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Investigation on Combustion Characteristics in Channel with Obstacles for Internal Combustion Wave Rotor

Jianzhong Li[1]*, Li Yuan[2], Erlei Gong[1], Wei Li[2], Kaichen Zhang[1]

[1]Key Laboratory of Aero-Engine Thermal Environment and Structure, Ministry of Industry and Information Technology, Nanjing University of Aeronautics and Astronautics, Nanjing, China
[2]School of National Defense Engineering, PLA University of Science and Technology, Nanjing, China
Email: *ljzh0629@nuaa.edu.cn, 80njyuanli@163.com

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Abstract

This paper establishes a simplified test system for internal combustion wave rotor with a single channel and designs different intensifying combustion obstacles and arrangements. Moreover, this paper analyzes the intensifying effect of obstacles on combustion process of the internal combustion wave rotor from the stable operation range, pressure gain and flame progression process perspective. The results show that the range of inlet velocity under stable operation of the internal combustion wave rotor narrows after the addition of obstacles, and the corresponding velocity values substantially reduce while the flame propagation speed can be improved by 2 - 4 times. At the rotation rate of 1500 rpm, the pressure gain increases significantly during the combustion process. These results provide technical supports for further research and application of the internal combustion wave rotor.

Keywords

Internal Combustion Wave Rotor, Obstacles, Combustion Characteristics

1. Introduction

Internal combustion wave rotor (ICWR) is a new power plant based on unsteady combustion mainly consisting of two seal plates, a wave rotor and a series of airflow ports with different functions [1] [2], wherein the wave rotor is usually a drum-shaped structure formed by a series of wave rotor channels distributed uniformly in the circumferential direction. In recent years, since the advantages and potential in improving the overall performance of propulsion systems, the ICWR has been deeply investigated [3] [4] [5] [6] [7].

Operation of the internal combustion wave rotor includes processes of filling mixed gas, pre-compression, unsteady combustion and exhausting. The sum of the duration of each of the above phases is considered as one cycle of the internal combustion wave rotor. The work cycle is shorter, and the operating frequency of the ICWR is higher. Operating frequency is an important performance indicator of unsteady combustion device. A high operating frequency generally means stronger power capability. Combustion process of the internal combustion wave rotor equals to a period ranging from a successful ignition to the fully combustion of mixed gas within the channel of wave rotor, and the period depends on the intensity of the chemical reaction. Intensifying combustion in the channel with obstacles shortens the combustion duration of internal combustion wave rotor. Shortening of a single cycle period and improving the operating frequency are of importance for improving the power capability of propulsion system of the internal combustion wave rotor. At present, many extensive studies on the combustion characteristics of internal combustion wave rotor have been carried out. For example, the Rolls-Royce company, in cooperation with Purdue university, has installed a test platform for internal combustion wave rotor [8] which realized the rapid pressurization combustion by taking ethylene as the fuel [9] [10] and fuel injection, ignition delay and flame progression have been investigated. Using the numerical simulation, A. Karimi *et al.* [11] have studied the influences of several nozzle movements on ignition delay time and flame propagation velocity within the channel of wave rotor and have analyzed the causes of different chemical reaction rates based on intermediate products such as OH groups. Prasanna Chinnathambi *et al.* [12] have studied the characteristics of lateral jet ignition within the channel of wave rotor. The test results show that the ignition delay time using ethylene as a fuel is shorter than that using methane. Moreover, the use of a mixture of methane and hydrogen as a fuel causes the ignition delay time shorten and the flame propagation accelerate achieving the optimal effect when the jet movement time is 6.1 ms. Gong Erlei *et al.* [13] have established a simplified test system of internal combustion wave rotor with a single channel and adopted jet ignition to study the combustion characteristics of internal combustion wave rotor. Pressurized combustion was achieved, but with relatively low flame propagation speed.

