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Performance of rotating detonation engine with stratified injection*

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Abstract: In this study, a numerical study based on Euler equations and coupled with detail chemistry model is used to improve the propulsion performance and stability of the rotating detonation engine. The proposed fuel injection called stratified injection functions by suppressing the isobaric combustion process occurring on the contact surface between fuel and detonation products, and thus the proportion of fuel consumed by detonation wave increases from 67% to 95%, leading to more self-pressure gain and lower entropy generation. A pre-mixed hydrogen-oxygen-nitrogen mixture is used as a reactive mixture. The computational results show that the propulsion performance and the operation stability of the engine with stratified injection are both improved, the temperature of the flow field is notably decreased, the specific impulse of the engine is improved by 16.3%, and the average temperature of the engine with stratified injection is reduced by 19.1%.

Key words: Rotating detonation engine; Injection pattern; Propulsion performance; Instability
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1 Introduction

Detonation combustion is a kind of chemical reaction pattern that can yield a higher heat release rate but lower entropy production compared to the ordinary isobaric combustion. Due to the unique advantages of detonation combustion, more scholars have begun to pay attention to the use of detonation to achieve aerospace propulsion. In recent years, the use of detonation for energy release in engines has attracted worldwide attention. Rotating detonation engine (RDE) has a simple structure, which can provide continuous thrust and only requires one ignition. These advantages and expected application prospects brought RDEs a lot of attention. To bring the concept of RDE into practical use, significant studies have been performed. In 1960, rotating detonation was shortly achieved by Voitsekhovskii (1960), and up to now, many characteristics of the RDE have been widely explored.

As injection remains the key issue affecting RDE's performance, a large number of studies on the effect of injection have been carried out (Liu et al., 2015; Tsuboi et al., 2015; Gaillard et al., 2017; Smirnov et al., 2018, 2019; Zhang et al., 2018; Wang et al., 2019; Zheng YS et al., 2019). Smirnov et al. (2018, 2019) tested the initiation and propagation process of rotating detonation wave using three types

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of gas mixture and different injection patterns. In their studies, the rich mixture and the lean mixture kept the initial rotating detonation regime. Unusual phenomena were discovered in the stoichiometric mixture case: the detonation wave passed normally in the first cycle; then, some other secondary waves appeared consuming the fresh mixture and extinguishing the primary wave. Also, it was demonstrated that the lateral injection of oxygen increased the stability of the rotating detonation wave in their small model chamber (length 10 cm and width 5 cm). In the simulation conducted by Zhang et al. (2018), the effects of injection conditions were explored using micro-convergent-nozzle injection. An unstable detonation wave was found propagating circumferentially at the fuel inlet. Meanwhile, the shape of the injected mixture layer was irregular, which was regarded as an instability phenomenon. The oscillation of the detonation wave was thought to be connected to the interaction of fuel injection and weak transverse shock wave. Wang et al. (2019) experimentally studied the effect of the throat width of plug nozzles on the combustion mode in RDE, and showed that the throat width was crucial to the operation mode of the engine. Zheng YS et al. (2019) analyzed the initiation process of the RDE with three different injection patterns. In their study, the transition time, the distribution of the fresh mixture, and the formation of the detonation wave were found to be related to the injection patterns. Tsuboi et al. (2015) compared the thrust performance of the RDE under different injection conditions and found either the specific impulse or the thrust was governed by the mass flow rate of injected fuel. Liu et al. (2015) investigated five different injection patterns. Their results showed that it was the interaction of the products and fresh gas occurring on the fuel-detonation products' contact surface that affected the detonation stability. In (Gaillard et al., 2017), a developed flame surface was observed around the fuel-detonation products' contact surface. Injection through discrete holes caused nearly 30% consumption of the injected mass by deflagration, which was unfavorable to the improvement of the thermal cycle efficiency.

It can be inferred from the above discussion that there exists deflagration combustion on the contact surface between fuel and detonation products. This isobaric combustion process has lower thermal cycle efficiency than detonation combustion and may cause detonation instability. Conventional interval injection patterns barely have the ability to restrain such deflagration combustion. Also, only a few injection strategies have been designed to weaken the contact-surface chemical reaction deliberately (Edwards, 1977). Thus, a new injection pattern named "stratified injection" is designed for decreasing the contact-surface chemical reaction in an RDE. The design has no moving mechanical parts or valves. In the first half of this study, the physical model and realization method of stratified injection pattern are described. We alter the conventional interval injection by adding inert gas injectors around fuel injectors, and the injected fuel is stratified by inert gas. The second part of this study is to analyze the flow field and propulsion performance of the engine with stratified injection. The difference between the conventional interval injection method and stratified injection method is compared, and results show that the thrust performance and the operation stability are notably improved under new injection pattern. This study will help in designing the injection system of RDEs.

