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Combustion Characteristics of a Supersonic Combustor Model for a JAXA Flight Experiment

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Abstract

A flight-ground test comparison program is undergoing at JAXA to clarify so-called "facility effect" on hypersonic aerodynamics and combustion phenomena, and to develop a CFD tool, which can predict actual data in flight from ground test data. The final goal is to conduct a flight experiment to obtain data of aerodynamic heating and supersonic combustion in a real flight and to validate the CFD tool using the flight data and corresponding ground test data. The present study is related to design of a supersonic combustor flow-path suitable to clarify influence of differences in test flow composition between flight and ground test conditions on combustion. The candidate configurations proposed by CFD study were evaluated by direct-connect combustion tests with ethylene fuel. The results showed that a combustor flow was symmetric when fuel equivalence ratio was low, while it became asymmetric when the equivalence ratio became high and the pressure in the combustor rose. Such the asymmetric flow is not suitable for the CFD validation so that the total equivalence ratio was limited. The upper limit of the total equivalence ratio to maintain the symmetric combustor flow was 0.44 in the present flow condition. The combustor model equipped two-stage fuel injectors and cavity flame holders to obtain ethylene combustion. A depth of the cavity flame holder had little influence on combustion, but the number of injection holes for the 2nd injector located downstream of the cavity affected the combustor pressure. Based on the combustion test results, the combustor flow-path design was finalized. In addition, an ethylene fuel ignition method using a pilot hydrogen injection, which is adopted for the flight experiment, was also demonstrated successfully.

Keywords: *Supersonic combustion, Ground testing, Flight experiment, Hydrocarbon fuel, CFD*

1. Introduction

To realize a hypersonic flight system, research and development of hypersonic air-breathing propulsion systems such as a scramjet has been actively conducted in various countries of the world. Both ground tests and CFD play important roles for their development. By making the best use of these, it is expected to reduce the number of the necessary flight tests and to reduce the development costs.

To apply the combustion test data to the actual engine design, however, it is necessary to consider the influence of the flow characteristics, which the ground test facility produces, on the combustion test data, that is, "facility effect". For example, to reproduce the high-speed airflow corresponding to the scramjet operating conditions in the wind tunnel, it is necessary to heat up the airflow to raise the total temperature. JAXA has built a large blow-down-type wind tunnel for the high-speed air-breathing engine test at the Kakuda Space Center, named as Ramjet Engine Test Facility (RJTF) [1]. The RJTF has capability to reproduce flow conditions for the hypersonic air-breathing engine tests, which correspond to the flight Mach numbers of 4, 6, and 8. The engine model up to 3 meters in length can be tested. The RJTF has two different types of the airflow heating devices. One is a storage air heater (SAH) and the other is a vitiation air heater (VAH). The SAH heats the airflow by heat exchange with the heated bricks while the VAH raises the total temperature of the airflow by adding hydrogen and

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oxygen to the airflow and burning them. The oxygen concentration in the VAH test flow is kept at 21% in mole but water vapor is introduced in the test flow. The unique capability of the RJTF is that both the SAH and VAH can reproduce the test flow condition corresponding to Mach 6 flight. The past work has shown that there were some differences in the combustion test results with different airflow heating method [2]. It was considered due to the influence of difference in the flow enthalpy and the influence of water vapor contained in the VAH test flow on combustion. It is known as "vitiation effect". Since the test flow condition beyond Mach 6 flight cannot be reproduced without use of the VAH, such phenomena must be clarified. Therefore, JAXA has started five-years research program to understand the influence of the flow turbulence and the difference of the test flow composition between the flight and ground test conditions on aerodynamic heating and combustion, and to develop CFD tool which is able to predict the actual flight data from the ground test data. The final goal of the project is set to conduct the flight experiment to obtain the aerodynamic heating data and the supersonic combustion data in the real flight and to validate the prediction tool by both the flight data and the corresponding ground test data [3].

Figure 1 shows schematic of the JAXA RD1 flight experiment vehicle (FEV) for supersonic combustion. The length is 1.75 m. The FEV will be launched by a S-520 rocket. The FEV has an axisymmetric shape, which fits in the nose cone of the launcher. After acceleration by the launcher, the FEV is separated and continues to fly along a ballistic trajectory. The supersonic combustion experiment will be conducted in the descend phase when the FEV is re-accelerated to reach Mach number around 6. The combustor model is symmetrical in the height direction and is mounted along the FEV central axis. Considering the inlet start capability at low flight Mach number before the combustion experiment starts, a so-called alligator-type inlet was adopted. In addition, the inlet is a mixed-compression-type one to minimize the length to fit in the nose cone of the launcher. The internal flow-path downstream of the internal inlet exit consists of an isolator, a combustor, and a downstream extension duct. The isolator is a 300 mm-long, constant cross-sectional area duct with a rectangular cross-section, which is 38.1 mm high and 50.8 mm wide, and is installed to prevent the flow disturbance caused by high pressure in the combustor from propagating back into the inlet to cause an inlet un-start. The combustor flow-path is two-dimensional and diverges symmetrically in the height direction. The fuel is gaseous ethylene. The ignition method of the ethylene fuel using self-ignition of gaseous hydrogen as a pilot fuel, instead of a torch ignitor or a spark plug, is applied to reduce electric power requirement of the FEV and to mitigate high voltage leakage risk. The wall pressure distribution in the combustor model will be measured as the supersonic combustion data. In addition, the aerodynamic heating to the FEV surface and the turbulence intensity of the airflow captured by the inlet of the combustor model will be also measured in flight.

