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Experimental study on the effect of combustor configuration on the performance of dual-mode combustor

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A B S T R A C T

Scramjet design is still a great challenge for researchers. It proves to be a critical issue for scramjet combustor to avoid intensive thermal choking while increasing combustion efficiency. Focusing on this target, the relationship between combustor configuration and the performance of dual-mode combustor was investigated using a direct-connected scramjet facility. Combustor was constituted by constant area part and divergent part, while cavities equipped in the expanded wall as flame-holding device. Ethylene was injected normally into the Ma 2.5 mainstream by both wall and cavity injectors. Two critical parameters of configuration, cavity location and the divergent angle, were changed during experiments. Combustion efficiency could evaluate the combustor performance, which was measured by an optical sensor based on tunable diode laser absorption spectroscopy (TDLAS). Combined with traditional wall static pressure and schlieren measurement, combustion efficiency and possible heat release both streamwise and spanwise were analyzed for different cases. It is found that combustion apparently is well organized with smaller divergent angle. Combustor could avoid inlet unstart and get disperse heat release with double cavities, but there is still space to increase efficiency by changing the location of recirculation zone. And experimental results show that the cooperation of cavities is essential for stabilizing combustion downstream.

1. Introduction

Scramjet is considered as the most prosperous technology to achieve hypersonic flight. It has been 50 years since relevant research was conducted, however many difficulties still exist including organizing supersonic combustion in high flow velocities [21]. The engine design involves ram/scram transition, start/unstart characteristics, mixing and combustion performance. And these problems mostly are coupled by some complex physical processes which have not been controlled completely, such as turbulent combustion, shock-boundary layer interaction and chemistry reaction mechanism [6]. Due to the complicated physical process and harsh environment, design of combustor in scramjet has attracted much attention.

High flow velocities and extremely low fuel residence times in scramjet combustor require a flame-holding device to form a recirculation zone. Cavity has been proved to be valid and adopted by a number of researchers [1,8–10,14,20,23]. Mathur et al. [14] found the combination of wall injection and downstream cavity to be the most efficient flame-holding method. Ben-Yakar et al. [1] concluded with the stabilization effect of mixing and combustion by cavity, and also showed experimental results of cavities with different length/depth. However, there also exists a thermal choking problem during combustor operation, driving researchers to adopt different cavity groups. The combustor area must be designed to diverge in the proper manner as the heat is added in order to achieve reasonable release. On the one hand, it is necessary for enhancing mixing to arrange fuel injection reasonably. Focusing on the characteristic, Rasmussen et al. [20] studied flame position and the influence of equivalent ratio and injector position to cavity injectors. Kang et al. [10] examined three kinds of cavity shape to achieve higher combustion pressure. On the other hand, divergent angle is another essential factor for the influence of airstream residence times and heat release. Yu et al. [25] examined the combustor configuration with different divergent angles and large equivalent ratios, and concluded that large divergent angles could reduce thermal choking and have an adverse effect on ignition performance. Chun et al. [4] had a similar conclusion about thermal performance, and evaluated the influence on ranges of different combustion modes. From the above, request of seeking for the best match of these factors is brought up.

The operation of scramjet is a process of transforming chemical energy into kinetic energy, and combustion efficiency is an im-

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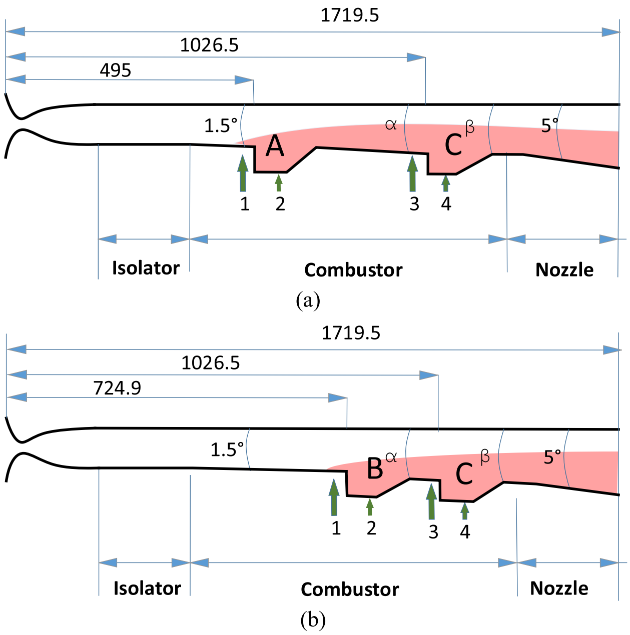

Fig. 1. Scheme of combustor model. (a) Configuration of combustor with A+C cavity. (b) Configuration of combustor with B + C cavity.