2 Physical model and numerical method

2.1 Physical model and computational domain

The combustor of a traditional RDE is shown in Fig. 1. The annular rotating detonation chamber (RDC) has a length of 100 mm, and the average diameter of the annular combustion chamber is 95.5 mm. The detonation wave (DW) continues to consume the newly injected mixture circumferentially near the bottom. Detonation product is ejected from the top outlet. This special mixture injection method of RDE can provide fresh reactive mixture in front of DW, and so DW can continue to revolve around the axis. In this study, we focus on the propulsion performance of the engine with stratified injection and its improvement in comparison to the interval injection method. In (Tsuboi et al., 2015), the difference of propulsion performance calculated by the 2D and 3D simulations was evaluated. The specific impulse for the 2D RDE is only 10 s larger than the specific impulse for the 3D RDE. In addition, the overall flow structure coincides. Thus,

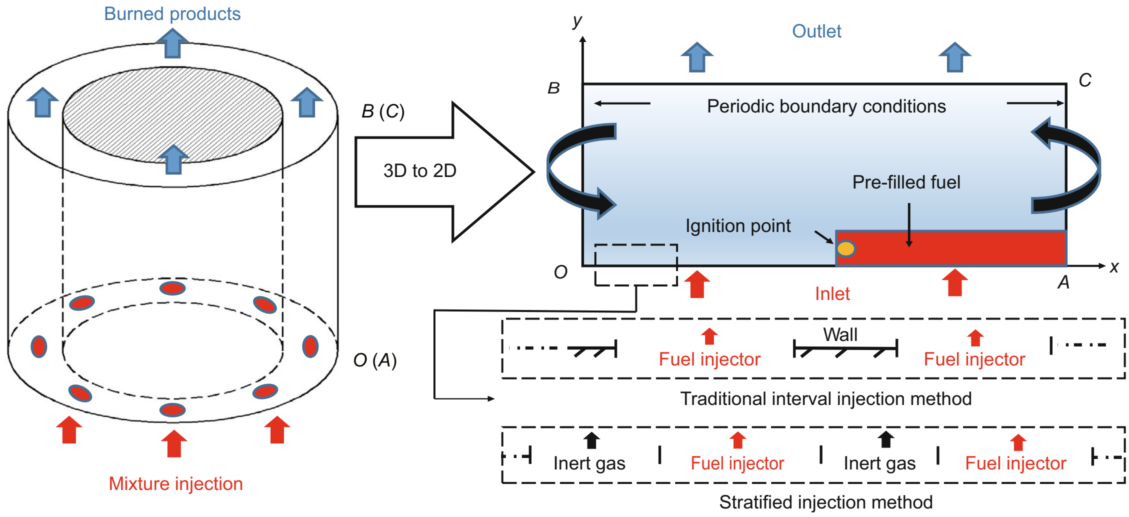

Fig. 1 Combustion chamber and computational domain

the chamber radial height is assumed negligible relative to the mean radius in this study. The 3D model is changed to a 2D model for calculation. Fig. 1 shows the 2D calculation domain $OBCA$, which is obtained by unwrapping the 3D model. These simplification methods can give reasonable results when the thickness of combustion chamber is negligible (Kindracki et al., 2011; Fujii et al., 2017; Deng et al., 2018). OB and AC are identical lines before the computational domain is deformed, which are connected by setting periodic boundary conditions. The open exit is BC, and the length of OB is 100 mm and that of BC is 300 mm. Inlets and headwalls locate on OA.

In the early stage, for convenience and computational efficiency, full-area injection (every grid point on inlet is used as fuel injection nozzle) is used to approximate the fuel injection process in most simulations (Tsuboi and Hayashi, 2007; Fujiwara et al., 2009). However, the actual fuel injection in most experiments is accomplished by holes, slits, or their combination. Later, more practical injection method is proposed, and individual injectors are used for RDE simulations (Schwer and Kailasanath, 2011; Dubrovskii et al., 2015). In (Yao et al., 2015, 2017), some important experimental observations were captured, such as the spontaneous formation of new DWs, which were usually absent in conventional RDE simulations with full-area injection. The essential difference between practical injection pattern and full-area injection is that the former blocks some specific area on the inlet plane, and thus the injection of fuel is interval. The interval injection method conforms more to the actual conditions in experiments and has the ability to reveal some important phenomena in RDEs.

2.2 Problem statement

To improve the propulsion performance and stability of the rotating detonation engine, a new injection pattern named stratified injection is tested and compared with the traditional interval injection pattern. Two engine models are simulated in this study, one is using the traditional interval injection method, while the other using the newly proposed stratified injection method. Settings are identical in both engine models except the inlet conditions on boundary OA. In the interval injection model, fuel injectors (orifices) are virtual converging nozzles which are evenly distributed on the inlet OA. The width of each fuel injector is 4 mm and the number of fuel injectors is 50. The nozzles are separated by walls, and each wall length is 2 mm. In the stratified injection model, fuel injectors are identical to those in the interval injection model. The difference is that the fuel injectors are separated by inert gas injectors instead of the walls. The width of each inert gas injector is 2 mm and the number of inert gas injectors is 50. The injector distributions of two injection methods adopted in this study are shown in Fig. 1. The mixture injection total pressure p_{st} is 10 atm (1 atm=101 325 Pa) and injection total temperature

