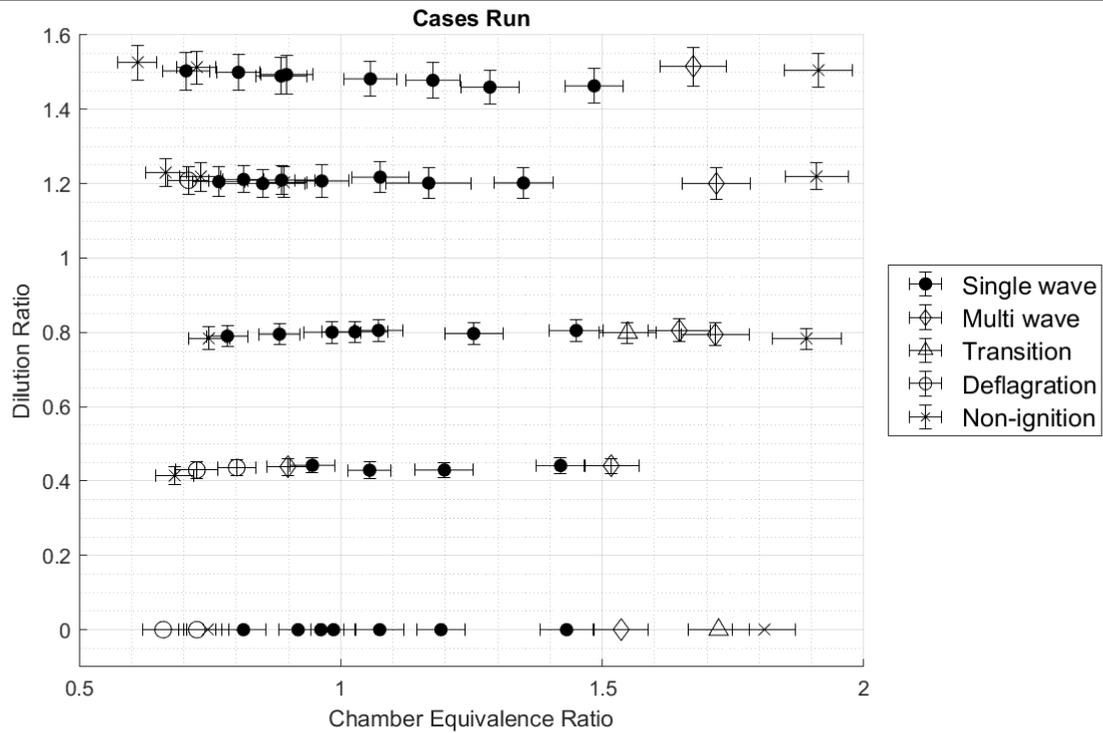
Figure 4: Wave modes observed.

3.2 Effect on Backpressure

Fotia et al. quantified the level of backpressure as the ratio of the mass flux in the nozzle to the mass flux in the combustion channel [2]. In the geometry of this disk-shaped combustor, the mass flux varies significantly within the combustion chamber, with the area at the outer diameter of the disk-shaped combustor being about 6 times larger than the area in the nozzle. The mass flux ratio in this paper is defined as the mass flux at the outer diameter of the combustor to the mass flux at the nozzle exit.