Table 1
Divergent angle of combustor model.

Model	α	β
1	1.5	2
2	2	3
3	3	3

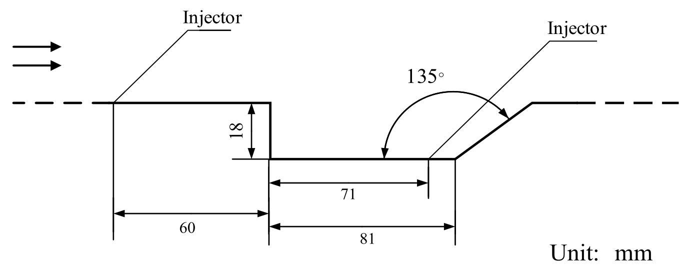

Fig. 2. Scheme of each cavity with wall injector and cavity injector.

portant indicator to evaluate energy utilization efficiency in either direct-connected or free-jet experiments. As quantitative measurement of efficiency is extremely hard in scramjet combustor, in the past years, there existed some researchers using one-dimensional method to qualitative analyze efficiency [6,22]. Gas sampling also provided another approach to efficiency by approximation in a certain degree [3,17]. It is even hardly possible to give the exact experimental errors. Usually combustor technology was evaluated by wall static pressure profiles, mixing with the influence of various gas states and three-dimensional effects. However, development of laser spectroscopy technology provides another sight with only non-traditional contact. This paper adopted advanced laser measurement technology to obtain accurate exit parameters of combustor, which could directly quantify global combustion efficiency, aimed to consider the influence of three divergent angles, two kinds of cavity locations with multiple fuel injectors.

2. Experimental system

2.1. Experimental instrument

Combustion experiments were conducted in a direct-connected scramjet facility. A schematic of the facility was shown in Fig. 1. This facility was divided into three parts: constant area isolator, combustor and nozzle. The air enters the isolator whose cross section is 40 mm (height) × 85 mm (width) at a Mach number of 2.5. In the experiments air was heated to stagnation temperature 1650 K through an H_2–O_2 combustion heater, and the corresponding stagnation pressure was 1.0 MPa.

Three sections with each divergent angle could integrate a combustor. Two of them changed in the experiments were labeled as α and β (Fig. 1). Since divergent angle plays a critical role in combustor performance, three groups of angles were examined. Table 1 presents the details of divergent angles. For the purpose of mixing enhancement and flame stabilization, combination of double cavities in tandem was adopted, which has been validated by former studies [7,12,15,18,19]. Cavities were located as A + C and B + C groups anchored in the expanded wall (Fig. 1, bottom).

Multiple orifices, shown as 1, 2, 3, 4 in Fig. 1, injected C_2H_4 as a fuel. Each injector included seven parallel orifices. Multiple injectors were used for dispersive, homogeneous heat release in the case of thermal choking. Cavity size and injector location are given in Fig. 2. Two cavities have no difference in size.

2.2. Measurement method

Several measurement instruments were utilized simultaneously during experimental tests. Static pressure measurements were used to characterize axial behavior of gas flow. A total of 30 pressure-tap ports were equipped along the length of the test-section in order to acquire static pressure data in the flow direction. The experimental uncertainty in wall pressure measurement was estimated to be ±2%. High speed schlieren was adopted to the position of upstream cavity to observe shock wave and flame front. It could take photo at the position of the first cavity in each case. Due to the blockage of the side wall, flow in the cavity could not be shown in schlieren photos. This system was arranged by Z-shape double reflector, recording at 5000 fps with a CamRecord 5000 camera.