T_{st} is 600 K. Reactive mixture is premixed hydrogen, oxygen, and nitrogen (2 : 1 : 7.3). The inert gas injectors provide pure argon with the same state parameters. Mixture injection process is assumed as isentropic flow, and the inlet parameters (p_{in}, T_{in}, and u_{in}) are determined by the pressure p near the inlet. If $p > p_{st}$, the inlet boundary is closed.

$$p_{in} = p,\ T_{in} = T,\ u_{in} = 0, \tag{1}$$

where T is the boundary temperature in the combustor, and u_{in} is the normal value of the velocity field at the boundary. When $p_{cr} \leq p \leq p_{st}$, where p_{cr} is the critical pressure, the inlet parameters are calculated according to the isentropic solutions:

$$p_{in} = p, \tag{2}$$

$$T_{in} = T_{st}\left(\frac{p_{in}}{p_{st}}\right)^{\frac{\gamma-1}{\gamma}}, \tag{3}$$

$$u_{in} = \sqrt{\frac{2\gamma}{\gamma-1}RT_{st}\left[1-\left(\frac{p_{in}}{p_{st}}\right)^{\frac{\gamma-1}{\gamma}}\right]}, \tag{4}$$

$$p_{cr} = p_{st}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}, \tag{5}$$

where γ is the specific heat ratio of the mixture, and R is the gas constant. When $p \leq p_{cr}$, $p_{in} = p_{cr}$, boundary temperature and velocity are calculated by Eqs. (3) and (4), respectively. Pressure and temperature in the combustor before ignition are p=1 atm and T=293 K. Outlet pressure p_{out} is obtained by

$$p_{out} = p \cdot (1-r) + p_{\infty} \cdot r, \tag{6}$$

where r is a constant equal to 0.05, p is the combustor pressure close to the outlet, and p_{∞} is the environment pressure (1 atm). Such boundary condition is non-reflective and has no influence on the propagation of developed DW (Gamezo et al., 1999). In experiments, the pre-detonator is widely used to initiate an RDE by "injecting" DWs into the combustion chamber tangentially. To achieve ignition, a small square area is set with higher temperature and pressure. Ignition point rapidly detonates the reactive mixture and thus initial DWs are obtained.

2.3 Governing equations and computational methods

Euler equations with additional chemical reactions are used as governing equations, the same with Lei et al. (2020).

Fractional step method (Yanenko, 1971), also known as time splitting approach, is used to solve the Euler equations. Thus, the transport process is decoupled from the reactive one. Stiff ordinary differential equation system related to chemical reaction model is solved using the semi-implicit Bulirsch-Stoer method (Bader and Deuflhard, 1983). Convective terms in governing equations are calculated with the scheme of Kurganov et al. (2001). The second-order Crank-Nicolson scheme is used for time evolution.

3 Results

3.1 Grid independence analysis

This study aims to investigate the propulsion performance of the engine. The average grid size of 0.2 mm is used. As DW propagates near the lower area which is close to the inlet, the grid is stretched in the y direction. The minimum grid size Δy is 0.1 mm and the average Δy is 0.2 mm. Grid size in x direction (Δx) is fixed at 0.2 mm. A 1D detonation tube is adopted to validate the code and verify the grid independence. Four kinds of orthogonal grid sizes are 0.1, 0.2, 0.5, and 1.0 mm. The stoichiometric hydrogen-air mixture is filled in the calculation domain at the initial pressure p=1 atm and temperature T=293 K. Table 1 shows the comparison between simulation results, theoretical solutions (Deng et al., 2018), and experimental data (Ginsberg et al., 1994).

It can be seen in Table 1 that both the velocity of DW and the pressure at the Chapman-Jouguet point are close to the theoretical values and experimental results when grid size is equal or less than 0.5 mm. Thus, the algorithm is validated in terms

Table 1 Comparison between simulation results, theoretical solutions (Deng et al., 2018), and experimental data (Ginsberg et al., 1994)

Item	Grid size (mm)	u_{DW} (m/s)	Error (%)	p_{CJ} (MPa)
Simulation	1.0	1960.0	0.835	1.72
	0.5	1970.6	0.299	1.71
	0.2	1971.9	0.233	1.69
	0.1	1972.0	0.228	1.68
Theoretical solution	–	1976.5	–	1.61
Experimental data	–	1970.0	–	–

u_{DW}: velocity of detonation wave; error: error of u_{DW} with theoretical value; p_{CJ}: pressure at Chapman-Jouguet point of the detonation velocity. Furthermore, for 2D simulation of the stratified injection case, the flow field is computed based on 0.1-mm grid size and 0.2-mm (averaged) grid size. Pressure contours are shown in Fig. 2. It can be seen that although the 0.1-mm grid system revealed fine structures of DW, the essential features of rotating detonation field such as pressure distributions do not have a remarkable difference. Both thrust performances and operation frequencies are close to each other. Thus, the above comparison proves the numerical convergence and grid independence.