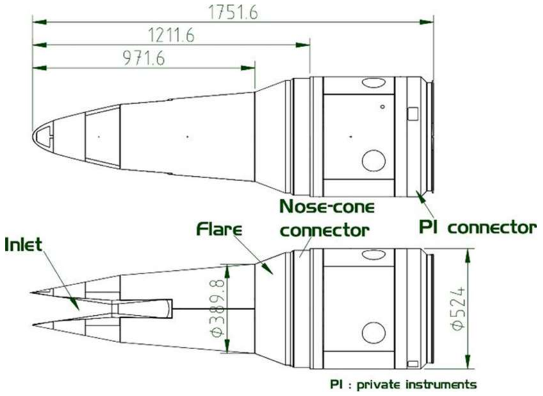


Fig 1. Schematic of JAXA RD1 flight experiment vehicle for supersonic combustion

The present study is focusing on the vitiation effect, that is, the influence of the difference in the test flow composition on combustion. The internal flow-path design of the combustor model is one of the most important design issues for the RD1 FEV. As the first step of the flow-path design, 1D analysis and 3D CFD have been performed for the supersonic combustor flow to establish the flow-path design guidelines of the combustor model [4] [5]. The major requirements for the flow-path design were the following two: Firstly, sizable difference of the wall pressure distribution would be obtained due to the difference in the composition of the combustor incoming flow between the flight and facility conditions. Secondly, supersonic-combustion mode operation should be achieved because of rather simple flow structure in the combustor, higher sensitivity to the difference in the flow composition due to lower pressure and lower temperature in the combustor, and less risk of transition to catastrophic inlet unstart situation during the flight test comparing with the subsonic-combustion mode. The CFD study showed that it is necessary to increase the fuel equivalence ratio while preventing the transition to subsonic combustion mode in order to satisfy the first design requirement. The target value set from the CFD study was the total equivalent ratio of 0.5 [4] [5]. In the meantime, past studies on wall injection into a supersonic crossflow reported that mixing process changes significantly depending on whether pseudo-shock waves are formed or not [6]. It was also reported that the shape of the fuel injector hole affects the mixing efficiency when the injector locates in an attached flow region, while the mixing efficiency becomes less sensitive to the hole shape when the injector locates in a separated flow region [7]. The presence of pseudo-shock waves and large-scale separated flows due to the subsonic combustion mode operation makes the flowfield complicated so that it would make CFD prediction difficult. In addition, detection of the change in the combustion characteristics due to the difference in composition of the incoming flow would also become difficult. Therefore, establishment of supersonic combustion mode operation is essential. It is noted that the present research project targets the combustor operation condition, at which the velocity of the test flow is high and cannot be reproduced without use of the VAH. On the other hand, at such a high total temperature flow condition, the pressure rise due to combustion tends to become small so that the combustor operation is likely to become the supersonic combustion mode. Therefore, aiming to establish the supersonic combustion mode operation is consistent with the high velocity airflow condition targeted by the present research.

In the present study, the combustion characteristics of the candidate combustor configurations proposed by the CFD study were evaluated by combustion tests with the ethylene fuel. As will be shown later, soon after we started the combustion tests, we came to realize that a symmetric combustor flow could be maintained when the total equivalence ratio of ethylene fuel was low, but the combustor flow became asymmetric in the combustor height direction as the fuel equivalence ratio was increased and the pressure in the combustor became high, although the supersonic combustion mode operation was still maintained. It is noted that, in the present CFD for the design study, the symmetric combustor flow in both the height direction and the spanwise direction of the combustor was assumed, and the steady RANS was applied so that the CFD could never predict such the asymmetric combustor flow. The test data taken from such the asymmetric combustor flow is not suitable for CFD validation because it would be more difficult for CFD to simulate than the symmetric flow. By taking the new findings into account, the second requirement for the combustor flow-path design was modified in the present study to be that the symmetric combustor flow with the supersonic combustion mode operation should be established while the first design requirement remained the same. Influence of the shapes of the cavity flame-holder and fuel-injector holes, and that of the fuel supply conditions on the combustion characteristics were clarified, and both the combustor flow-path design and the fuel supply condition, those would be suitable for the RD1 flight experiment, were determined. In addition, the ethylene fuel ignition method by using pilot hydrogen injection is adopted for the RD1 flight experiment. Since the present ignition method is not commonly used, it was also demonstrated in the present combustion tests.

2. Combustion test

2.1. Combustor model

The purpose of the present study is to investigate the influence of difference in the test flow compositions between the flight and the ground test conditions on combustion. The requirements for the flow-path design were the following two: Firstly, sizable difference in the wall pressure profiles should appear due to difference in the composition of the combustor incoming flow between the flight condition and the ground test condition with the VAH. Secondly, as described in the previous section, the symmetric combustor flow with the supersonic-combustion mode operation should be established with both the flight and ground test conditions. The CFD study showed that it is necessary to increase the fuel equivalence ratio while maintaining the supersonic combustion mode operation [4]. Since it was reported that the combustor adopted for the HIFiRE Flight 2 experiment has achieved the supersonic-mode operation with the total fuel equivalence ratio of unity and the combustion efficiency of 0.7 or higher at Mach 8 flight condition [8], its flow-path configuration was referenced as the baseline design. When the design study was conducted, the representative test condition of our flight experiment was set at the flight Mach number of 6.1 and the dynamic pressure of 62.5 kPa, which were different from those for the HIFiRE 2. Therefore, the modification of the flow-path has been studied by CFD [4] [5].