Studies on intensifying combustion of internal combustion wave rotor have not been reported currently. However, many studies have been carried out on intensifying technology for the pulse detonation engine among which the use of intensifying combustion obstacles is the most widely applied technology. For example, Zheng Dianfeng *et al.* [14] [15] have studied the influence of obstacle shape, blockage ratio, obstacle number and obstacle spacing on peak pressure of detonation wave by using the test method. Valiev D. *et al.* [16] investigated the influence of obstacle on acceleration of flame within the detonation tube combining theoretical analysis and numerical simulation. These studies have shown that the action of obstacles accelerates significantly the flame acceleration process, and the flame acceleration rate reduces with increasing initial Mach number.

Using an experimental approach, this paper studies the intensifying effect of intensifying combustion obstacles on combustion process of an internal combustion wave rotor and discusses the influence of intensifying combustion obstacles with different blockage ratios on the combustion pressurization and flame propagation characteristics of the internal combustion wave rotor.

2. Experimental Setup and Test Method

The research is implemented on a simplified test system with a single channel. Figure 1 shows the simplified experimental setup, which mainly includes hot jet igniter, ICWR channel, inlet and outlet seal plates and drive motor. Among these parts, ICWR channel is fixed on the experimental platform through channel support and is in a stationary state. The inlet and outlet seal plates with different functional ports are connected to the shaft and rotate with respect to the ICWR channel under the drive of the drive motor. A sight window made of quartz glass is set on one side of the ICWR channel. Through the sight window, flame propagation process is recorded with high-speed photography. A jet igniter is installed on one side of the outlet seal plate, and the center of the jet igniter is aligned with the center of the ICWR channel. Fuel enters the intake pipe from the fuel inlet and mixes with air to form combustible mixture gas. With the rotation of the seal plate, the combustible mixed gas enters the ICWR channel, and then the hot jet enters the ICWR channel through the jet port on the outlet seal plate to ignite the mixture gas. A pressure transducer installed on the ICWR channel measures the pressure gain during combustion, and high-speed photography also records the flame's progression process.

To study the effect of obstacles on the combustion characteristics of ICWR, obstacles with different structures and arrangements were designed, as shown in Figure 2. Two kinds of obstacle structures were studied, i.e. "Blockage A" is 2.5 mm high with blockage ratio of 10%, and "Blockage B" is 5.8 mm high with

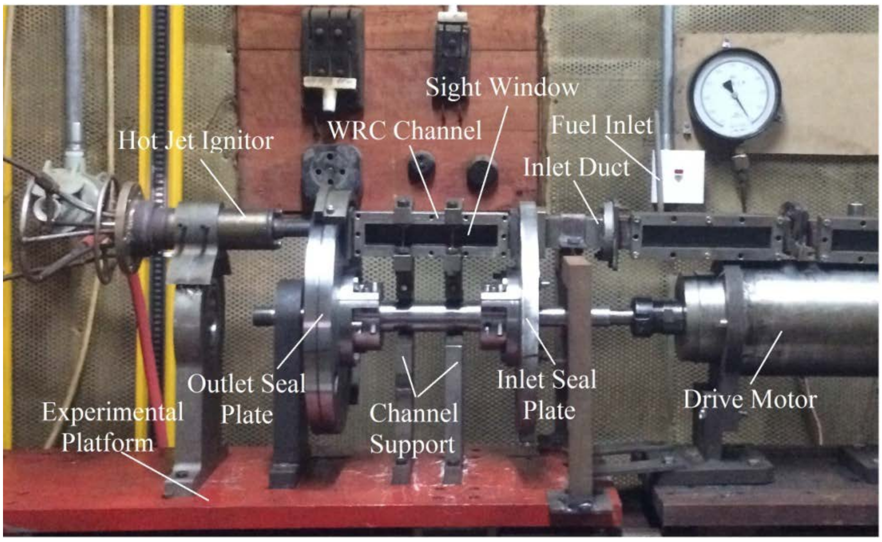


Figure 1. The simplified test system of ICWR with a single channel.

