Propagation Characteristics of Continuous Rotating Detonation Wave under Different Temperature Air

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1 Introduction

Continuous rotating detonation (CRD) is an alternative for energy conversion in chemical engines. CRD-based engine benefits from a higher thermodynamic efficiency, a shorter and more compact combustor [1-3]. Besides, it works with frequency of ~kHz and requires only one initiation. Recent researches mainly focus on the rocket engine mode [4-7], while the airbreathing mode [8] is less reported due to a higher total temperature of the air. When higher-total-temperature air is used as oxidizer, both the temperature of the mixture upstream the detonation wave and its product are expected to increase. As a result, the propagation characteristics of the continuous rotating detonation wave (CRDW) might be different. Moreover, it is expected to promote the deflagration of the mixture near the contact surface, affect the stability and detonation wave number of CRDW [3], and even give rise to new detonation patterns [9].

In the present study, experiments on CRD were carried out using air with different total temperature, namely, 300K and 860K. Both the wall pressures and high-frequency pressures were acquired. The propagation frequency of the CRDW was analyzed, based on which the relative standard deviation is obtained to describe the propagation stability. The effects of the air total temperature on the propagation characteristics of CRDW were studied.

2 Experimental facility and methodology

2.1. Direct-connect facility

The direct-connect facility shown in Fig. 1 is composed of an air-heater, a constant-area isolator, a CRD combustor, a pre-detonator and an exhaust pipe. The air-heater is adopted to simulate the high total temperature air in the air-breathing mode. Similar to the air-heater used in [9, 10], pure ethyl alcohol burning with oxygen is used to heat the air to a total temperature (T_t) of 860 K. The total pressure (p_t) and total mass flow rate of the air-heater are 860 kPa and 600 g/s, respectively. The mass fraction of oxygen of the vitiated air is 23.2%.

The CRD combustor consists of an area-expansion section and an annular detonation combustor. The inner diameter D_i and the outer diameter D_o of the annular detonation combustor are 80 mm and 108 mm, respectively, and its length L is 210 mm. The hydrogen is injected through 90 evenly distributed orifices with a diameter of 0.6 mm, located on the outer surface of the inner cylinder.

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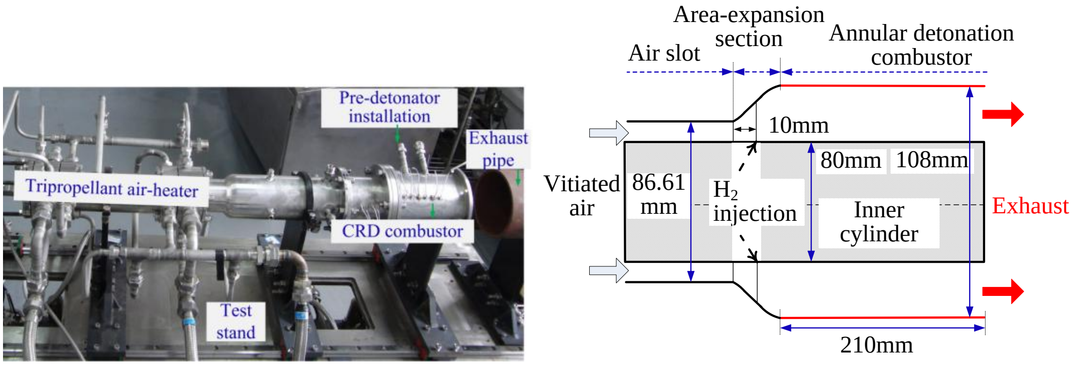

Figure 1. Schematic view of detonation combustor configuration

As illustrated in Fig. 2, a pre-detonator tangent to the detonation combustor is used for detonation initiation, with H_2 and O_2 chosen as fuel and oxidizer, respectively. The H_2/O_2 mixture is ignited by an ordinary spark plug; thereafter, the combustion products flow into the detonation combustor and initiate the CRDW.

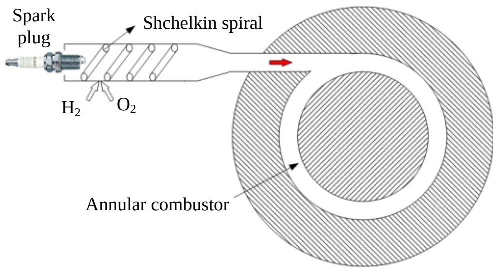

Figure 2. Schematic diagram of pre-detonator

Dynamic piezoelectric pressure sensors (PCB Company, Model 113B24) were installed on the outer wall to acquire the high-frequency pressure in the air slot and detonation combustor. Wall pressure (Maxwell Company, Model MPM480) was also measured to see the pressure level, and also to confirm the formation and flameout of the CRDW. The installation of the transduces is shown in Fig. 3.

