Design Considerations for a Premixed Rotating Detonation Combustor

Ken Matsuoka
Nagoya University/California Institute of Technology
Nagoya, Aichi, Japan / Pasadena, CA, USA

Donner T. Schoeffler
California Institute of Technology
Pasadena, CA, USA

Joseph E. Shepherd
California Institute of Technology
Pasadena, CA, USA

1 Introduction

A rotating detonation engine (RDE) [1] can realize continuous detonation wave in an annular or cylindrical combustor. In contrast to a pulse detonation engine, about 100-fold higher frequency operation can achieve higher thrust density with small combustor. Thus, RDEs could be utilized both as a rocket [2] and air-breathing [3] propulsion systems.

In the last decade, the pressure gain ratio, the product total pressure divided by that of reactant, has been investigated for RDE combustors. Models [4] indicate that pressure gain combustion (i.e., the total pressure ratio > 100%) could be achieved with a premixed reactant if there is no backflow of the high-pressure products into the upstream reactant manifold. However, there are many nonideal combustion effects [5] and other processes causing total pressure loss in RDE combustors. Matsuoka et al. [6] directly observed the backflow process of the high-pressure products. Bach et al. [7] measured the total pressure of the product by a Kiel stagnation pressure probe. They reported that the pressure gain ratio increased with increase in the ratio of injector cross-sectional area to combustor channel under the same reactant mass flux. They suggested that the total pressure loss in the reactant injection process was a significant factor in reducing the pressure gain ratio.

Using non-premixed oxidizer and fuel with mixing process occurring within the combustor complicates modeling and analyzing RDEs. A strategy to simplify modeling and control the total pressure loss associated with mixing is to use premixing of the fuel-oxidizer systems upstream of the combustor. Voitsekhobsky et al. [8] demonstrated a rotating detonation wave by using oxygen/acetylene premixed reactant and a disk-shaped combustor. Andrus et al. [9] carried out ethylene/air premixed RDE operation. The flashback of detonation wave into the manifold was successfully arrested by five narrow

Correspondence to: matsuoka@nuae.nagoya-u.ac.jp

slit injectors. The experimental propagation speeds of the detonation waves were approximately 1000 m/s, much lower than the CJ speed because fresh reactant mixed with the products created in the previous cycle of detonation propagation.

To clarify the relationship between injector total pressure loss and pressure gain by detonation, we will be carrying out tests using premixed reactants in a model RDE combustor. The paper describes the estimation of the total pressure loss in the injection and mixing processes, and the design and fabrication details of the RDE combustor test facility.

2 Total Pressure Loss Estimation in Injection and Mixing Process

Total pressure loss is created by the abrupt expansion of the flow at the injector exit. To estimate the loss, an integral analysis was carried out using the control volume shown in Fig. 1. The inlet surface (subscripts: inj) is placed in the uniform flow upstream of the expansion. The outlet surface (subscripts: c) is located sufficiently far downstream of the expansion in uniform flow leading into the combustor. In the case of subsonic injection (i.e., Mach number at the inlet $M_{\mathrm{inj}} < 1$), the pressure p_{s} on the left surface is assumed to be equal to the inlet pressure p_{inj}.

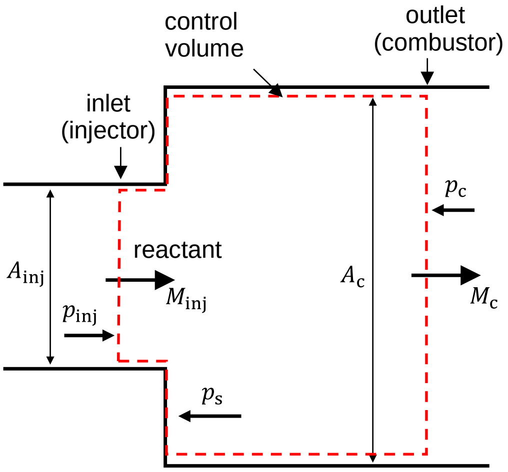

Figure 1: Control volume at reactant injector

Assuming a compressible, steady flow of an ideal gas with constant specific heat ratio γ, we used the conservation of mass, momentum, and energy in the control volume to determine the total pressure ratio,