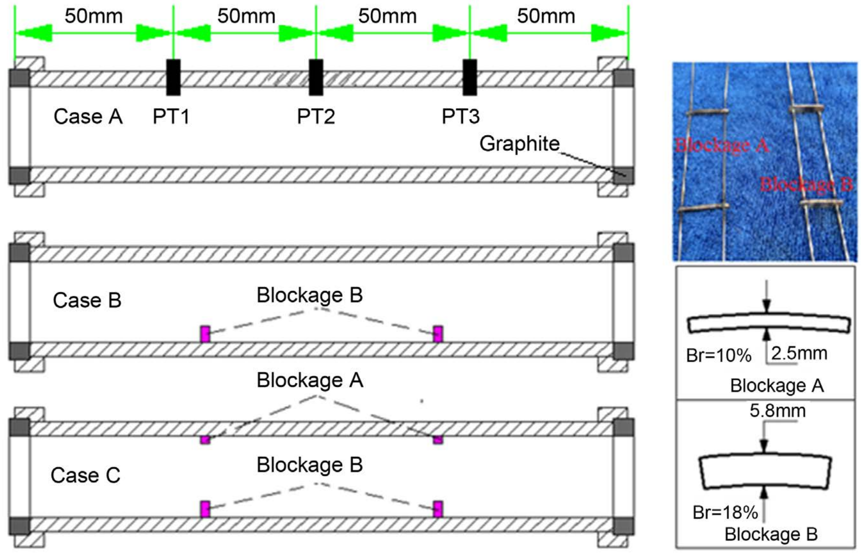


Figure 2. The obstacle structures and arrangements.

blockage ratio of 18%. In the arrangement referred as Case A, the ICWR channel is a fan-shaped straight channel and the total blockage ratio is 0; in Case B, only two pieces of "Blockage B" are arranged inside the concave surface of the ICWR channel with a total blockage ratio of 18%; in Case C, two pieces of "Blockage A" are arranged outside the concave surface and two pieces of "Blockage B" are arranged inside the concave surface of the ICWR channel with total blockage ratio of 28%. The following experiments were carried out to analyze the influence of obstacles on operation range, pressure gain and flame propagation.

3. Results and Discussion

3.1. Influence of Obstacles on Operation Range of the ICWR

The changes of inlet velocity range under the stable operation of ICWR after addition of a turbulence device is shown in Figure 3. While the obstacle is installed, the inlet velocity range under stable operation of the ICWR is obviously reduced. Meanwhile, at the same rotation rate, the internal combustion wave rotor is operated under relatively low inlet velocity after the addition of the obstacles. This is because the obstacles reduce channel cross-sectional area, causing the velocity of airflow within the channel increase. Therefore, a relatively small initial velocity is required to achieve the desired filling state. As for the internal combustion wave rotor, the hot jet ignition process is affected substantially by turbulence. With respect to the results in Figure 3, without obstacles the internal combustion wave rotor can operate stably within a certain range of inlet velocity. After the introduction of obstacles, boundary layer effect, jet disturbance and disturbance of obstacles mainly cause turbulence of mixture gas in the ignition process occur. By keeping constant the inlet velocity and hot jet parameters, the disturbance of the obstacles increases the turbulence intensity of airflow substantially. In such a case, the parameter $D_a = \tau_t / \tau_c$ for evaluating the jet igni-