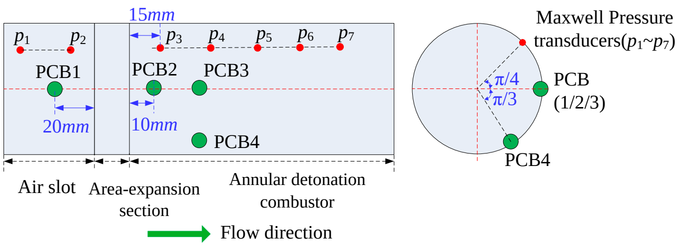

Figure 3. Location of the transducers

2.2. Time sequence of experiment and operation conditions

The time sequence that controls the process of the experiment is shown in Fig. 4. Each test includes the following phases: propellant filling, air-heater working, CRD and air-heater blown off. The CRD is performed when continuous air flow is fed, with total temperature of 860K (air-heater working) or 300K (only room-temperatuer air is fed).

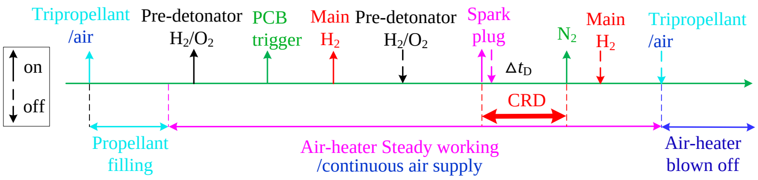

Figure 4. Time sequence of experiment.

A series of tests on CRD were performed, and the operation conditions are listed in Table 1, where T_t is the total temperature of the air; m_{air}, m_{H2} and ϕ denote the mass flow rates of the air, the mass flow rate of the hydrogen, and the equivalence ratio of the hydrogen/air mixture, respectively; p_c is the maximum wall pressure in the detonation combustor, f_{av} is the average propagation frequency of the CRDW, S and μ denote the standard deviation and relative standard deviation of the instantaneous propagation frequency of the CRDW, respectively.

Table 1: Experiment condition

Test	T_t/K	m_{air}/(g/s)	m_{H2}/(g/s)	φ	p_c/kPa	f_{av}/kHz	S/kHz	μ/%
#1	860	621.0	14.86	0.82	167	3.50	0.157	4.49
#2	860	609.0	16.97	0.96	177	3.82	0.083	2.18
#3	860	623.0	19.90	1.10	193	4.08	0.092	2.25
#4	300	606.0	14.33	0.81	185	3.86	0.106	2.75
#5	300	606.0	16.71	0.95	191	4.25	0.0885	2.08
#6	300	609.0	19.88	1.12	197	4.58	0.0896	1.96

3 Results and discussion

3.1 Propagation characteristics of CRDW

As shown in Fig. 5, the pressures in the air-heater and propellant pipelines are generally steady during the operation in test #2, including the duration of the CRDW. As a result, the work of the air-heater is not affected by the CRDW. Furthermore, the pressure in the detonation combustor increases rapidly when the CRDW was initiated and reaches a maximum of 177 kPa.

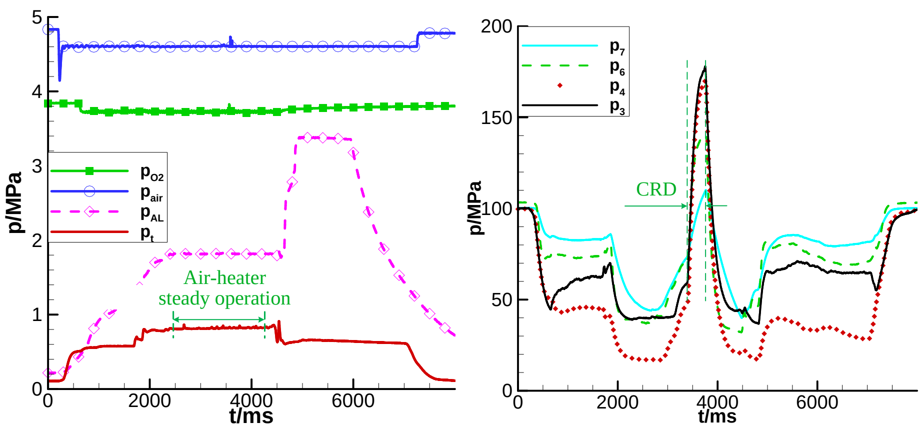

Figure 5. Pressure results of test #2. Left: Pressure in the air-heater. Right: Wall pressure in the CRD combustor.

Fig. 6 presents the high-frequency pressure in the detonation combustor. From the periodical oscillation that can be clearly recognized, it is judged that the CRDW is formed and propagating in the one wave homo-rotating mode [9].