Figure 5 shows the chamber pressure before and after ignition. Before ignition, an increased dilution ratio led to an increase in chamber pressure, illustrating the higher backpressure produced in the combustor. After ignition, the chamber pressure of the single-wave modes generally produced pressures higher than those of the deflagration and multi-wave modes. Non-ignition cases, where no combustion was established, were omitted from this graph. In general, fuel-rich chamber mixtures ($\phi_c > 1$), indicated in red, produced chamber pressures that were higher than fuel-lean chamber mixtures ($\phi_c < 1$), indicated in blue. The suppressive effect of backpressure on the operation of the disk PGC is not clear, as single-wave modes can still be established at higher backpressures for mass flux ratios tested up to 16. A possible reason for the non-suppression of detonation initiation is the reduction in mass flux of approximately $17.8 \ \mathrm{kg/m^2s}$ at the chamber outer diameter to $112.7 \ \mathrm{kg/m^2s}$ at the chamber exit. This is in comparison to the mass flux of $40 - 115 \ \mathrm{kg/m^2s}$ which remains almost constant from the start of the combustion chamber to the location of dilution addition in experiments by Fotia et al. [2]. The Mach numbers in the nozzle were estimated using the properties measured in the nozzle. The Mach number of the combustor exhaust ranged from 0.20 to 0.29, while the Mach number at the middle of the nozzle ranged from 0.66 to 0.82. Most cases at and above the dilution ratio of 0.8 also exhibited choking at the nozzle exit when a detonation mode was in operation.
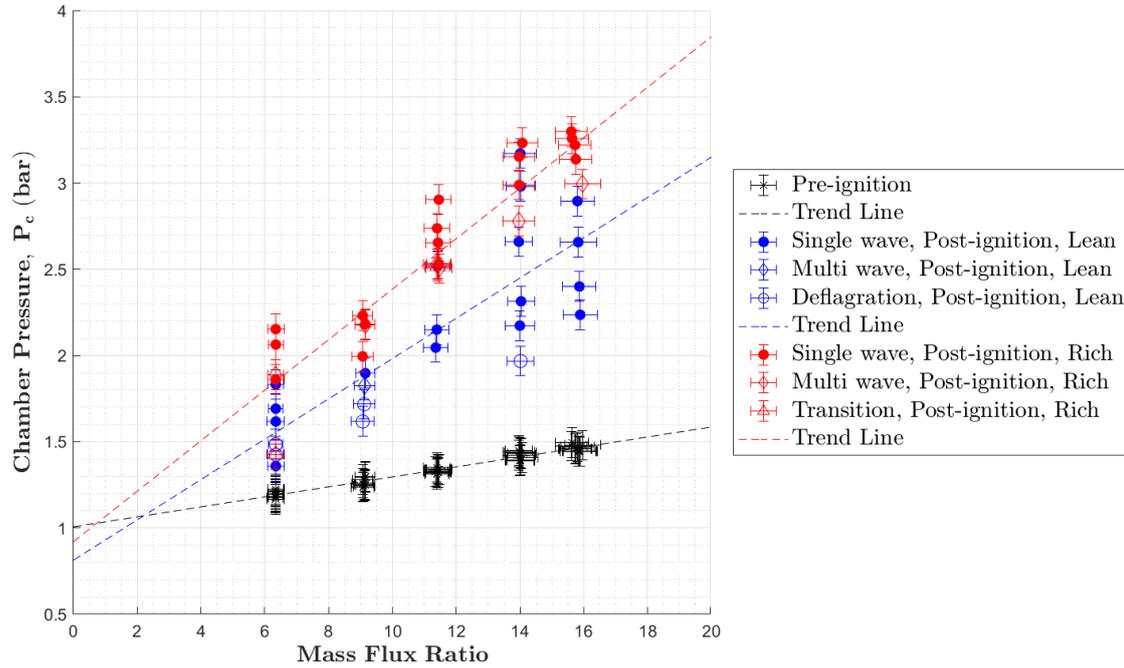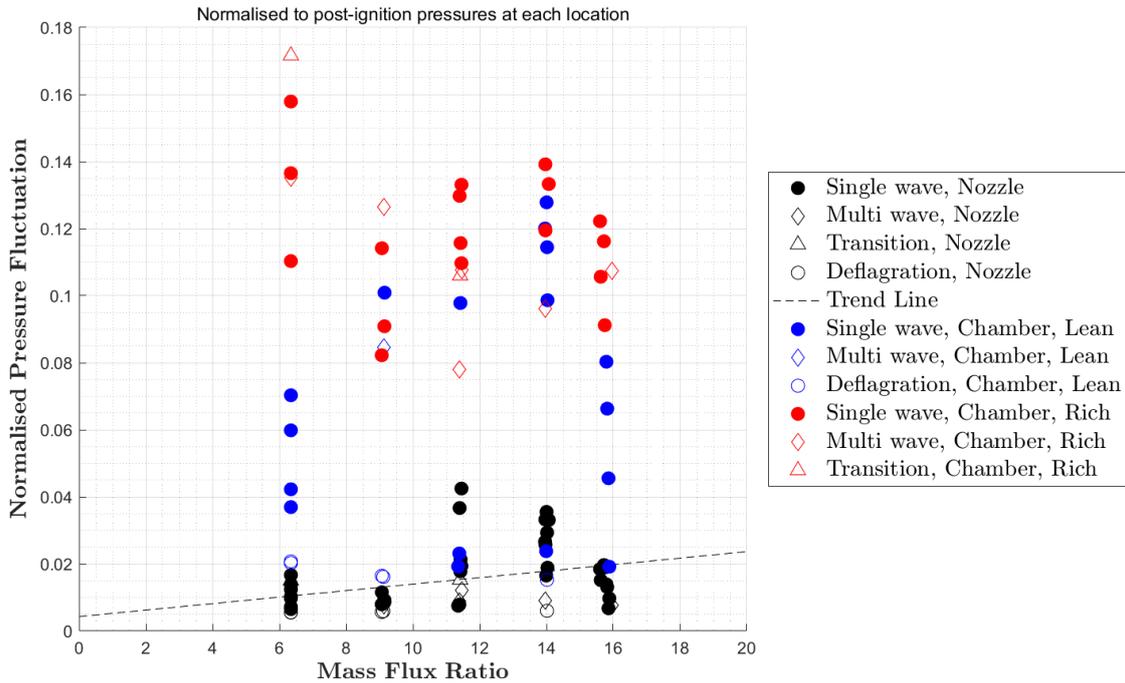
Figure 5: Backpressure effect on chamber pressure.