3.2 Flow field of stratified injection

Compared with interval injection, stratified injection has the same fuel injectors but extra inert gas injectors are added around them (Fig. 1). Both engines are operating at one-wave mode (there exists only one DW propagating in the combustor) after ignition. The operation frequency of the engine with interval injection is 5096.8 Hz and the operation frequency of the engine with stratified injection

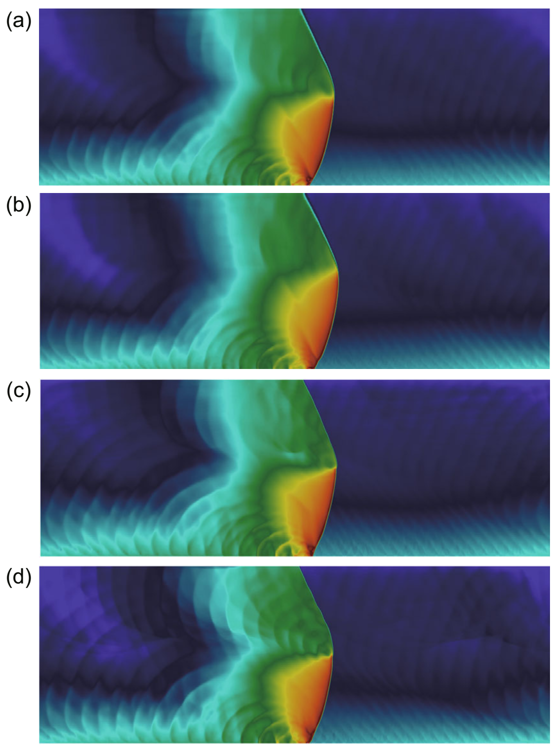

Fig. 2 Pressure contours given by different grid systems: (a) 0.2-mm (averaged) grid size, t = 1196 μs; (b) 0.2-mm (averaged) grid size, t = 2217 μs; (c) 0.1-mm grid size, t = 1196 μs; (d) 0.1-mm grid size, t = 2217 μs

is 4527.2 Hz, and the corresponding velocities of DW are 1529.1 m/s and 1358.2 m/s, respectively, for the engine with interval and stratified injection. The decrease of velocity is attributed mainly to the following two reasons: (1) the distribution of reactive mixture is discontinuous due to stratified injection; (2) the extra injected argon dilutes the reactive mixture. A similar velocity decrease phenomenon was reported and analyzed by Fujii et al. (2017) in their numerical investigation.

Fig. 3 shows the hydrogen distribution, temperature field, and heat release energy of the engines with interval injection and stratified injection. The main difference is the distribution of reactive mixture. Figs. 3a and 3b are the hydrogen mass fraction contours. As shown in Fig. 3a, the distribution of hydrogen is continuous in most areas when interval injection is applied. This is due to the newly injected fresh mixture which expands and fills all the space around the inlet plane gradually. The distribution of hydrogen with stratified injection is shown in Fig. 3b, where the existence of extra inert gas squeezes the expansion area for hydrogen, and thus the hydrogen is less expanded and its distribution stratified. Typical structures of rotating detonation flow fields are described in Figs. 3c and 3d. In the interval injection condition, the fresh mixture (blue area in Fig. 3c) is directly injected into the detonation products whose temperature is over 1700 K. The heat release energy shown in Fig. 3e indicates 33% of the injected fuel is consumed at the surface of contact, so only 67% of the reactive mixture is burned by detonation combustion. A similar phenomenon is also observed by Gaillard et al. (2017) that 30% of the injected mass is consumed by the contact-surface chemical reaction. Such chemical reactions burn fuel at approximately constant pressure conditions, so they generate more entropy than detonation combustion (Kailasanath, 2000; Heiser and Pratt, 2002), which is unfavorable to improve the thermal cycle efficiency. The temperature field of stratified injection is shown in Fig. 3d. Due to the special layout of the nozzles, most of the fuel-detonation products contact surface is replaced by fuel-inert gas contact surface. As stratified injection method reduces the contact area between reactive mixture and high-temperature detonation products effectively, the heat release energy on the contact surface is lower (Figs. 3e and 3f), and only 5% of the injected fuel is consumed at the surface of