Laser measurement method were introduced to high speed flow field in recent years. Multichannel TDLAS (tunable double laser absorption spectroscopy) sensor has been proved to succeed in measuring gas temperature and partial pressure vertical distribution in supersonic combustion experiments [5,11]. Fig. 3 presents the scheme of the laser measurement device. TDLAS sensor used two water vapor absorption lines (7185.60 cm^{-1}, 7444.35 cm^{-1}) and wavelength scanning method with repetition rate of 4 kHz. The measured cross-section was located at 100 mm downstream of combustor exit, 200 mm upstream of the nozzle exit. In order to obtain the parameter distribution in a single test, both the emission and collection collimators were moved to scan the cross-section within 0.5 s using a motorized precision translation stage. This period is shorter than the facility valid time (one second in this case).

This TDLAS sensor can provide data of temperature and water vapor concentration distribution in the whole cross section combined with translation stage. Combustion efficiency was calculated as the ratio of water vapor concentration generated in combustor and that of complete combustion. The uncertainty for TDLAS was estimated to be 5%. Laser measurement method was used to quantify combustion performance, which is more accurate than gas sampling and one-dimensional analysis methods. Detailed formulas were presented by (1) and (2).

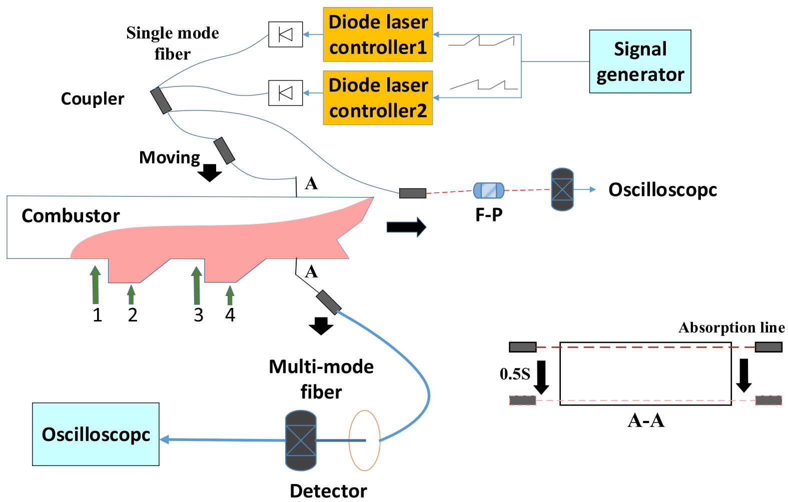

Fig. 3. Scheme of TDLAS measurement device. Calculation method of combustion efficiency.

Table 2
Experimental conditions for experiments.

Case	Model	Cavity	Injector	φ	T_{exit}	$P_{X_{H_2O,exit}}$	η
A1	1	B + C	2, 3	0.42	1225	0.12509	70.51
A2	2	B + C	2, 3	0.44	1095	0.10197	43.97
A3	3	B + C	2, 3	0.38	1295	0.11071	35.04
B1	2	B + C	1, 2, 3, 4	0.8	1156	0.1033	27.5
B2	2	A + C	1, 2, 3, 4	0.8	1273	0.11314	38.9
C1	3	B + C	1, 2, 3, 4	0.69	1164	0.13941	44.1
C2	3	A + C	1, 2, 3, 4	0.69	1098	0.10572	30.3

$$\eta = \frac{X_{H_2O,exit} - X_{H_2O,Inlet}}{2\Phi X_{H_2O,Inlet}/3 - X_{H_2O,Inlet}} \quad (1)$$

$$X_{H_2O,exit} = P_{X_{H_2O,exit}}/P_{exit} \quad (2)$$

In formula (1), $X_{H_2O,exit}$ is water vapor mole fraction of combustor exit cross-section, $X_{H_2O,Inlet}$ is water vapor mole fraction of isolator entrance, Φ is global equivalent ratio, a variable in different cases. In formula (2), $P_{X_{H_2O,exit}}$ is water vapor partial pressure of combustor exit cross-section, P_{exit} is static pressure of the same position.