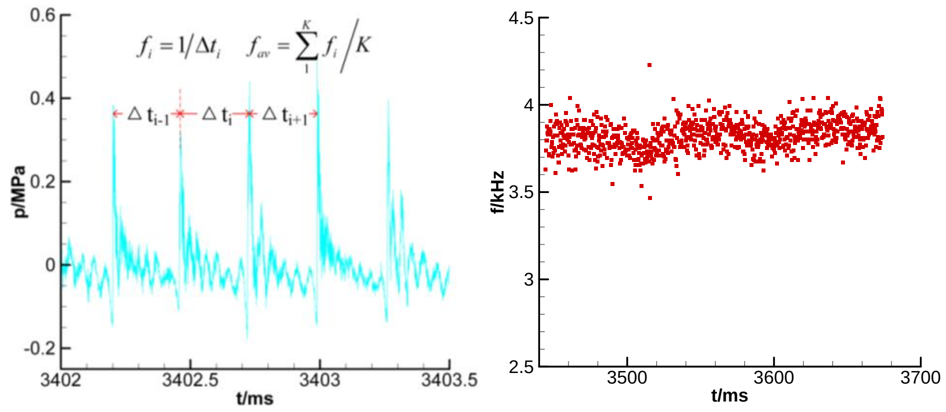

Figure 6. High-frequency pressure results of test #2. Left: Local view of the high-frequency pressure. Right: Propagation frequency distribution of CRDW.

The instantaneous propagation frequency of the CRDW f_i was calculated using the methodology described in the left of Fig. 6. The f_i varies in the range of 3.47 - 4.23 kHz and the average is 3.82 kHz. The standard deviation S and relative standard deviation μ are calculated to describe the propagation stability with the following formula:

$$S = \sqrt{\left(\sum_{1}^{N}\left(f_i - f_{av}\right)^2\right)\Big/\left(N-1\right)}$$

$$\mu = S / f_{av}$$

3.2 Effects of the air total temperature

The average propagation frequency of the CRDW in different tests is presented in Fig. 7. With a higher equivalence ratio, the propagation frequency f_{av} increases under both T_t equivalent to 300K and 860K. Besides, the f_{av} is higher under T_t = 300K. The maximum wall pressure in the detonation combustor presented in the right shows similar trends. As both of f_{av} and p_c could be used to indicate the combustion intensity, it could be drawn that the CRDW is more intensive under T_t = 300K.

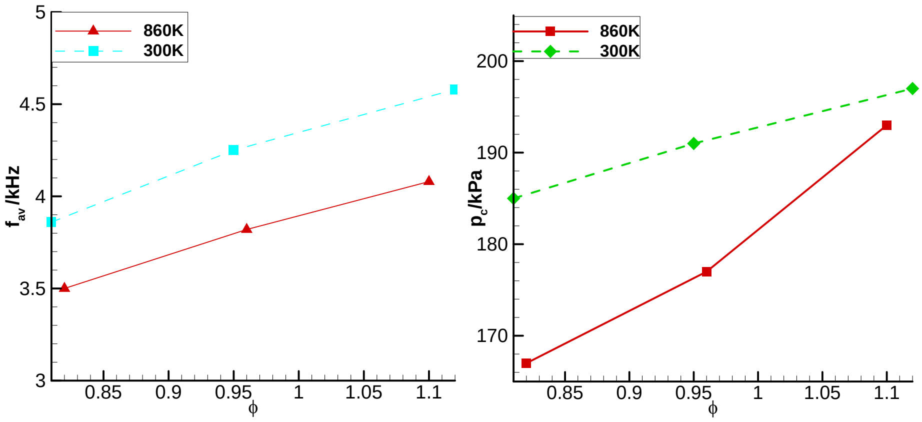

Figure 7. Effect of the air temperature. Left: Average propagation frequency of CRDW. Right: maximum wall pressure in the detonation combustor.

The higher f_{av} under T_t = 300K could be attributed to the lower air velocity in the air slot, which promotes the mixing of the air/H_2, and thus increases the heat release of the CRDW and its propagation velocity (frequency). On the other hand, the total pressure of the air is decreased due to the lower T_t to ensure the same mass flow rate of the air. As a result, the pressure of the mixture upstream the CRDW is lower, which would decrease the heat release of the detonation and thus the f_{av}. As seen from the result, the f_{av} is actually higher under T_t = 300K, and this implies that the improved mixing overcomes the negative effects of the decreased pressure.

Fig. 8 shows the relative standard deviation μ of the instantaneous propagation frequency in different tests, and it is lower under T_t = 300K, indicating a more stable propagation process of the CRDW.