$$\frac{p_{\mathrm{t,c}}}{p_{\mathrm{t,inj}}} = \phi \frac{M_{\mathrm{c}}}{M_{\mathrm{inj}}} \left[\frac{2 + (\gamma - 1)M_{\mathrm{c}}^2}{2 + (\gamma - 1)M_{\mathrm{inj}}^2}\right]^{\frac{\gamma+1}{2(\gamma-1)}},$$

where p_{t} is total pressure, and ϕ is cross-sectional area ratio $A_{\mathrm{inj}}/A_{\mathrm{c}}$. For specified values of γ, M_{inj} and ϕ, the outlet Mach number M_{c} can be obtained as a solution to:

$$\frac{M_{\mathrm{inj}}\sqrt{2 + (\gamma - 1)M_{\mathrm{inj}}^2}}{(1/\phi) + \gamma M_{\mathrm{inj}}^2} = \frac{M_{\mathrm{c}}\sqrt{2 + (\gamma - 1)M_{\mathrm{c}}^2}}{1 + \gamma M_{\mathrm{c}}^2},$$

Fig. 2 shows the total pressure loss corresponding to the inlet Mach number M_{inj}. The specific heat ratio was constant at $\gamma = 1.4$. The symbols in Fig.2 are the experimental values taken by Benedict et al. [10]. The typical RDEs [6], [7] have the cross-sectional area ratio $0.1 < \phi < 0.5$. If the RDE operates under the condition close to sonic injection, the total pressure loss become significant. This result shows that in order to reduce total pressure loss it is necessary to minimize the injection Mach number, or increase the cross-sectional area ratio. However, if we increase ϕ or decrease M_{inj} excessively, this may result in insufficient mixing and reactant fill height for sustaining detonation wave.

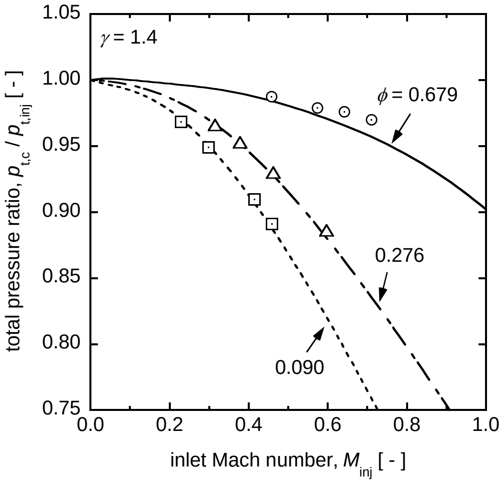

Figure 2: Total pressure loss by abrupt expansion,
symbols are experimental values taken by Benedict et al. [10]

The total pressure loss by mixing was also estimated by a control volume analysis. Figure 3 shows the control volume in which the oxidizer (subscript: o) and fuel (subscript: f) are injected parallel into the combustor and fully mixed reactants exit as parallel flow downstream. The inlet pressures p_{o} and p_{f} were assumed to be identical.

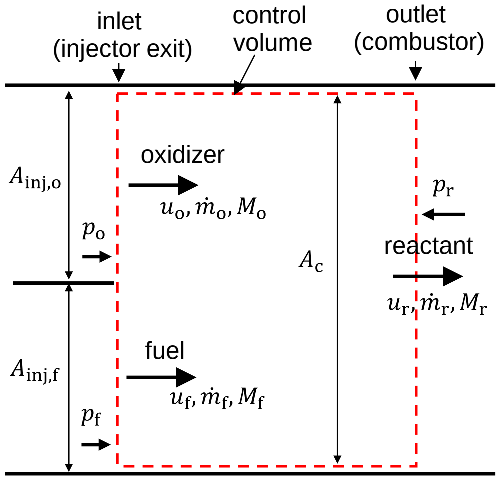

Figure 3: Control volume for parallel injection

Using the same assumptions and methodology as in the abrupt expansion case, the total pressure ratio is determined to be