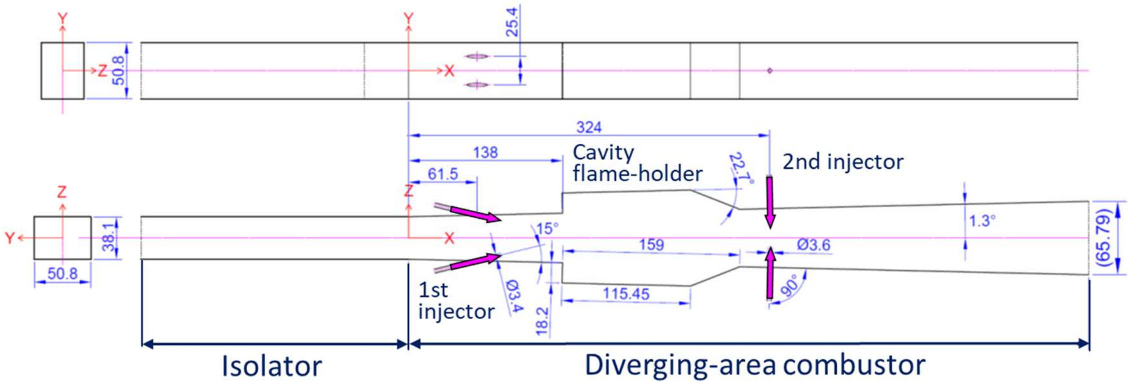


Fig 2. Example of combustor flow-path configuration

Figure 2 shows an example of the supersonic combustor flow-path configuration. It is a 2D diverging-area duct combustor. The combustor flow-path is symmetric in its height direction. Both the top and bottom walls have a half-diverging angle of 1.3 degree. The height and width of the combustor entrance are 38.1 mm and 50.8 mm, respectively. The two-stage fuel injection was adopted. The fuel supplied from the upstream injector, referred as the 1st injector, would burn well with support of the cavity flame holder to raise the pressure in the cavity, expecting the influence of difference in the flow enthalpy on the combustion pressure and that of the water vaper in the test flow on combustion would be observed. It was also expected that the combustion of the 1st injector fuel would supply radicals, which promote the ignition and flame-holding of ethylene supplied from the downstream injector, referred as the 2nd injector. The pressure rise due to combustion of the 2nd injector fuel was expected to become indicator to show the influence of the water vapor on delays of the ignition and combustion heat release in the expanding flow. Referring the injector configuration of the HIFiRE 2 combustor, which also adopted the two-stage injection, the injection angle of the 1st and 2nd injectors were set to be 15 degrees and 90 degrees to the combustor wall, respectively. A large cavity flame-holder was mounted between the two injectors on both walls. In the combustion test, the influence of the following four parameters on the combustion characteristics were investigated:

(1) Fuel equivalence ratio of the 1st and 2nd injectors
(2) The depth of the cavity flame holder
(3) The diameter, the number, and the spanwise spacing of the injection hole for the 1st injector
(4) The diameter, the number, and the spanwise spacing of the injection hole for the 2nd injector

The values of each parameter are summarized in Table 1. Regarding to the fuel equivalence ratio, three values of the total equivalence ratio were compared, those were 0.38, 0.44, and 0.54. For the total equivalence ratios of 0.44 and 0.54, influence of the split ratios of the ethylene fuel supplied from the 1st and 2nd injectors on combustion was also investigated. For example, the same amount of ethylene was supplied from the 1st injector and the 2nd injector in the cases 2 and 4, although the total equivalence ratio was different. On the other hand, smaller amount of ethylene was supplied from the 1st injector than the 2nd injector for the other cases aiming to lower the pressure in the cavity and prevent transition to the asymmetric combustor flow, or that to the subsonic combustion mode operation. In comparison of the cavity depth, the aperture length, which was defined as the length from the cavity upstream edge to the cavity aft-ramp end, was fixed at 159 mm, expecting that air would be entrained into the cavity with the same mass flow rate through the shear layer between the main airflow and the cavity recirculating flow, while the degree of the flow expansion due to sudden expansion of the flow-path cross-section in the cavity section and the residence time of the fuel-air mixture in the cavity would be different with the cavity depth. In comparison of the 1st and 2nd injector configurations, the diameter of the injection hole is known as a scale factor for fuel penetration height while the number of the holes is likely to change flow blockage due to difference in the distribution of combusting fuel flows. The spanwise spacing between two injector holes was expected to affect spanwise distribution of the fuel.

Table 1. Parameters for the combustion tests

Equivalence ratio	**Case**	**1st injector**	**2nd injector**	**Total equiv. ratio**
	1	0.16	0.22	0.38
	2	0.22	0.22	0.44
	3	0.17	0.27	0.44
	4	0.27	0.27	0.54
	5	0.10	0.33	0.43
	6	0.20	0.33	0.53
Cavity depth	**Type**	**Depth, mm**	**Aperture leng., mm**	**Aft-ramp angle, deg**
	α	25.7	159	22.7
	β	18.2		
	γ	12.85		
1st injector	**Type**	**Diameter, mm**	**Number**	**Spacing, mm**
	c	4.8	1	-
	d	3.4	2	25.4
	e	3.4	2	17
	f	2.4	2	17
2nd injector	**Type**	**Diameter, mm**	**Number**	**Spacing, mm**
	A	3.6	2	25.4
	C	3.6	1	-
	D	2.5	2	17
	E	2.5	1	-

On the other hand, the following parameters were fixed in the present study. Regarding to the combustor geometry, a half expansion angle of the top and bottom wall of the combustor was 1.3 degree. The entrance height was 38.1 mm, the width was 50.8 mm, and the length was 610 mm. As for the cavity flame-holder geometry, the aperture length was 159 mm, the aft-ramp angle was 22.7 degrees, and it was installed 138 mm downstream from the entrance of the diverging-area combustor. As for the 1st injector, it was mounted 61.5 mm downstream from the combustor entrance, and the injection angle was 15 degrees to the combustor wall. As for the 2nd injector, it was installed 324 mm downstream from the combustor entrance, and the normal injection was applied.