3. Results and analysis

Two configuration parameters: combustor divergent angle and cavity location were analyzed to estimate their influence to combustion efficiency in the current section. Table 2 indicates experiment conditions and measured efficiency results. Cases are named as group A, B and C for comparison. Divergent angles increased in the order from models 1, 2 and 3. In this table, φ represents global equivalent ratio, T_{exit} represents local average temperature and $P_{X_{H_2O,exit}}$ represents local average water vapor partial pressure, η represents combustion efficiency.

3.1. Divergent angle

Firstly, experiments with two injectors were demonstrated with various divergent angles in case A. Fig. 4 shows static pressure flow distribution for case A1, A2, A3. Fuel was injected at 806 mm and 966 mm from combustor entrance, and cavities were kept as B + C group. Wall static pressure decreases obviously with bigger divergent angle. The peak pressure of A1 reached 1.6 atm before injection, which indicates intensive heat release of small divergent angle resulted in thermal choking. In case A3, equivalent ratio is about 0.19 at 800 mm, and gas fails to ignite in the recirculation of cavity B. Due to low equivalent ratio in the shock train is kept from the exit of isolator, which could accommodate the combustion heat in case of inlet unstart.

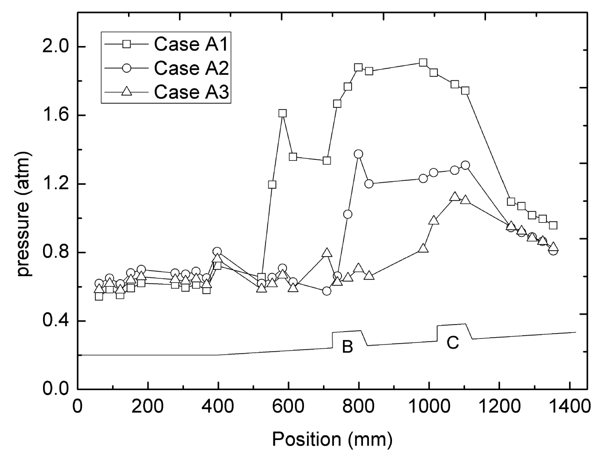

Fig. 4. Static pressure flow distribution for case A.

The peak pressure for A2 was found to be 1.4 atm. Yu and Li [24] concluded that trapezoid pressure distribution in combustor was considered as a total process of adiabatic compression, constant pressure heat release and expansion heat release. Combustor with small divergent angle gets longer heat release process after shock wave compression. In case A3, pressure rise at 800 mm position near cavity A is caused by fluid-mechanical obstruction created by fuel injection rather than combustion. Airstream without compression by normal shock wave can be supersonic throughout, which means excessive divergent angle accelerated gas expansion, requiring longer ignition distance.

The shape of shock wave varies with heat release situations. Pseudo-shock train in isolator was found in ramjet mode with intensive heat release. Fig. 5 shows the result of the high-speed schlieren of cavity B in case A. Cavity was blocked by the side wall and dashed lines represent shock waves observed. 'X' shape shock wave in the middle of Fig. 5(a) located at cavity B, and the combustion reaction begins just behind the shock wave. The 'X' wave was proved to be parts of pseudo-shock train but heat release intensity is not enough to push it upstream in this case. Fuel and air is well mixed downstream as flame propagates deeply into the airstream. There is only an oblique shock wave on the right side of Fig. 5(b), which matches the conclusion of static pressure profile. In case A3 backpressure is lower due to a weaker oblique shock wave, which is more curved than that in A2.