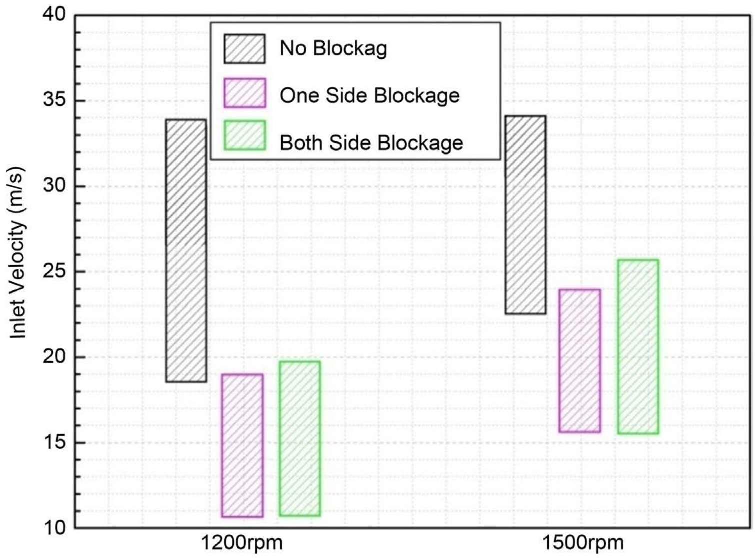


Figure 3. Influence of obstacles on inlet velocity under operation of the ICWR.

tion increases rapidly and deviates from the reliable ignition range, eventually resulting in ICWR malfunctioning. When the inlet velocity decreases, the boundary layer effect, and turbulence from the disturbance caused by the airflow passing through obstacles will both decrease, and Da will accordingly return to a reasonable range. Therefore, the internal combustion wave rotor will operate stably within lower inlet velocity after addition of the obstacles.

When the internal combustion wave rotor is under stable operation of ICWR with and without the obstacles, the equivalence ratio operation ranges are compared in Figure 4. The internal combustion wave rotor is operated mainly within lower inlet velocity range under the action of obstacles. The range of equivalence ratio (Φ) in operation is broadened compared to that without obstacles, and such change in width is even more obvious at the rotation rate of 1500 rpm because the inlet airflow is slow at this time, and flame is relatively easy to be stable in the low-speed airflow. In addition, when the airflow flows through obstacles, a recirculation zone will be formed behind the obstacles. The hot burned gas in the recirculation zone can be used as a stable ignition source to ensure that the flame propagation in the ICWR channel is not easily quenched. Moreover, when arranging obstacles at both the concave surfaces inside and outside the ICWR channel, the corresponding range of equivalence ratio broadens, but no significant changes occurs in the corresponding value of the equivalence ratio. When arranging obstacles only inside the concave surface of the ICWR channel, the corresponding range of equivalence ratio broadens. Meanwhile, the range extends to the fuel-rich area and the boundary of the poor-fuel area shrinks.

3.2. Influence of Obstacles on Pressure Gain of the ICWR

To analyze the influence of obstacles on pressure gain of ICWR, three dynamic pressure transducers PT1, PT2 and PT3 (as shown in Case A of Figure 2) were evenly arranged on the ICWR channel to record the pressure change inside the