2.2. Test facility

The combustion tests were conducted using a supersonic wind-tunnel with the VAH in JAXA Kakuda space center, named as "KWT". By mixing and burning hydrogen and oxygen in the high-pressure airflow, the total temperature of the airflow is raised, and the high-speed airflow is generated by expanding the hot and high-pressure air through the facility nozzle. Oxygen is added so that the oxygen concentration in the test flow after the combustion-heating is maintained to be 21 %mol, which is equal to that of actual air. The combustion test was conducted in a direct-connect configuration, in which the combustor model was connected to the facility nozzle via a 240 mm-long constant-area duct isolator, and the facility nozzle flow simulated the airflow compressed by the inlet of the RD1 FEV. Figure 3 shows the combustor model installed in the KWT. The combustor model was installed by rotating 90 degrees around its center axis so that the side wall, on which the observation window was mounted, was facing up. The walls facing to right and left in Fig. 3 were termed as the top wall and the bottom wall, on which the fuel injectors and the cavity flame holder were mounted.

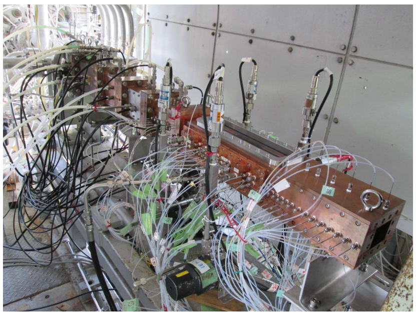


Fig 3. The combustor model installed in the KWT at JAXA Kakuda space center

The facility test flow conditions were set at the total pressure of 2.0 MPa and the total temperature of 1700 K. The Mach 3 facility nozzle was used to supply the high-speed airflow to the combustor model. The nozzle was designed so that the core flow Mach number of the facility flow matches the cross-sectional average Mach number of the airflow after compression by the inlet of the RD1 FEV under the representative flight test conditions, those are the flight Mach number of 6.1 and the dynamic pressure of 62.5 kPa. The fuel supplied to the combustor model was gaseous ethylene. For preventing condensation of ethylene due to adiabatic expansion in the fuel supply lines, ethylene was warmed up to 40 degree-Celsius before being supplied to the combustor model by putting the ethylene cylinder in a hot water tub.

2.3. Measurements

In the combustion test, wall pressure measurement was conducted by installing 42 and 39 ports along the center line of the top and bottom walls, 7 ports on the side wall with the large observation window and 38 ports on the other side wall. The total number of the wall pressure ports was 126. PSI (currently, Measurement Specialties Inc.) System 8400 was used for the simultaneous multipoint measurement of the wall pressure. One 64-channel scanner head for 45 psiG range (310 kPaG) and one for 100 psiG range (690 kPaG) were connected to the System 8400. The sampling frequency was 20 Hz for each channel. In addition, ethylene flame in the combustor was recorded with a video camera.

2.4. Ignition method of ethylene fuel

In the RD1 flight experiment, the ignition method of ethylene fuel by using pilot hydrogen injection is adopted because it is difficult to install spark plugs or torch igniters on the RD1 FEV to reduce electric power requirement and to mitigate high voltage leakage risk. Since the present ignition method was not commonly used, its feasibility was also examined in the present combustion tests. Hydrogen is highly reactive gas so that it easily self-ignites. In the present ignition method, firstly, pilot hydrogen gas was injected to achieve self-ignition and its flame holding. It is noted that the pilot hydrogen was supplied only from the 1st injector, which locates upstream of the cavity flame holder so that long residence time of hydrogen in the cavity would ensure its self-ignition. Then, ethylene fuel started to be supplied and it was ignited by the pilot hydrogen flame. Finally, the pilot hydrogen supply was shut down and pure ethylene combustion started. The present ignition method was demonstrated, at first, by supplying the pilot hydrogen gas using the hydrogen gas supply system of the KWT in a steady manner. After confirming that the ignition method works, it was used regularly in the subsequent combustion tests. In addition to this, we also demonstrated the ignition method with supplying the pilot hydrogen gas filled in a 1-liter run-tank with a blowdown manner assuming application to the actual RD1 FEV.