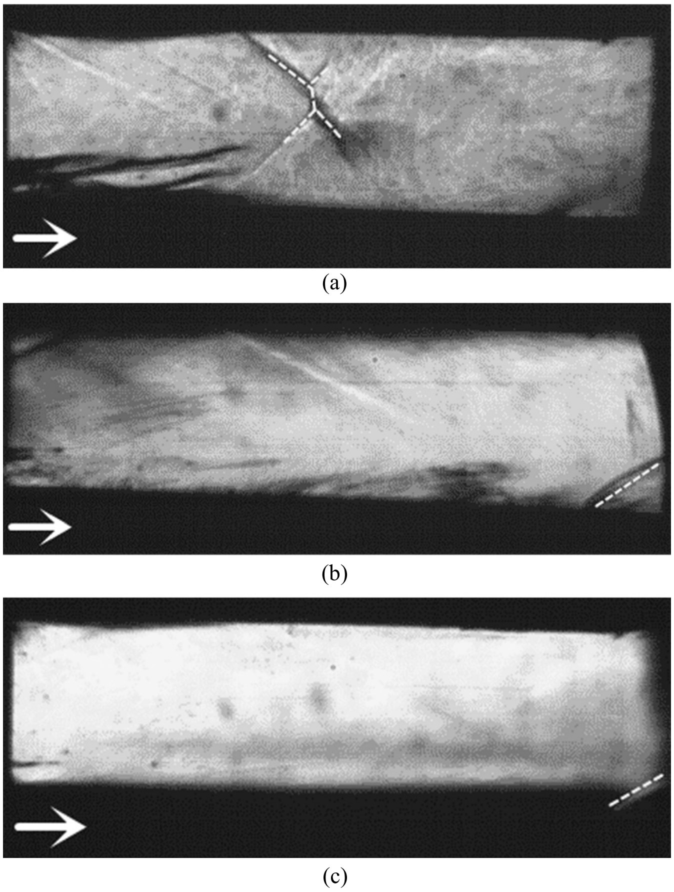

Fig. 5. Picture of schlieren of cavity B for case A. (a) Picture of schlieren of cavity B for case A1. (b) Picture of schlieren of cavity B for case A2. (c) Picture of schlieren of cavity B for case A3.

Fig. 6 presents temperature and water vapor partial pressure distribution at the combustor exit cross section, which gives penetration depth and quantifies combustion efficiency. As combustion distribution in case A is largely different (over the 1900 K temperature in A3), the gradient could give more information. Temperature appears to decrease slightly until 70 mm in the exit cross-section of A1, comparing with 45 mm in A2, which means case A1 obtains better mixing. As shown in Table 1, combustion efficiency appears to be 70.51% for A1 and 43.97% for A2, thus A1 has more intense combustion heat.

Billig and Schetz [2] considered that fuel-jet momentum ratio determined penetration depth in cross-flow. It is proved in Fig. 6 that fuel penetration in A3 is much more insufficient than in other cases. Incomplete combustion reaction in case A3 causes lower backpressure, which cannot form normal shock wave decelerating gas flow. Thus it leads to a large airstream momentum before injection. High temperature of A3 is believed to be the consequence of long ignition delay and hysteretic reaction. The pressure at TDLAS position in both A2 and A3 was decreased to nearly 0.8 atm. And the last five pressure data before that appeared to be steadily decreased without fluctuation, which means there is no combustion happening at the TDLAS cross-section and no interference by the exit backpressure (atmospheric pressure). As a conclusion, case A3 performed only 35.04% for combustion efficiency, which should further utilize stabilization structure to enlarge recirculation zone to overcome the problem of excessive expansion.

Temperature distribution distinguishes penetration depth and flame stabilization mode. In Fig. 7, Micka and Driscoll [16] found two kinds of flame stabilization mode in a wall injection and cavity combustor experiments: jet-wake and cavity stabilization mode. Jet-wake stabilization mode forms lifted diffusion flame independently of cavity structure, whose temperature profile gets large gradient in cross section near the bottom wall. And cavity stabilization mode performs more like premix flame with better fuel–air mixing. Cases A1 and A2 approach the jet-wake mode, and case A3 depends on cavity stabilization, which means that recirculation zone of cavity with big divergent angle cannot provide stabilized combustion. From the above, double cavities with two injectors make a progress in dispersing heat release and avoiding inlet unstart. However, small divergent angle is necessary in case of incomplete mixing and low efficiency.

3.2. Cavity location

3.2.1. Model 2

As presented in Table 1, case B examined the implication of B + C and A + C cavity in model 2 (middle divergent angle). Fuel was jetted by four injectors, and equivalent ratio reaches 0.8. Table 1 also shows TDLAS results and calculated efficiency.