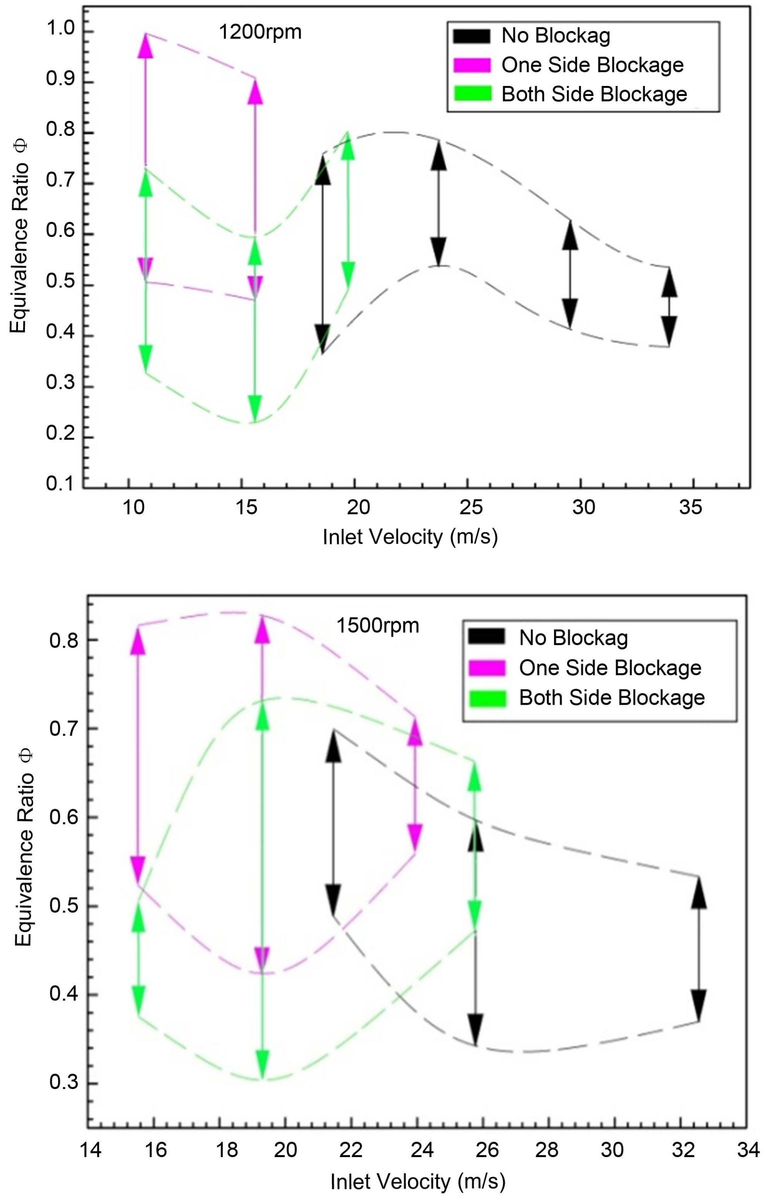


Figure 4. The influence of obstacles on Equivalence Ratio range of ICWR with different rotation rate.

channel during combustion. For ease of the comparison, the experimental conditions are set to be at the intersection of the range of the inlet velocity with that of the equivalence ratio corresponding to the obstacle arrangements, as shown in Figure 3 and Figure 4. At the rotation rate of 1200 rpm, inlet velocity of airflow is selected to be 19.7 m/s and the equivalence ratio is 0.75. At the rotation rate of 1500 rpm, inlet velocity of airflow is 22.5 m/s and the equivalence ratio is 0.61.

Figure 5 compares the peak pressure gain of combustion during operation of ICWR with and without the obstacles. At a rotation rate of 1200 rpm, it seems that the introduction of obstacles has no intensifying effect on combustion, and the peak pressure gain of combustion is much lower than that of condition without obstacle. However, at 1500 rpm, the obstacles play an obvious role in