3. Results and Discussion

3.1. Observation of ethylene flame in the combustor

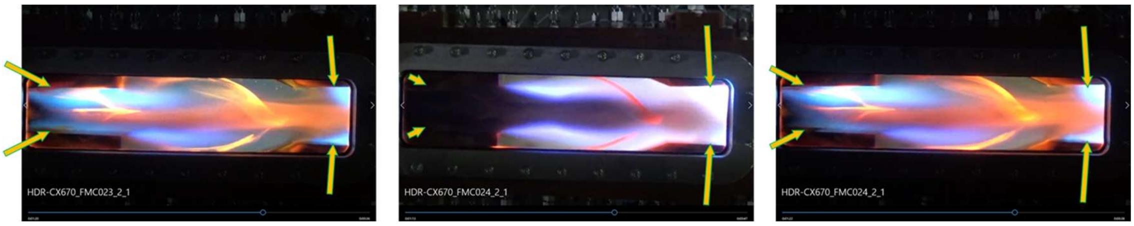
Figure 4 shows the flame structure inside the combustor under each fuel injection condition. The figure shown here is the single frame image taken from the video movie recorded in the KWT combustion tests. The orange arrows in Fig. 4 indicate the positions of the 1st and 2nd injections, and the length of the arrow represents the fuel mass flow rate supplied from each injector. The cavity flame holder was type *β*, which was 18.2 mm-deep. The 1st injector was type *d*, which had two holes with 3.4 mm-diameter and 25.4 mm-spacing. The 2nd injector was type *C*, which had single hole with 3.6 mm-diameter. The pale blue region in each figure was due to self-emission from the ethylene flame. On the other hand, the red emission was considered due to a deposit adhering on the observation window glass being heated. The source of the deposit was considered to be oil mist, which came from the air compressor to accumulate high-pressure air.

It is clearly seen in all the pictures of Fig. 4 that both the ethylene fuel supplied from the 1st injector and the 2nd injector were burning well. The more the ethylene fuel was supplied, the stronger the luminosity of the ethylene flame became. With the injection conditions of cases 1, 2, 3, and 5, where the total equivalence ratio was 0.44 or lower, the ethylene flame was almost symmetric in the combustor height direction. On the other hand, in the cases 4 and 6, where the total equivalence ratio was 0.54, the flame luminosity of ethylene fuel supplied from the 1st injector was obviously stronger and spread wider near the top wall than near the bottom wall. The flame around the 2nd injector hole on the top wall penetrated high into the main airflow while the flame on the bottom wall side was stretched in the main airflow direction. The results clearly showed that the combustor flow became significantly asymmetric. In the case 1, where the total equivalence ratio was the lowest, and the case 5, where the equivalence ratio of the 1st injector was only 0.1 while the total equivalence ratio was the same as cases 2 and 3, the flame was formed from the upstream edge of the cavity and was stretched along the shear layer between the main airflow and the recirculating flow in the cavity. In the cases 2 and 3, where the total equivalence ratio was 0.44, a part of the recirculating flow region in the cavity penetrated upstream beyond the cavity upstream edge because more fuel was supplied and the pressure in the cavity rose. As a result, the pale emission region spread upstream. In the cases 4 and 6, where the total equivalence ratio was the highest, the recirculation region reached further upstream, and the combustor flow became totally asymmetric.

As mentioned in Section 1, transition to the asymmetric combustor flow was newly found in the present combustion tests. Such the asymmetric flow is not suitable for the CFD validation because it would be more difficult for CFD to simulate accurately than the symmetric flow. The upper limit of the total equivalence ratio, with which the symmetric combustor flow can be maintained, was 0.44.

Based on the discussion above, we decided to evaluate the candidate combustor configurations by the combustion test results with the fuel injection cases of 2 and 3, where the total equivalence ratio was the same as 0.44 but the split ratio between the 1st injector and the 2nd injector was different. It is noted that the upper limit equivalence ratio of 0.44 was 12% lower than the target value of 0.5, which has been set from the CFD study assuming the symmetry of combustor flows.

(a) Case 1: $\phi 1/\phi 2$=0.16/0.22 (b) Case 2: $\phi 1/\phi 2$=0.22/0.22 (c) Case 3: $\phi 1/\phi 2$=0.17/0.27



(d) Case 4: $\phi 1/\phi 2$=0.27/0.27 (e) Case 5: $\phi 1/\phi 2$=0.10/0.33 (f) Case 6: $\phi 1/\phi 2$=0.20/0.33

Fig 4. Single frame image of ethylene flame in combustor model at each fuel injection condition: cavity flame holder of type *β*, 1st injector of type *d*, 2nd injector of type *C*; $\phi 1$ and $\phi 2$ denote equivalence ratio of ethylene supplied from 1st injector and 2nd injector, respectively.

3.2. Influence of the cavity depth on combustion characteristics

Fig. 5 shows the comparison of the wall pressure distributions measured in the combustion tests with the different cavity depths, those were 25.7 mm, 18.2 mm, and 12.85 mm, referred as the types *α*, *β*, and *γ* in Table. 1. The aperture length was 159 mm for all the three cavities. The 1st injector was the type *d* and the 2nd injector was the type *C*. The left and right figures show the results with the fuel supply condition of case 2 and case 3, respectively. The wall pressure distributions along the center line of the top wall and those of the bottom wall are shown. In addition, the results with fuel injection and those without fuel injection are shown by solid symbols and open symbols, respectively. The upper half of the combustor flow-path shapes and the injector locations are also shown in Fig. 5.