$$\frac{p_{\mathrm{t,r}}}{p_{\mathrm{t,o}}} = \frac{\alpha+1}{1+\psi}\frac{M_{\mathrm{o}}}{M_{\mathrm{r}}}\frac{\sqrt{(\gamma-1)(1+\alpha\beta^2)M_{\mathrm{o}}^2+2+2\beta\psi}}{\sqrt{(1+\alpha)[2+(\gamma-1)M_{\mathrm{r}}^2]}}\frac{\left(1+\frac{\gamma-1}{2}M_{\mathrm{r}}^2\right)^{\frac{\gamma}{\gamma-1}}}{\left(1+\frac{\gamma-1}{2}M_{\mathrm{o}}^2\right)^{\frac{\gamma}{\gamma-1}}},$$

where the subscript r is reactant, α is the ratio of the mass flow rate $\dot{m}_\mathrm{f}/\dot{m}_\mathrm{o}$, β is the ratio of the inlet velocity $u_\mathrm{f}/u_\mathrm{o}$, and ψ is the injector cross-sectional area ratio $A_\mathrm{inj,f}/A_\mathrm{inj,o}$. For specified values of α, β, ψ, and M_o, the reactant Mach number M_r can be obtained as a solution to

$$\frac{1+\gamma M_\mathrm{r}^2}{M_\mathrm{r}\sqrt{(1+\alpha)[2+(\gamma-1)M_\mathrm{r}^2]}} = \frac{1}{1+\alpha}\left[\frac{\gamma M_\mathrm{o}^2(\alpha\beta+1)+\psi+1}{M_\mathrm{o}\sqrt{(\gamma-1)(1+\alpha\beta^2)M_\mathrm{o}^2+2+2\beta\psi}}\right],$$

Figure 4 shows the ratio of reactant to oxidizer total pressure, $p_\mathrm{t,r}/p_\mathrm{t,o}$ for $\alpha = 0.29$, $\beta = 1$, and $\gamma = 1.4$. The total pressure ratio increases with increasing M_o at a constant area ratio $\psi = 0.1$. In contrast to this trend, the ratio of reactant to fuel total pressure, $p_\mathrm{t,r}/p_\mathrm{t,f}$ decreases and the total entropy in the control volume increases. In this model, the temperature ratio $T_\mathrm{f}/T_\mathrm{o}$ of oxidizer and fuel at the inlet are related by

$$\frac{T_\mathrm{f}}{T_\mathrm{o}} = \frac{\beta\psi}{\alpha},$$

If $\alpha = 0.29$ and $\beta = 1$, the temperature difference is zero at $\psi = 0.29$ and the entropy generation was minimized. The range of ψ for a typical RDE [3], [6] is approximately $0.05 < \psi < 0.2$. We conclude that the total pressure loss due mixing is insignificant compared to the loss due to area expansion in the injection process.

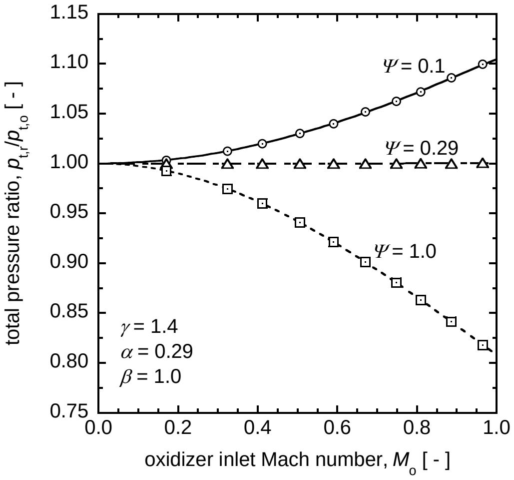

Figure 4: Total pressure loss by parallel injection mixing

3 Design of a Premixed Rotating Detonation Engine System

Based on these considerations we have designed an RDE combustor using premixed reactants.