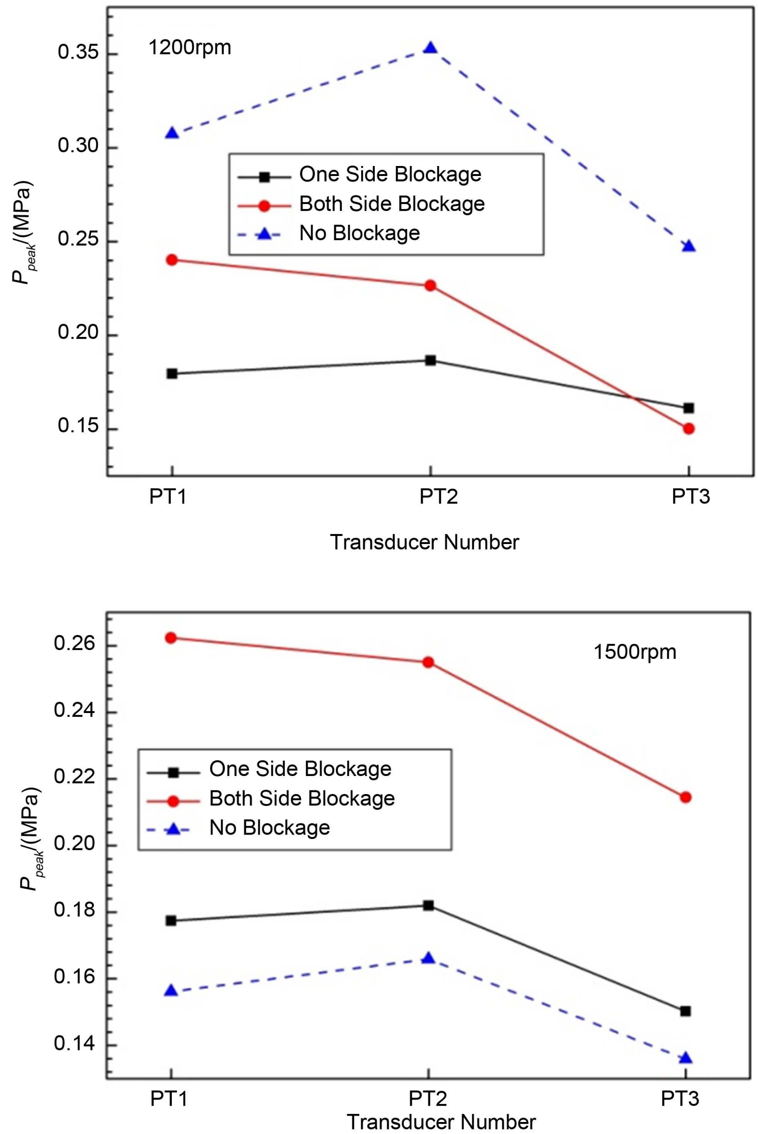


Figure 5. The comparison of the peak pressure gain of combustion in ICWR with and without obstacles.

intensifying the combustion, and the higher the blockage ratio of obstacles, the better the intensifying effect on the combustion process. Figure 5 shows that the peak pressure of combustion with obstacles arranged on both sides is higher than that occurring with obstacles arranged on one side only, indicating that the obstacles can strength the combustion at any rotation rate. Comprehensive factors such as acting sequence of wave rotor and blockade of airflow by obstacles are involved. These comprehensive factors result in that the turbulence device fails to play a better intensifying combustion effect at 1200 rpm rotation rate.

3.3. Influence of Obstacles on Flame Progression of the ICWR

Figure 6 shows the influence of obstacles on flame propagation speed and flame progression. Herein the flame propagation speed is defined as