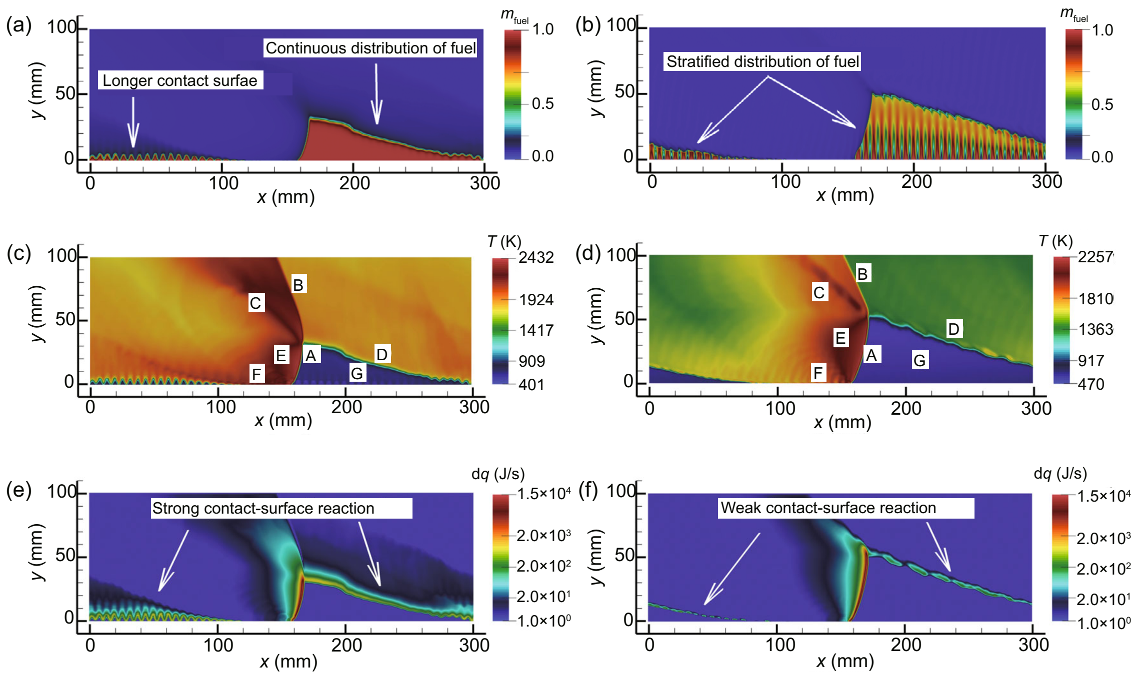

Fig. 3 Comparison of the flow fields using interval injection and stratified injection: (a) hydrogen distribution of interval injection; (b) hydrogen distribution of stratified injection; (c) temperature field of interval injection; (d) temperature field of stratified injection; (e) heat release energy (dq) of interval injection; (f) heat release energy of stratified injection

m_{fuel}: mass fraction of premixed fuel. A: DW; B: oblique shock wave; C: shear layer; D: fuel-detonation products' contact surface; E: expansion region; F: blocking region; G: triangular fuel bed. References to color refer to the online version of this figure

contact. This fact indicates that the contact-surface chemical reaction is weakened.

The relatively high temperature of combustor not only makes it difficult to obtain manufacturing materials but also becomes a barrier to practical long-time operation. In addition, the integration with a gas-turbine also requires the temperature of the combustor outlet to be within a certain range. The thermal fatigue life would decrease if the total temperature of turbine inlet gas increases (Zheng XQ et al., 2011).

The average temperatures of the combustor ($T_{\mathrm{Combustor}}$) and the outlet plane (T_{Outlet}) are shown in Fig. 4. When the engine is operating with an interval injection pattern, the time-averaged temperatures of the combustor and at the outlet plane are 1648.3 K and 1710.1 K, respectively. The corresponding temperatures of the engine with stratified injection pattern are 1310.2 K and 1382.7 K, respectively. Due to the existence of an unburned mixture in the combustors, the averaged outlet temperature is higher than the averaged combustor temperature

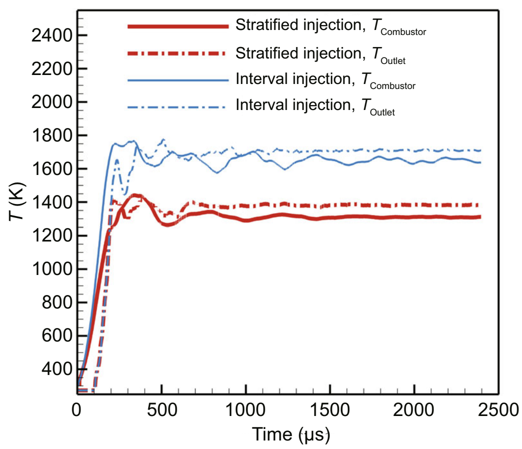

Fig. 4 Average temperature-time profile

in both cases. By applying the stratified injection method, the outlet temperature of the engine is reduced by 327.4 K, which is 19.1% lower than the engine with the traditional interval injection method. The typical distribution of temperature along x axis at the outlets is shown in Fig. 5. DWs propagate from left to right and both locate around $x = 0.16$ m. The