Fig. 8 gives axial static pressure distribution of cases B1 and B2, and corresponding schlieren result of B1 is shown in Fig. 8. In these cases, B2 with cavity A + C provides longer heat release, and the backpressure exerted on the isolator (300 mm). The shock wave was not found through this window, which is believed to be pushed upstream into isolator. Inlet unstart would be easy to achieve for this configuration when adding fuel. Case B2 consumed the most fuel of all cases, although it is not the most effective

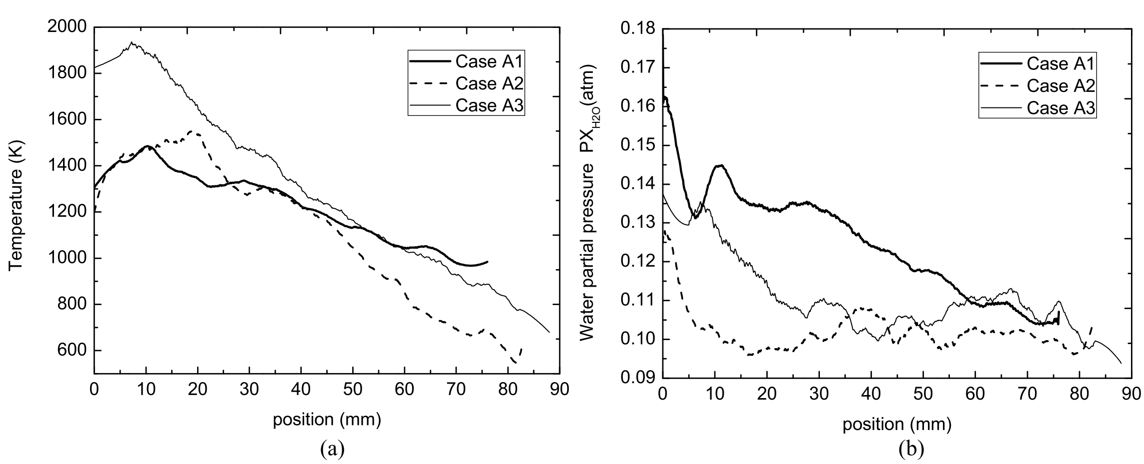

Fig. 6. Vertical temperature and H_2O partial pressure distribution for case A. (a) Temperature distribution for case A. (b) H_2O partial pressure distribution for case A.

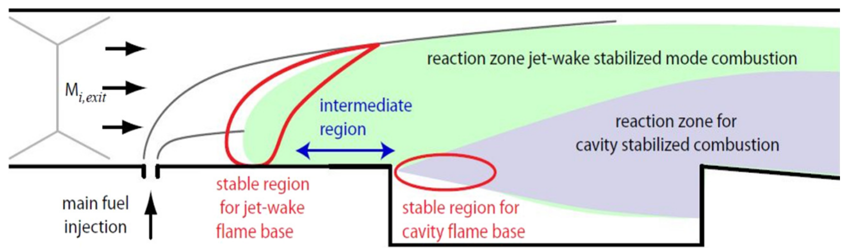

Fig. 7. Scheme of jet-wake stabilized and cavity stabilized combustion mode [16].

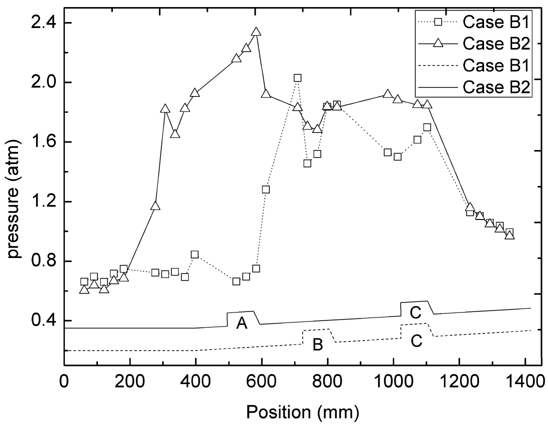

Fig. 8. Static pressure flow distribution for case B.