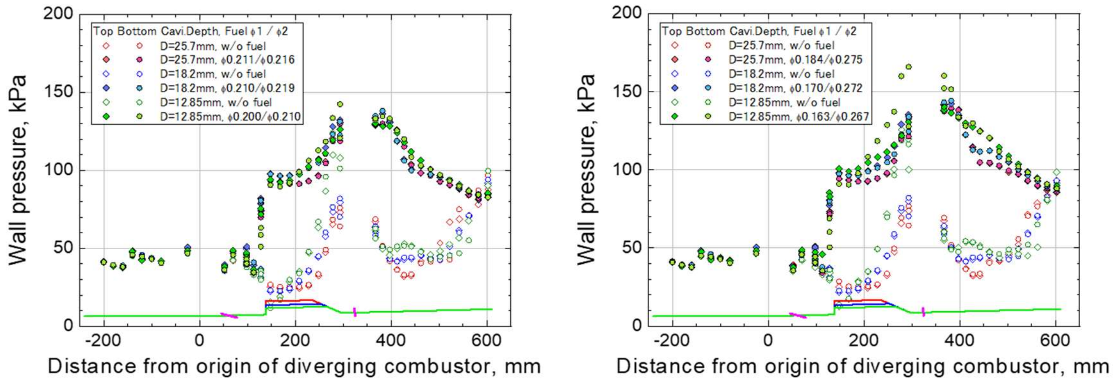
In both wall pressure distributions, the pressure-rise due to ethylene fuel combustion started at slightly upstream of the cavity upstream edge location because, as shown in Figs. 4(b) and 4(c), a part of the recirculating flow region in the cavity penetrated upstream beyond the cavity upstream edge. The pressure continued to rise gradually toward the cavity aft-ramp end, and then, it reached its peak value around the 2nd injector location. In the downstream of the 2nd injector, the pressure continued to drop in the downstream direction as the cross-sectional area of the combustor duct increased. In the case without fuel supply, the pressure dropped at the cavity upstream edge due to the sudden expansion of the flow-path in the cavity section. The pressure rose rapidly in the cavity toward its aft-ramp, and then it reached its peak value near the downstream edge of the aft-ramp. In the downstream of the 2nd injector, the pressure became low. It is noted that the pressure recovery near the exit of the combustor duct was due to the boundary layer separation against high back pressure.

The pressure in the combustor tended to rise slightly as the cavity depth became shallower. This trend can be seen more clearly in the wall pressure distribution without the fuel supply. The reason of the slightly higher pressure with the shallower cavity was less expansion of the main airflow in the cavity section because the change of the flow-path cross sectional area was smaller with the shallower cavity than the deeper one. The pressure difference between the type *α* cavity and the type *γ* one seemed to be slightly smaller in the case with combustion than those in the case without the fuel supply. In the case with combustion, the pressure in the cavity flame holder rose due to combustion, and the recirculation region tended to expand and push up the shear flow toward the center axis of the combustor. Consequently, the influence of the sudden expansion of the flow-path cross sectional area on the combustor flow became weaker in the case with combustion than in the case without the fuel supply. The result suggested that the combustion efficiency with the type *γ* cavity would remain almost the same as that with the type *α* one. It is noted that CFD predicted almost the same wall pressure distribution and the same combustion efficiency for these three cavities [5]. The interesting point of the CFD results was that the flow in the cavity recirculated mainly in a plane parallel to the center plane of symmetry in the spanwise direction for the type *α* and type *β* cavities, while it recirculated mainly in a plane parallel to the center plane of symmetry in the combustor height direction for the type *γ* one. The depth of the type *α* cavity, which was 25.7 mm, was almost the same as a half of the combustor width so that the size of the recirculating flow formed in the cavity was almost the same for these three cavities. The reason why the combustor flow except in the cavity flame holder became almost identical for these three cavities in the CFD results was still under investigation. On the other hand, in the combustion tests, it is difficult to know how the recirculating flow was formed in each cavity. However, the pressure in the combustor was almost the same or slightly higher so that the combustion efficiency was also likely to be the same or slightly higher with the type *γ* cavity comparing with the other cavities. Therefore, the CFD prediction was expected to be in some agreement with the combustion test results.

There was another finding from the combustion tests. The wall pressure distribution on the top wall and the bottom wall agreed well in the results shown in Figs. 5(a) and 5(b) except those with the type *γ* cavity and with the fuel supply condition of case 3, in which a clear difference appeared between the wall pressure distribution on the top wall and that on the bottom wall so that the combustor flow became asymmetric. It suggested that the margin for maintaining the symmetric combustor flow was smaller with the type *γ* cavity than with the other two cavities.

In the meantime, we also evaluated the self-ignition capability of the ethylene fuel without the pilot hydrogen injection, considering recovery from the ignition failure using the pilot hydrogen or the flame-holding failure of ethylene. The results showed that the self-ignition capability of the type *β* cavity was the best among these three. It was considered because the pressure and temperature drop due to the main airflow expansion in the cavity section would be the largest with the deep cavity of type *α*, while a recirculating flow would be difficult to be formed in the shallow cavity of type *γ* unless combustion occurs in it, and therefore, the residence time of the fuel and air mixture in the cavity was not long enough to initiate ethylene ignition.

Based on the above discussion, we selected the cavity depth of 18.2 mm, referred as the type *β*, for the RD1 combustor.