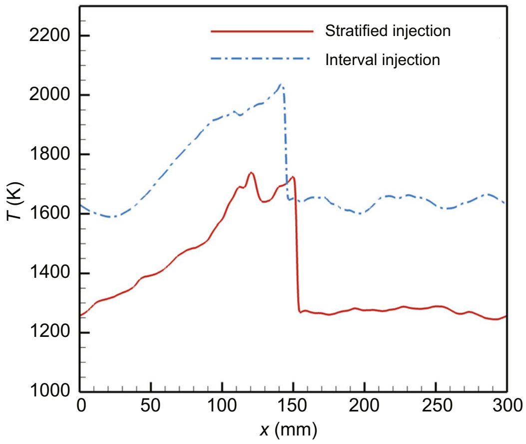

Fig. 5 Temperature distribution along x axis at the outlets

peak temperatures are caused by detonation products heated by oblique shock waves. It can be seen from Fig. 5 that the application of stratified injection reduces the maximum temperature by 285 K compared with interval injection method. The decrease of temperature is primarily due to the added argon. In this scenario, the massive inert gas acts as coolant. Therefore, stratified injection proposed in this study is beneficial to reduce the temperature of the combustion chamber.

3.3 Propulsion performance with stratified injection

Thrust and specific impulse are critical indexes to evaluate the propulsion performance of an engine. The fuel mass flow rate $\dot{m}_\mathrm{f}$, the axial thrust F, and the specific impulse I_sp are calculated according to the following equations:

$$\dot{m}_\mathrm{f} = \int_\mathrm{inlet} \rho_\mathrm{f} w \mathrm{d}s, \tag{7}$$

$$F = \int_\mathrm{outlet} (\rho w^2 + p)\mathrm{d}s - \int_\mathrm{inlet} (\rho w^2 + p)\mathrm{d}s, \tag{8}$$

$$I_\mathrm{sp} = \frac{F}{g\dot{m}_\mathrm{f}}, \tag{9}$$

where ρ_f is the density of fuel, w is the axial velocity, s is the area, ρ is the density of the flow field, and g is the acceleration of gravity. The flow fields become dynamically balanced after 1500 μs, and RDCs continuously create thrust. Fig. 6 shows the thrust history of the RDCs with two injection patterns, while Fig. 7 shows the mass flow rate of hydrogen. Fig. 8 is the truncated version of the specific impulse-time traces which displays the comparison of specific impulse during stable operation period. The time average values of fuel mass flow rate, thrust, and specific impulse are summarized in Table 2. Although the injection total pressures of fuel injectors are the same in both injection patterns, seven of 50 fuel injectors are blocked in interval injection and 14 of 50 fuel injectors are blocked in stratified injection. This is mainly because the supply of argon increases the pressure in the combustor. Thus, the mass flow rate of hydrogen is different.

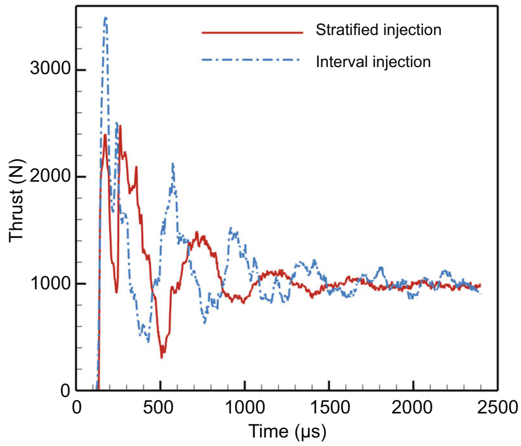

Fig. 6 Thrust history of the RDCs

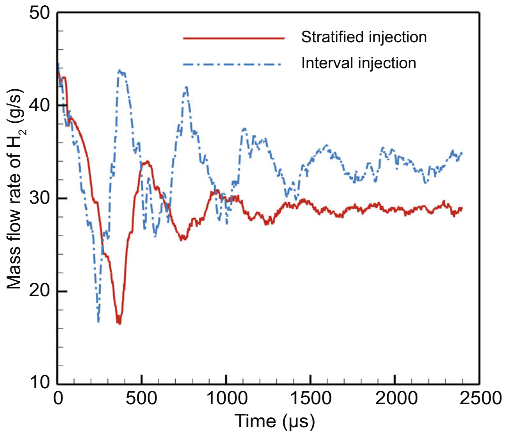

Fig. 7 Fuel mass flow rate history

The engine with stratified injection creates 987.9-N thrust, almost identical to the engine with interval injection (992.3 N). However, their fuel consumption rates (Fig. 7) are quite different. As a result, the specific impulse of the RDC with stratified injection is 16.3% higher than the RDC with interval injection. This proves that the proposed new injection pattern enhances the efficient utilization of fuel by the engine. It is worth noting that