Figure 6: Backpressure effect on the normalised pressure fluctuations in the chamber and nozzle.

3.3   Effect on Shockwave Propagation

Annular combustors typically have significant shockwave propagation downstream as a result of the oblique shocks formed from the propagation of detonation waves. This may cause flow or structural

vibration problems with downstream devices, which are conventionally designed for steady flows. The shockwave propagation is investigated for the disk-shaped PGC, which has a significant converging area as the flow enters the nozzle; this paper attempts to quantify pressure spikes from the shockwaves to analyse the effect of backpressure.

The pressure fluctuations were determined by the range of pressure spikes as measured by the dynamic pressure PCB transducer, taking the difference between the 99th percentile of peaks and the 99th percentile of troughs in the signal. This measurement is then normalised by the averaged static pressure measurements measured by the CTAP at the respective locations. The resulting quantities are illustrated in Fig. 6. The normalised pressure spikes in both the chamber and the nozzle do not have a clear trend with the dilution ratio, but there is a significant reduction in the normalised pressure fluctuations from the chamber to the nozzle. At a mass flux ratio of 25, no dilution air was added, and normalised pressure fluctuation was reduced from up to 0.17 to 0.01. As the dilution ratio increases, the mass flux ratio also increases but did not result in further reduction of normalised pressure fluctuations in the nozzle. Hence, the reduction of pressure spikes from the chamber to the nozzle is likely primarily due to geometry, as the nozzle has a smaller cross-sectional area for flow. The pressure fluctuation in the nozzle was calculated to vary from 6 to 69% of that in the chamber, with the average ratio of normalised pressure fluctuation in the nozzle to the chamber for single-wave mode cases being 21.4%. High-speed pressure transducers (e.g. Kulite) should be used to measure fluctuations in the static pressure to give a better overall picture of pressure variations in the chamber and the nozzle, as these dynamic pressure transducers are limited in its ability to measure the pressure fluctuations.

4   Conclusion

In conclusion, the dilution of the exhaust of a $141\,\mathrm{mm}$ diameter disk-shaped PGC using room temperature air was explored. The ethylene-air disk PGC successfully operated with a range of wave modes observed for $\dot{m}_a = 132\,\mathrm{g/s}$. The wave modes observed were briefly described, and most runs exhibited a single-wave mode. The effects of backpressure were quantified and were not seen to significantly affect operation at the mass flow rates tested. The effects of pressure spikes were quantified, and the reduction in pressure spikes from chamber to nozzle was postulated to be primarily due to the geometry effects of the nozzle rather than by increases in dilution. The average ratio of the normalised pressure fluctuation values from the chamber to the nozzle was calculated to be 21.4% for single-wave modes. These results show promise in the use of disk-shaped PGCs for reducing pressure spikes and their operation with added dilution.

References

[1] M. Fotia, J. Hoke, and F. Schauer, *Experimental Ignition Characteristics of a Rotating Detonation Engine under Backpressured Conditions*, 2015.

[2] M. L. Fotia, J. Hoke, and F. Schauer, "Study of the ignition process in a laboratory scale rotating detonation engine," *Experimental Thermal and Fluid Science*, vol. 94, pp. 345–354, 2018.

[3] A. Lim, P. H. Chua, X. Huang, P.-H. Chang, Z. W. Teo, J.-M. Li, C. J. Teo, and B. C. Khoo, "Total temperature estimation through dilution of a disk-shaped pressure gain combustor," *Submitted to 13th International Workshop on Detonation for Propulsion*, 2024.

[4] F. Chacon and M. Gamba, "Detonation wave dynamics in a rotating detonation engine," 2019.