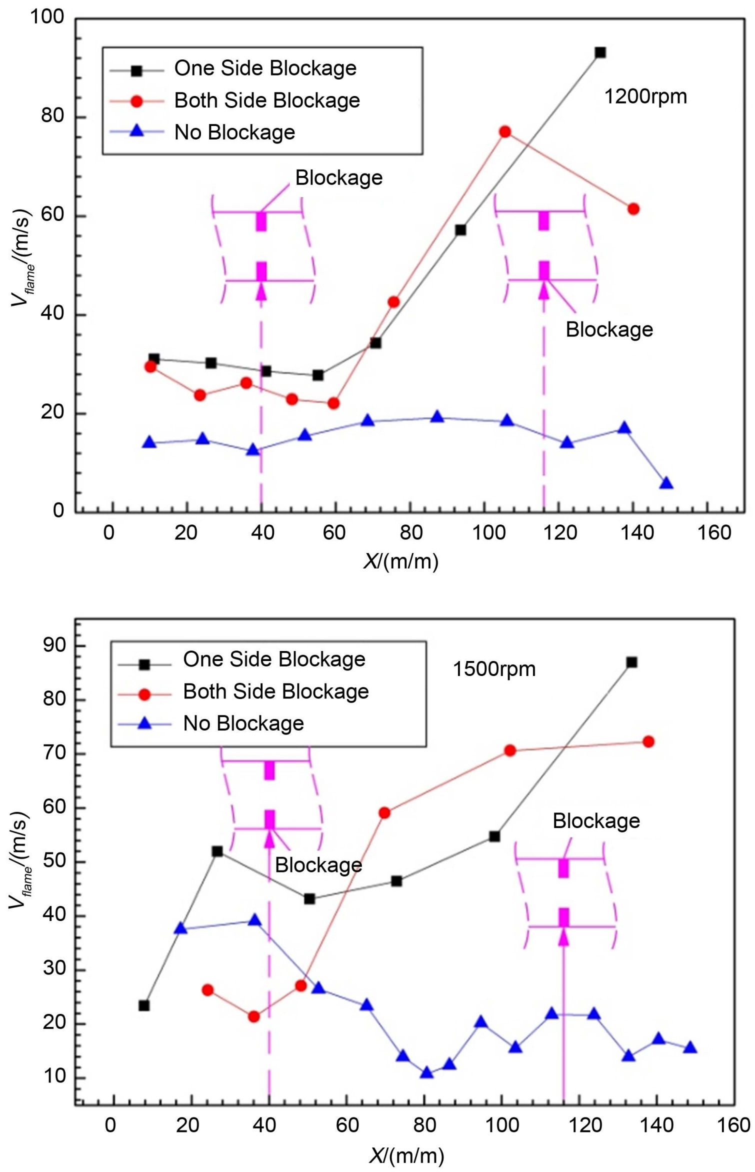
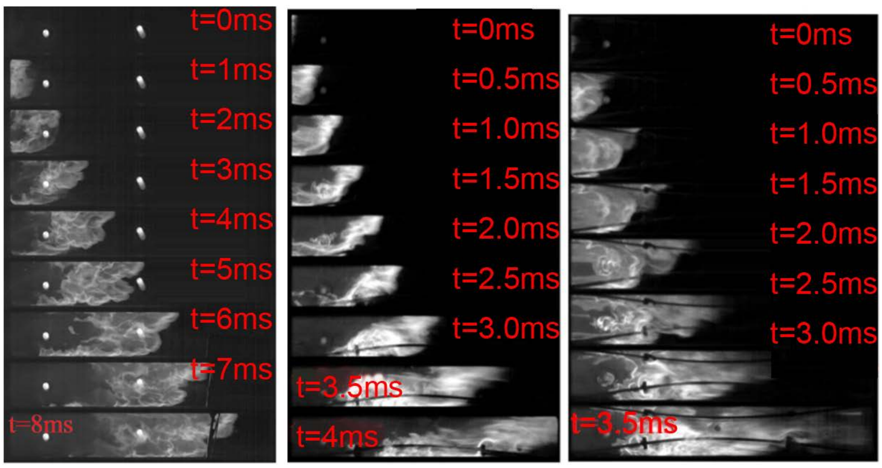


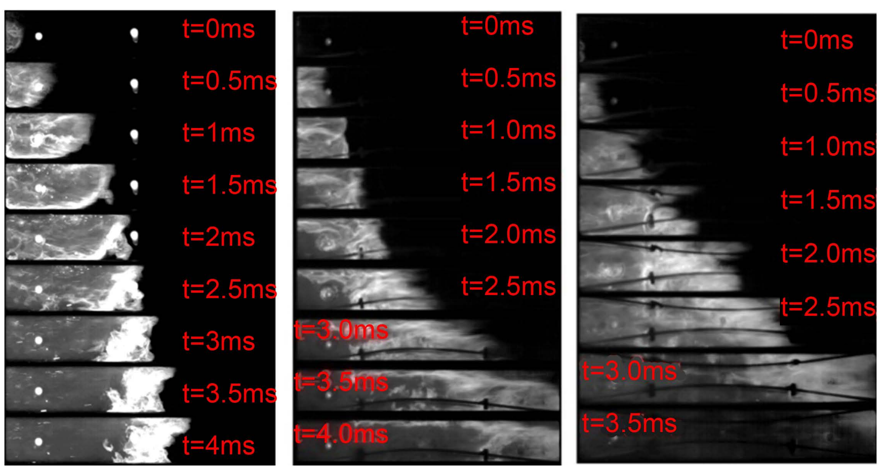
Figure 6. Influence of obstacles on flame propagation speed in the channel of ICWR.