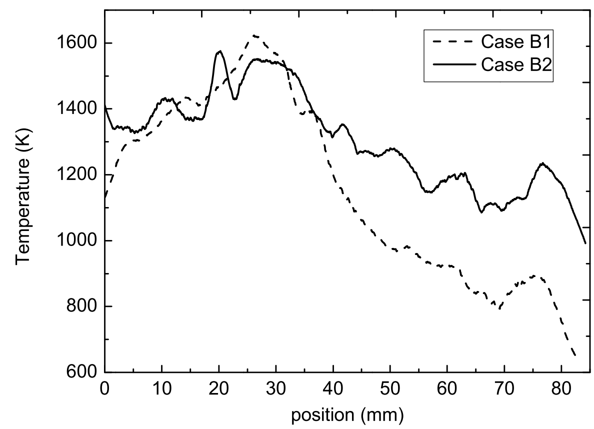

Fig. 10. Vertical temperature distribution for case B.

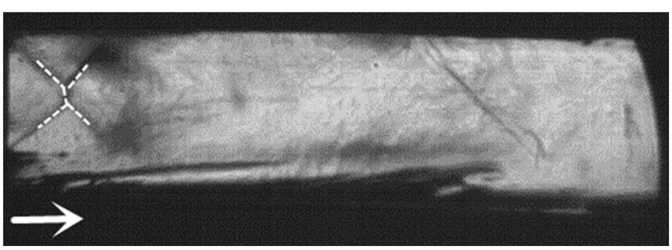

Fig. 9. Picture of schlieren of cavity B for case B1.

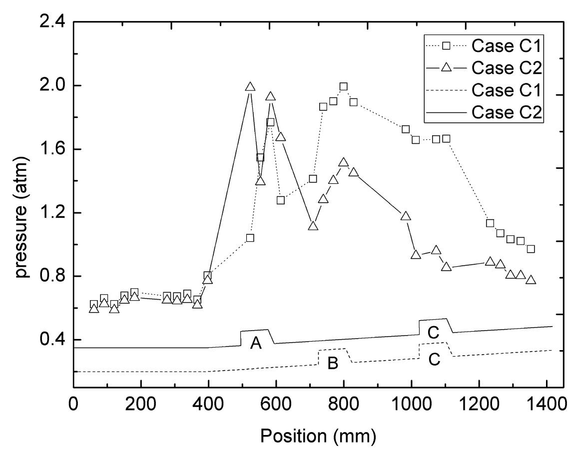

Fig. 11. Static pressure flow distribution for case C.

one (Table 1). For case B1, pressure has not risen until 600 mm (cavity B) and Fig. 9 shows an "X" shape shock wave attached to the combustion zone. The main problem is gas expansion. In case B1, diffusion flame could not be stabilized in the recirculation zone of cavity after expended combustor accelerating. Thus, apparently cavity A + C obtains higher combustion efficiency as measured data told, and moving cavities upstream with B + C could be positive.

It is noticeable that case B1 got only 27.5% combustion efficiency. But deep penetration could be seen in Fig. 9, which gives an opposite signal for efficiency. To explain similar results, Lin et al. [13] argued that wall injection coupled cavity injection lowered the rich limit of ignition as a result of the influence of penetration blockage and mixing characteristics. Hence, fuel combustion in B1 can be mainly weakened by unsuitable injector arrangement. Furthermore, cavities are only 300 mm apart and is more close to the nozzle downstream (Fig. 1). Airflow was accelerated before getting enough ignition and combustion distance. Under that configuration, mixing and combustion of fuel both got a bad performance.

At the exit of combustor, Fig. 10 contrasts the vertical temperature variation along cross-section. Cases B1 and B2 both got 1.0 atm at the last pressure port, but T_{exit} for B2 is 100 K higher than that for B1, which means cavity A + C is more capable of organizing combustion. As the profile observed, B1 and B2 show a similar trend under 40 mm due to similar characteristics of injectors 1 and 2. But B2 keeps over 1050 K from 40 mm to the top because of deep fuel penetration of injector 3 or 4. Thus, it is proved to be useful for multiple injectors with double cavities to achieve longer and disperse heat release without more concentrated fuel which may cause thermal choking and large total pressure loss.

3.2.2. Model 3

In case C, the number of injectors was increased to four and model 3 (large divergent angle) was used. Detailed data are given by Table 1.