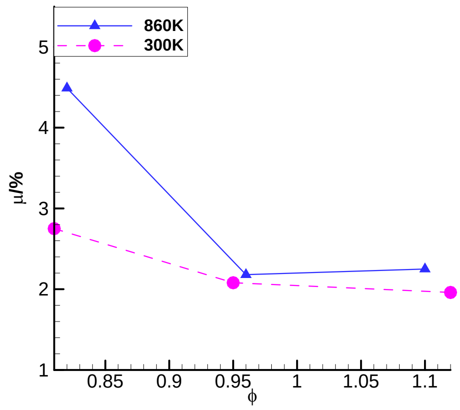

Figure 8. The relative standard deviation of propagation frequency of CRDW.

As shown in Fig. 9, the pressures in the detonation combustor are increased during the CRD both in test #2 and #5. Moreover, the pressures in the air slot are constant during the CRD in test #2, while they are increased in test #5. In other words, the influence of the CRD on the air flow is stronger and propagates more upstream under a lower total temperature of the air.

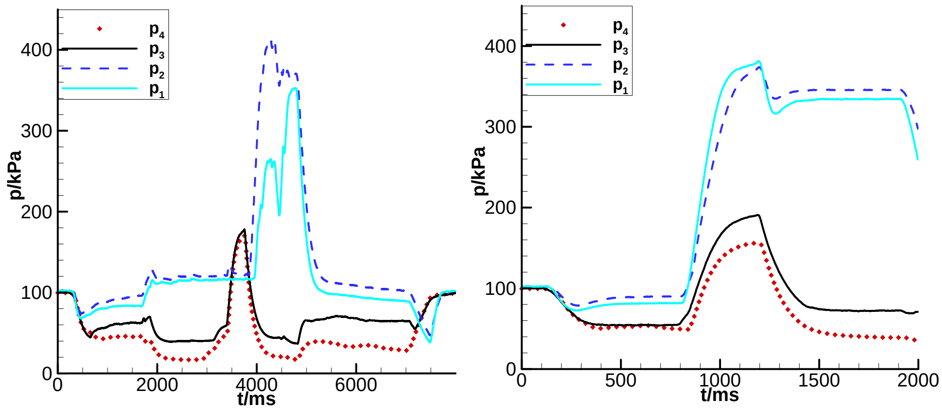

Figure 9. Effect of the air temperature: pressures in the air slot (p_1, p_2), pressures in detonation combustor (p_3, p_4). Left: Results of test #2 (T_t=860K). Right: Results of test #5 (T_t=300K).

As presented in Fig. 10, no obvious high-frequency pressure variation in the air slot could be recognized in test #2, compared with the periodical pressure oscillation in the detonation combustor. However, high-frequency pressures oscillation in the air slot is excited and fluctuating with the same frequency of the CRDW in test #5. This is in accordance with the constant wall pressure in the air slot in test #5, but increased wall pressure in test #2. This can be attributed to the more intensive CRDW in test #2. The wall pressure and high-frequency pressure in the other tests under T_t=300K and T_t=860K are similar to those of test #5 and #2, respectively.

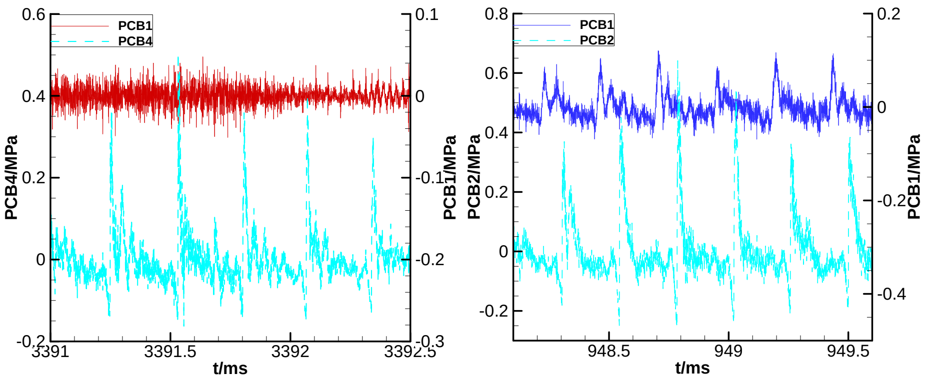

Figure 10. Effect of the air temperature: high-frequency pressures in the air slot (PCB1) and detonation combustor (PCB2, PCB4). Left: Results of test #2 (T_t=860K). Right: Results of test #5 (T_t=300K).

4 Conclusions

Experiments have been performed on CRD to study the influences of the air total temperature on the propagation characteristics of CRDW. Results showed that the CRDW propagates more stably with a higher average frequency under a lower total temperature of 300K than 860K. Pressure rise and high-frequency pressure oscillation are not excited under total temperature of 860K, but they could be clearly recognized under total temperature of 300K.

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