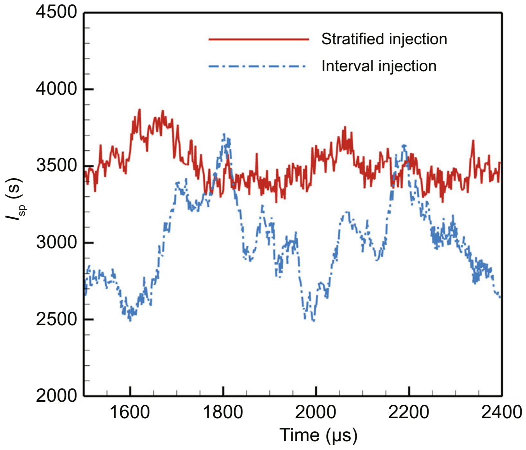

Fig. 8 Specific impulse history

Table 2 Time-averaged results of this study

Parameter	Value	
	Interval	Stratified
Injection total pressure (MPa)	1	1
Number of blocked injector	7	14
Mass flow rate of H_2 (g/s)	33.7	28.8
Thrust (N)	992.3	987.9
Specific impulse (s)	3008.8	3499.3

additional energy is needed to inject inert gas. The thrust benefiting from argon injection is about 100 N in stratified injection case, which means the absolute improvement of specific impulse benefiting from the injection pattern is 4.5%.

The better propulsion performance is attributed to that the way fuel is burned. There are two kinds of combustion processes in the RDCs, which are deflagration and detonation. Deflagration is an approximately constant pressure combustion process, and detonation is an approximately constant volume combustion process. Contact-surface chemical reaction belongs to the deflagration process. Detonation combustion has advantages such as self-pressure gain, faster heat release rate, and lower entropy generation (Kailasanath, 2000; Heiser and Pratt, 2002). Stratified injection protects the reactive mixture from the contact-surface chemical reaction, and thus, increases the proportion of fuel consumed by detonation wave from 67% to 95%. Therefore, less entropy is generated and more pressure gain is obtained. These facts together increase the specific impulse when stratified injection is applied.

3.4 Stability of the engine with stratified injection

It can be seen from Figs. 6 and 8 that the thrust and specific impulse of the RDCs are oscillating during operation. The fluctuation amplitudes of thrust and specific impulse of the engine are lower when the stratified injection method is applied, which indicates that the injection pattern proposed in this study may improve the stability of the engine. In most cases, pressure fluctuations are used to indicate the stability of an engine (Anand et al., 2015; Wang and Wang, 2015). The pressure-time traces in the combustors under two injection conditions are shown in Fig. 9. The numerical probes are fixed at the same location (x = 160 mm and y = 25 mm). The pressure peaks are observed when the detonation wave propagates across the numerical sensor. High-frequency and intermediate-frequency detonation instabilities are observed in this study.

The oscillations of peak pressure of DW (circles in Fig. 9) are regarded as high-frequency detonation instabilities in RDEs. These types of detonation instability have been reported in (Anand et al., 2015; Wang and Wang, 2015). The instabilities are primarily due to the coupling of the mixture injection and the movement of the DW. The unsteady chemical reaction from the DW movement can cause pressure fluctuations near the injectors, after which the flux starts to oscillate. If the flux is increased, it would strengthen the DW. More intensive DW, in turn, increases the pressure near the injectors and then decreases the flux. Thus, the high-frequency detonation instabilities caused by the DW movements are determined by the frequency of the engine.

Unsteady heat release from the contact-surface of chemical reactions results in pressure waves moving to the fuel injectors and reflected by inlet boundary. On one hand, the pressure waves will affect the fuel injection rate, and on the other hand, the pressure waves change the chemical reaction rate. This phenomenon leads to intermediate-frequency detonation instabilities. Two periods of such instabilities are indicated in parentheses in Fig. 9. The intermediate-frequency detonation instabilities are around 1274.2 Hz (interval injection) and 1810.8 Hz (stratified injection). If these pressure waves alter the burning rate with the correct phasing, detonation oscillations would be amplified. As the