Fig. 11 shows the pressure distribution contrast of case C. As presented in the profile, C1 is found to achieve peak pressure before cavity B, and pressure ascent caused by combustion is located at injector 2. But pressure at the exit is 0.2 atm higher than that of C2. Thus moving cavities upstream could improve efficiency in this configuration.

As to case C2 pressure decreases to 0.9 atm at the rear wall of cavity C due to fast expansion with model 3. The profile cannot maintain high pressure within a certain distance after injection.

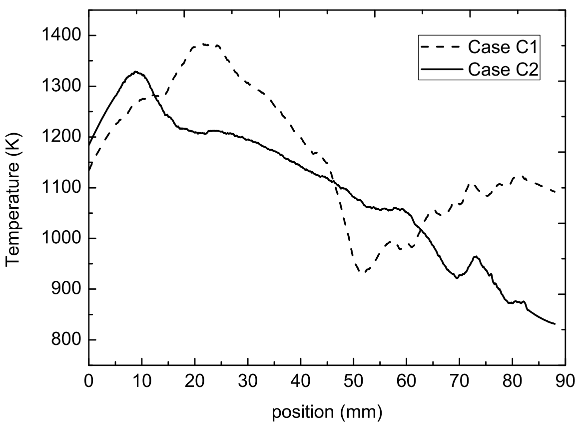

Fig. 12. Vertical temperature distribution for case C.

By contrast to high global efficiency in case C1, pressure profile of C2 shows better efficiency at cavity A which indicates that bigger downstream divergent angle does not decrease the efficiency of cavity A compared with case B. In the exit nozzle, cavity A + C gets a slight rise of pressure at the 1200 mm position, which indicates that a small amount of fuel was re-ignited in near wall region, however slight heat release here cannot achieve enough backpressure to change upstream flow structure. Combustion regions of cavity A and C would keep separately unless they were located closer. As discussed in Section 3.2.1, model 3 would be helpful for the cavity B + C group with large equivalent ratio due to higher efficiency (44.1%).

Configurations of cases B1 and C1 get especially similar pressure profile and global consumed fuel. Cavity B + C turns out to valid for forming enough recirculation to balance more expansion. Just the opposite, cases B2 and C2 prove that the distance from cavity A and C is too long to stabilize flame downstream, which also exerts on combustion in upstream cavity or even the isolator characteristics.

Fig. 12 presents static temperature distribution at the cross-section of combustor exit in case C. Temperature profile of C1 appears to be increased again over 50 mm as a result of multiple injectors. Backpressure formed by cavity B lowers the airstream momentum in order to improve fuel-jet momentum ratio of injectors 3 and 4, which made deeper penetration.

4. Conclusions

1. Experiments with ethylene fuel were conducted in a direct-connected scramjet facility at Mach 2.5. Model was changed by different divergent angles of combustor. Double cavities in tandem were applied as flame-holding device and two kinds of cavity locations were examined. Fuel was jetted by both upstream wall injector and cavity injector for each cavity with equivalent ratio varied from 0.38 to 0.8. Combining existing research conclusions, laser measurement method based on TDLAS provides a standard of analyzing combustion and heat release mechanisms especially by quantifying combustion efficiency.
2. Thermal choking is weakened with the configuration of large divergent angle, but fast flow results in incomplete reaction. For all the cases combustor could avoid inlet unstart and get disperse heat release under current configurations.
3. The most efficient case has a result of 70.51% while most of them appear to be under 40%. Measured temperature in the cross-section is much lower than that of ideal condition. It is proved to be insufficient of making use of air in the cross-section of these configurations.
4. Double cavities and multiple injectors need an accurate cooperation to be efficient. Downstream injectors coupled with cavity could make deep penetration and enhanced mixing while upstream cavity and injectors play a critical role of provide a compressed airstream. And deeper penetration was examined to be more efficient from the temperature distribution at the exit cross-section.
5. Reasonable distance between cavities stabilizes the flame when gas expands rapidly, indicating that double cavities enlarge the recirculation zone and achieve much better mixing.

Conflict of interest statement

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and company that could be construed as influencing the position presented in, or the review of, the manuscript entitled, “Experimental study on the effect of combustor configuration on the performance of dual-mode combustor”.

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