Figure 5 shows the photograph of the assembled system of our premixed RDE combustor test facility. This system consists of a 1.2 m^3 dump tank, annular combustor, reactant manifold, pre-detonator, and mixing chamber. A fan is located within the mixing chamber to ensure complete mixing of oxidizer and fuel which are measured using the method of partial pressures. The dump tank and RDE section (manifold, combustor, and pre-detonator) are isolated by a thin diaphragm. At the beginning of test, the entire system is evacuated, then oxidizer and fuel are filled into the RDE section and mixed. To start the test, a knife mounted on an air cylinder ruptures the diaphragm. When the diaphragm is ruptured, the pressure difference creates flow from the manifold through the annular combustor into the dump tank. A spark plug ignites the reactant mixture in the pre-detonator, transition-top-detonation creates a detonation wave that starts detonation rotation within the annular combustor. Six remotely controlled pneumatic valves are used to control the processes of evacuation, gas filling and mixing, and air cylinder motion.

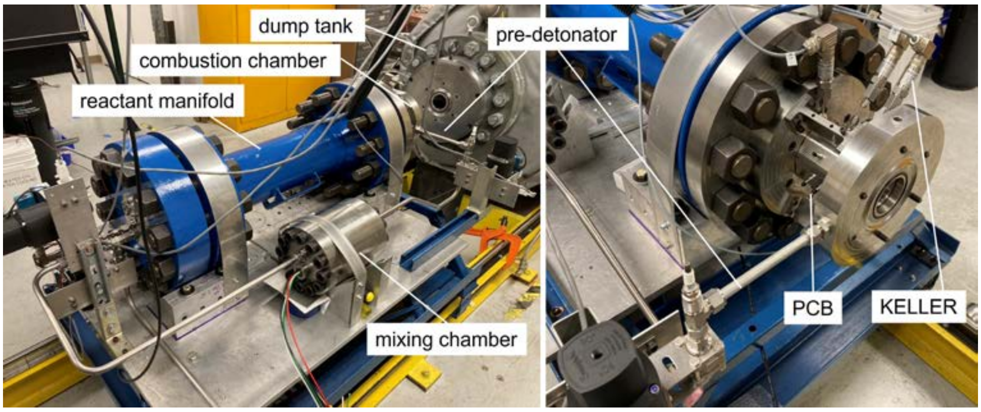

Figure 5: Premixed RDE system (left) and annular-shaped RDE combustor (right)

The outer diameter, channel width and length to diameter ratio of the annular combustor are 60 mm, 2.5 mm and 38, respectively. The reactant is injected in the combustor axial direction from the slit injector with a gap of 0.5 mm and length to diameter ratio of 20. The injector to channel area ratio, $A_{\mathrm{inj}}/A_{\mathrm{c}} = 0.20$ or 20%. The annular combustor has six piezoresistive pressure sensors (KELLER 23SY/23SHB series) and eight piezoelectric pressure transducers (PCB 113B26 series) to measure the time-averaged static pressure and detonation dynamic pressure, respectively. The manifold has a thermocouple and piezoresistive pressure sensors to estimate the reactant mass flow rate.

The duration of the reactant choking flow at the injector exit and reactant mass flux in the combustor channel were estimated using control volume method [11]. The reactants in the 10 L manifold were initially at 300 K, and the 1.2 m^3 dump tank pressure was set at 100 Pa. The effect of varying initial manifold pressure on test time was investigated by assuming that the reactant flow was choked (sonic) at the slit injector exit. The 70% of the ideal mass flow rate flowed into the combustor. The same amount of product at 3000 K was exhausted to the dump tank. The specific heat ratio was assumed to be constant at $\gamma = 1.4$.