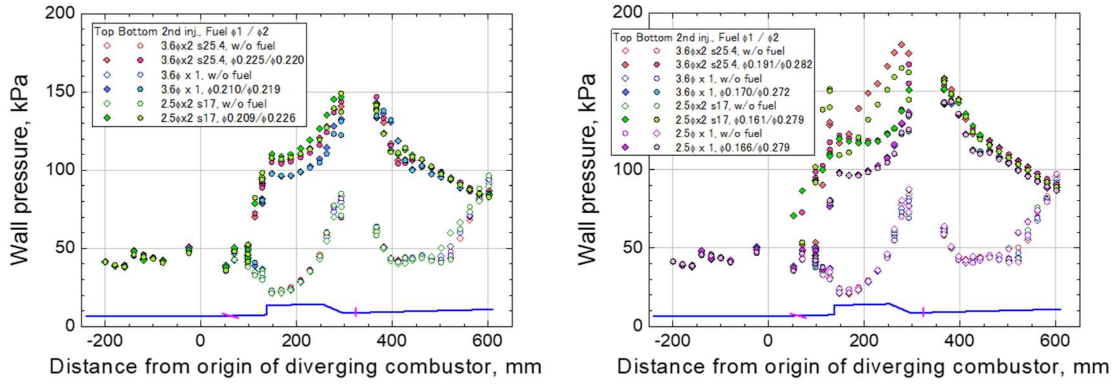


(a) Case 2; ϕ1/ϕ2=0.22/0.22 (b) Case 3; ϕ1/ϕ2=0.17/0.27

Fig 5. Influence of cavity depth on wall pressure distributions: 1st injector of type *d*, 2nd injector of type *C*

3.3. Influence of the 2nd injector configuration on combustion characteristics

Figure 6 shows a comparison of the wall pressure distributions measured with the different configuration of the 2nd injector. The cavity was the type *β*, and the 1st injector was the type *d*. Regarding to the parameters of the 2nd injector, the number of the injection hole had a clear effect on the wall pressure distribution. The pressure in the cavity section with the two-hole injectors was higher than that with the single-hole one. However, it was clearly seen in the result under the fuel supply condition of case 3 that clear difference appeared in the wall pressure distribution on the top wall and the bottom wall, and the combustor flow became totally asymmetric in the case with the two-hole injectors. Therefore, the candidates for the 2nd injector narrowed down to the single-hole injectors. On the other hand, the influence of the hole diameter on the combustion characteristics did not appear clearly on the wall pressure distribution. Considering situation in the RD1 flight experiment, firstly, the ethylene tank pressure will drop rapidly since the ethylene is supplied in a blowdown manner. Secondly, the combustion test will be conducted in the descend phase of the FEV flight and the flight dynamic pressure will rise from 25 kPa to 100 kPa in several seconds of the flight test time so that higher mass flow rate of the ethylene supply will be required with time. Therefore, the injection hole with the large diameter would be preferred. Based on the above discussion, we decided to adopt the type *C* configuration for the 2nd injector, which has single hole with 3.6 mm-diameter.



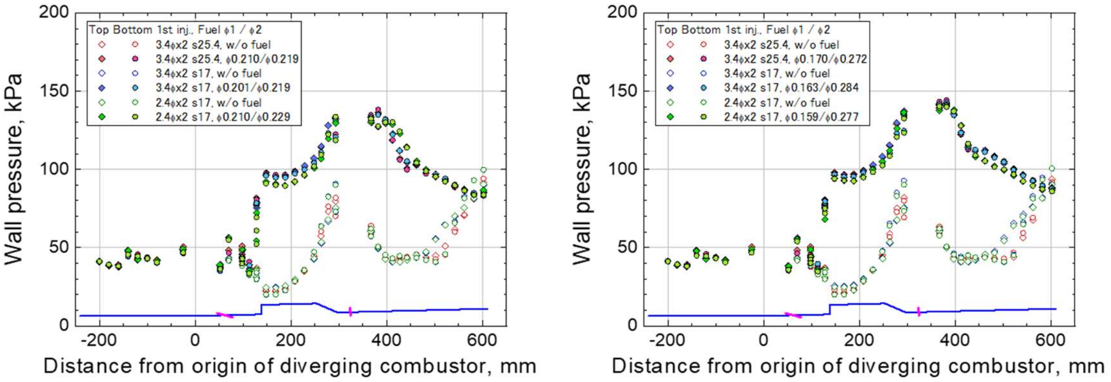
(a) Case 2; ϕ1/ϕ2=0.22/0.22 (b) Case 3; ϕ1/ϕ2=0.17/0.27

Fig 6. Influence of the 2nd injector configuration on wall pressure distributions: cavity flame holder of type *β*, 1st injector of type *d*

3.4. Influence of the 1st injector configuration on combustion characteristics

Figure 7 shows a comparison of the wall pressure distributions measured with the different configurations of the 1st injector. The cavity was the type *β*, and the 2nd injector was the type *C*.

Although the result is not shown here, the pressure rise due to combustion in the cavity region was smaller with the single-hole injector than that with the two-hole injector, especially under the low equivalence ratio condition. Therefore, the candidate for the 1st injector narrowed down to the two-hole injectors. The influence of the 1st injector configuration on the wall pressure distribution was small comparing with the 2nd injector. Regarding to the hole spacing, the wall pressure distribution with the type *d* and the type *e* were almost identical so that the influence of the hole spacing was hardly seen. On the other hand, regarding to the injector hole diameter with the same spacing, the pressure with 3.4 mm-diameter holes of the type *e* was slightly higher than that with 2.4 mm-diameter holes of the type *f*. There was weak tendency that the larger the hole diameter was, the higher the pressure in the cavity was, but the difference was small. Considering the requirement to supply ethylene fuel at large mass flow rate in the latter half of the RD1 flight test, as discussed in the previous subsection for the 2nd injector selection, the injection hole with the large diameter would be preferred. Therefore, we decided to adopt the type *d* configuration for the 1st injector, which is the two-hole type with 3.4 mm-diameter and 25.4 mm-spacing.