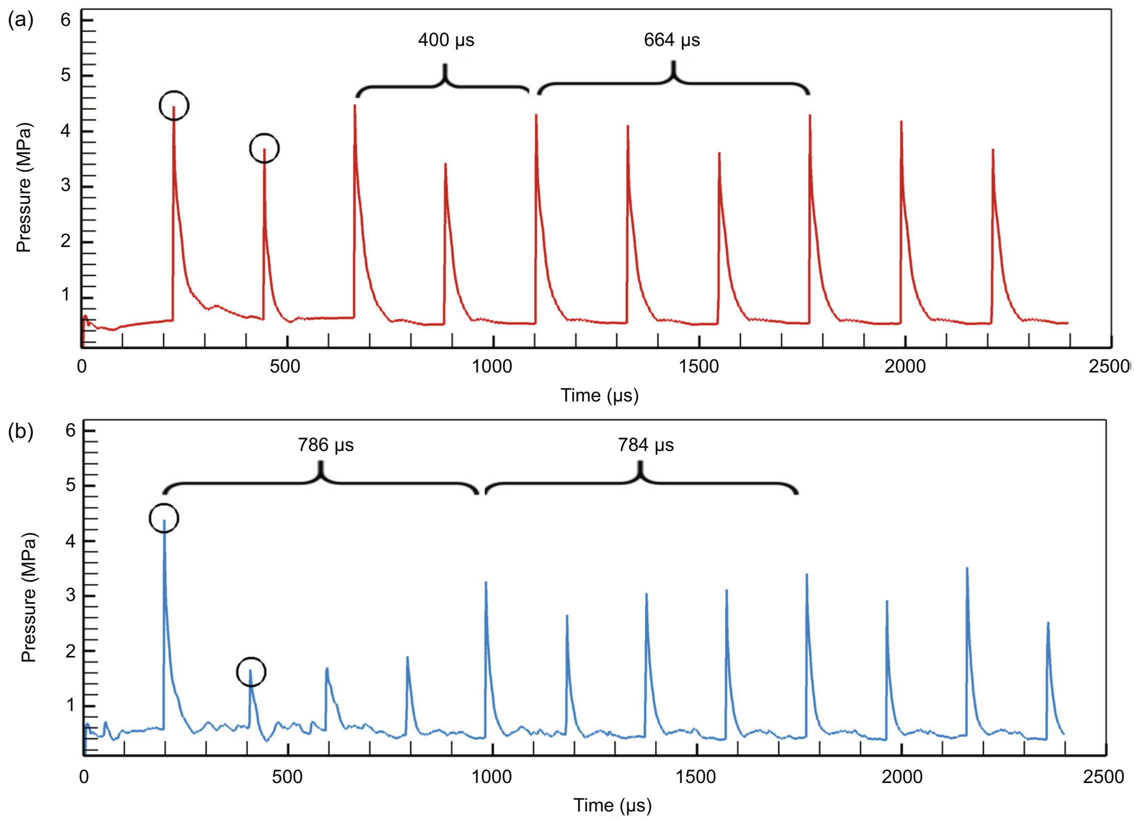

Fig. 9 Pressure-time trace: (a) engine with stratified injection; (b) engine with interval injection

contact-surface chemical reaction is highly suppressed with stratified injection condition, the oscillation magnitude caused by unsteady heat release will be well controlled. The magnitude of oscillation with stratified injection is considerably lower in comparison to the interval injection, as shown in Fig. 9. Thus, in the perspective of oscillation magnitude, the stratified injection is helpful to establish a more stable operation condition for RDEs.

4 Conclusions

Chemical reaction occurring on the contact surface between reactive mixtures and high-temperature detonation products is found unfavorable in the improvement of propulsion efficiency and operation stability of an RDE. A new injection method named "stratified injection" is proposed to suppress such isobaric combustion and increase the proportion of fuel consumed by detonation combustion. The conclusions are as follows:

1. A stratified injection pattern is achieved by adding inert gas injectors around fuel injectors, and the fuel distribution in the combustor changes from a continuous distribution to a stratified distribution.

2. In the engine models adopted in this study, two engines have an identical fuel injection area and identical injection total pressure/temperature. The contact-surface chemical reaction is weakened by adopting the stratified injection method. The proportion of fuel consumed near the fuel-detonation products' contact surface decreases from 33% to 5%, thereby indicating that the fuel consumed by detonation combustion increases from 67% to 95%.

3. The engines create almost identical thrust with both injection patterns, but the specific impulse of the engine with stratified injection is improved by 16.3%. After deducting the effect of additional argon injection, the improvement of specific impulse is 4.5%. This means that the stratified injection method is better for fuel economy. Moreover, the results of the study indicate that the fluctuation amplitudes of pressure, thrust, and specific impulse are reduced, which implies that the stability of the engine is enhanced.

4. Applying stratified injection notably decreases the temperature of combustion products. The average temperature at engine outlet reduces by 327.4 K, which is 19.1% lower than the engine with traditional interval injection method. This fact indicates that the stratified injection pattern maybe helpful to the process of integrating turbines.

Contributors

Pei-fen WENG, Xiao-quan YANG, Jue DING, and Zhi-di LEI designed the research. Zhi-di LEI and Xun-nian WANG processed the corresponding data. Zhi-di LEI drafted the manuscript. Xiao-quan YANG helped organize the manuscript. Jue DING revised and finalized the paper.

Conflict of interest

Zhi-di LEI, Xiao-quan YANG, Jue DING, Pei-fen WENG, and Xun-nian WANG declare that they have no conflict of interest.

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中文概要

题　目：旋转爆轰发动机中的燃料分层喷注方法

目　的：通过优化燃料喷注，提高旋转爆轰发动机的推进稳定性和推进效率。

创新点：1. 提出了燃料分层喷注的新方法，降低了燃料提前燃烧比率和燃烧室平均温度，进而有效地提高了旋转爆轰波的稳定性和发动机的比冲。

方　法：以数值模拟为手段，应用基元反应建立化学非平衡流动的数学物理模型，开展发动机推进性能优化研究。

结　论：1. 研究证实了燃料的提前燃烧现象是发动机推进性能的损失机制之一；2. 提出的燃料分层喷注方法可以有效提高燃料以爆轰形式组织燃烧的比例，并提高发动机比冲。

关键词：旋转爆轰发动机；燃料喷注模式；推进性能；推进稳定性