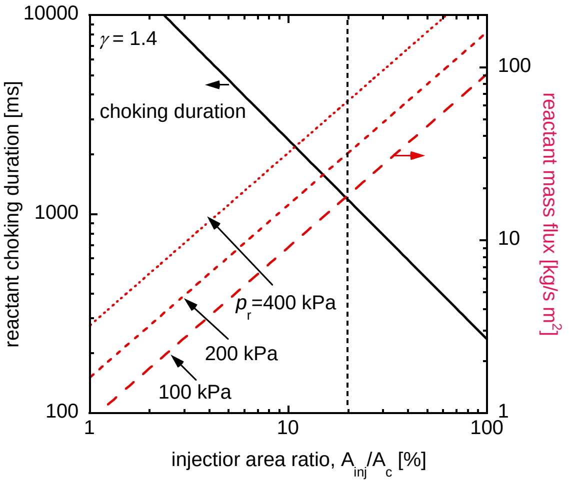

Figure 6: Choking duration and mass flux of reactants

As shown in Fig. 6, the choking duration in the range of the reactant initial pressure of 100 to 400 kPa was estimated to be on the order of a few seconds under the condition of $A_{\mathrm{inj}}/A_{\mathrm{c}} = 20\%$. The choking-duration-averaged mass flux of the reactant was in the range of 20 to 80 kg s^{-1} m^{-2}. According to Matsuoka et al. [6], the rotation of a single detonation wave is possible in a non-premixed ethylene-oxygen mass flux of 31.5 kg s^{-1} m^{-2}, combustor outer diameter of 60 mm, and $A_{\mathrm{inj}}/A_{\mathrm{c}} = 10$ to 50%. On this basis we expect to obtain a sufficient number of detonation rotation cycles to obtain useful data during the choked flow operation.

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References

[1] Bykovskii FA, Zhdan SA, Vedernikov EF. (2006). Continuous spin detonations. Journal of Propulsion and Power. 22: 1204.

[2] Goto K, Matsuoka K, Matsuyama K, Kawasaki A, Watanabe H, Itouyama N, Ishihara K, Buyakofu V, Noda T, Kasahara J, Matsuo A, Funaki I, Nakata D, Uchiumi M, Habu H, Takeuchi S, Arakawa S, Masuda J, Maehara K, Nakao T, Yamada K. (2023). Space flight demonstration of rotating detonation engine using sounding rocket S-520-31. 60: 273.

[3] Rankin, BA, Richardson, DR, Caswell, AW, Naples, AG, Hoke JL, Schauer FR. (2017). Chemiluminescence imaging of an optically accessible non-premixed rotating detonation engine. Combust. Flame. 176: 12.

[4] Kaemming TA, Paxson DE. (2018). Determining the pressure gain of pressure gain combustion. 2018 Jt. Propuls. Conf. AIAA 2018–4567.

[5] Chacon F, Gamba M. (2019). Study of parasitic combustion in an optically accessible continuous wave rotating detonation engine. AIAA Scitech 2019 Forum. AIAA 2019–0473.

[6] Matsuoka K, Tanaka M, Noda T, Kawasaki A, Kasahara J. (2021). Experimental investigation on a rotating detonation cycle with burned gas backflow. Combust. Flame. 225: 13.

[7] Bach E, Paschereit CO, Stathopoulos P, Bohon MD. (2021). An empirical model for stagnation pressure gain in rotating detonation combustors, Proc. Combust. Inst. 38: 3807.

[8] Voitsekhovsky BV. (1960). Spinning maintained detonation. Journal of Applied Mechanics and Technical Physics. 3: 157 (In Russian)

[9] Andrus IQ, Polanka MD, King PI, Schauer FR, Hoke JL. (2017). Experimentation of premixed rotating detonation engine using variable slot feed plenum. Journal of Propulsion and Power. 33: 1448.

[10] Helmbold HB, Luessen G, Heinrich AM. (1954). An experimental comparison of constant pressure and constant diameter jet pumps. Engineering report No. 147. University of Wichita.

[11] Matsuoka K, Takagi S, Kasahara J, Matsuo A, Funaki I. (2018). Validation of pulse-detonation operation in low-ambient-pressure environment. Journal of Propulsion and Power. 34: 116.