$V_{flame} = (x_{i+1} - x_i)/(t_{i+1} - t_i)$, wherein x_i and x_{i+1} are positions of flame front at time t_i and t_{i+1}, respectively (here the edge of sight window is defined as x = 0), obtained from the results recorded by high-speed photography. From **Figure 5**, in either condition of rotation rate of the wave rotor, the flame propagation speed without obstacles is relatively low during the whole combustion process, and gradually decreases in the late stage of combustion process. However, after addition of the obstacles, their disturbance action increases the flame propagation speed remarkably. After the flame passes the obstacles for the second time, the flame propagation speed increases by 2 - 4 times. Since the rotating rate is 1200 rpm, the flame propagation speed shows minor change before it encounters the obstacles for the first time; after the flame passes obstacles, the flame propagation begins to accelerate rapidly. When the flame propagates around the obstacles for the second time, the variation trend of the propagation speed does not change significantly and such acceleration continues until the combustion process ends. When the rotation rate of wave rotor increases to 1500 rpm, before the flame passes the obstacles for the first time, the flame propagation process has already been disturbed by the obstacles and the flame propagation begins to accelerate gradually. After being intensified by the obstacles twice, the flame propagation velocity eventually increases. Moreover, the acceleration of the flame speed shows no significant improvement when obstacles are both arranged on the concave surfaces inside and outside the ICWR channel indicating that, on the basis of, Br = 10%, and the current experimental conditions, there is no need to increase continuously the blockage ratio of the obstacles within the channel of the wave rotor in terms of flame propagation speed.

From the flame progressive process in Figure 7, there is a significant difference between the flame structures with and without the addition of obstacles, that is, the brightest areas cannot reach to the flame forefront which was recorded by high-speed photography. The difference shows that the position of flame front at this time is no longer the area with the most vigorous reaction.



(a)



(b)

Figure 7. The influence of obstacles on flame progression of ICWR. (a) 1200 rpm; (b) 1500 rpm.

The brightest area in the figure appears behind the position of obstacles, showing the most vigorous chemical reaction and higher heat release rate of combustion. This is because a re-circulation zone forms behind obstacles when the airflow induced by the chemical reaction flows around the obstacles. Hot burned gas involved in the re-circulation zone can reside for a longer time behind the obstacles thus acting as the combustible mixed gas around a high-energy ignition source. In addition, the lower airflow velocity behind the obstacles is conductive to the implementation of chemical reaction. The area around the flame front is relatively vague since the obstacles increase the turbulence intensity within the mixed gas. Under strong turbulence, the hot burned quickly spreads to the area of unburned mixture gas. The energy of hot burned gas is relatively scattered, so that the brightness of the reaction area reduces. However, just due to the rapid diffusion effect caused by turbulence, the heat release area of flame significantly increases, or it can be interpreted as meaning that the high-temperature combustible gas quickly spreads to the area of unburned mixed gas and ignites the mixed gas simultaneously at distinct positions, so that the flame propagation speed dramatically increases, achieving the purpose of intensifying the combustion.

4. Conclusion

This paper establishes a simplified test system for internal combustion wave rotor. Based on the test, it can be found that the range of inlet velocity narrows and the range of fuel-air equivalence ratio correspondingly broaden under the stable operation of the internal combustion wave rotor after the addition of obstacles. At the rotation rate of 1500 rpm, the addition of obstacles significantly intensify the pressure gain during the combustion process of the internal combustion wave rotor, and the higher the blockage ratio the better the intensifying effect. The obstacles sharply increase flame propagation speed in the internal combustion wave rotor. Compared with the case without obstacle, the flame propagation speed is increased by 2 to 4 times when the flame passes the second group of obstacles; continuously increasing the blockage ratio over Br = 10% does not substantially affect on the flame propagation speed. Compared with the flame shapes of the case without obstacle, the area with the most vigorous reaction within the channel of the wave rotor is located behind the obstacles.

Acknowledgements

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