(a) Case 2; $\phi 1/\phi 2=0.22/0.22$ (b) Case 3; $\phi 1/\phi 2=0.17/0.27$

Fig 7. Influence of the 1st injector configuration on wall pressure distributions: cavity flame holder of type *β*, 2nd injector of type *C*

3.5. Influence of fuel supply ratio of the 1st/2nd injectors on combustion characteristics

In Figs. 5, 6, and 7, the wall pressure downstream of the 2nd injector was always slightly higher with the fuel injection condition of case 3 than with that of the case 2 because larger amount of ethylene fuel was supplied from the 2nd injector and the combustion heat release due to ethylene supplied from the 2nd injector became larger with the case 3. Furthermore, it was seen in the wall pressure distributions with the type *γ* cavity in Fig. 5(b) and in those with the 2nd injectors of the types *A* and *D* in Fig. 6(b), those were the results with the fuel supply condition of case 3, that clear difference appeared between the wall pressure distribution on the top wall and that on the bottom wall so that the combustor flow became asymmetric. The results suggested that the fuel supply condition of case 2 would have larger margin in maintaining the symmetric combustor flow than the case 3. Consequently, the fuel supply condition of case 2, with the split ratio between the 1st injector and the 2nd injector of one-to-one, was chosen for the RD1 combustor.

3.6. Selection of the configuration and the fuel supply condition for the RD1 combustor

The combustor configuration and the fuel supply condition for the RD1 combustor model, those were proposed by the present study, are summarized as the follows. It is noted that the selected configuration is the same as that shown in Fig. 4.

(1) The cavity depth: type *β*, 18.2 mm.
(2) The 1st injector configuration: type *d*, two holes with 3.4 mm-diameter and 25.4 mm-spacing.
(3) The 2nd injector configuration: type *C*, single hole with 3.6 mm-diameter.
(4) The total fuel equivalence ratio, with which the symmetric combustor flow can be maintained, was 0.44. The split ratio of the fuel supply between the 1st injector and the 2nd injector was selected to be one-to-one.

3.7. Demonstration of ethylene ignition method by pilot hydrogen injection

It was confirmed that ethylene fuel can be ignited by the pilot hydrogen injection under the present test conditions in the KWT. As the first step of the demonstration, the pilot hydrogen was supplied to the combustor model by using the hydrogen gas supply system of the KWT in a steady manner. It was found that the key to ignite ethylene fuel is to provide time to overlap the pilot hydrogen supply and the ethylene fuel supply. The overlap time for the supply of hydrogen and ethylene was set for 0.3 seconds in the present study. The equivalent ratio of pilot hydrogen was 0.2. Assuming application of the present ignition method to the combustion test of a full flow-path combustor model, which includes an inlet and a downstream extension duct, in the RJTF, the present method was further demonstrated at the test flow condition with the total pressure of 1.5 MPa and the total temperature of 1570 K, and then, it was confirmed that ethylene could be successfully ignited with such the low pressure and low temperature flow conditions. Next, the ignition method with suppling the pilot hydrogen stored in the 1-liter run-tank in a blowdown manner was also demonstrated assuming application of the present method to the actual RD1 FEV. In this application, once the pilot hydrogen starts to be supplied, the pressure in the hydrogen tank drops rapidly. Therefore, it is necessary to set the initial filling pressure higher than the case using the hydrogen supply system of the KWT. It was confirmed in the present combustion test that the ethylene can be ignited with a feasible initial filling pressure of the hydrogen tank, which was 4 MPaG.

4. Conclusions

The direct-connect combustion tests of the supersonic combustor model for the RD1 flight experiment vehicle were conducted using the vitiation-air-heater-type supersonic wind tunnel at JAXA Kakuda Space Center to investigate the influence of the depth of the cavity flame holder and the configuration of the injection hole for the 1st and 2nd injectors, such as the number and diameter of the injection hole, on the combustion characteristics. Based on the combustion test results, the combustor flow-path design was finalized. The ignition method of ethylene fuel using pilot hydrogen injection, which is adopted for the RD1 flight experiment, was also demonstrated. The following results were obtained.

(1) The combustion test results showed that the symmetry of the combustor flow was maintained when the total equivalence ratio of ethylene fuel was low, but the combustor flow tended to become asymmetric in the combustor height direction as the fuel equivalence ratio increased and the combustor pressure became high while the supersonic combustion mode operation was still maintained. Since such the asymmetric combustor flow is not suitable for the CFD validation, the second requirement for the combustor flow-path design was modified in the present study to be that the symmetric combustor flow with the supersonic combustion mode operation should be established.

(2) The upper limit of the total equivalence ratio, with which the symmetric combustor flow can be maintained, was 0.44 under the present test flow condition. The split ratio between the 1st injector and the 2nd injector of one-to-one was selected because of the same reason.

(3) The depth of the cavity flame holder had little influence on the wall pressure distribution in the combustor as CFD predicted. The 18.2 mm-deep cavity was selected mainly because the self-ignition capability of ethylene fuel was the best among these three.

(4) The number of the injection hole of the 2nd injector affected the wall pressure distribution in the combustor. The single-hole injector with the 3.6 mm-diameter hole was selected because it was good to maintain the symmetric combustor flow comparing with the two-hole one.

(5) The influence of the 1st injector configuration evaluated in the present study on the wall pressure distribution in the combustor was not as large as that of the 2nd injector. The two-hole injector with the 3.4 mm-diameter hole was selected since the two-hole injector with the large diameter showed advantage to obtain high pressure in the cavity region for the wide range of the fuel equivalence ratio conditions, but the difference was small.

(6) The ethylene ignition method using pilot hydrogen injection was demonstrated. The key for the successful ignition was to provide time to overlap the pilot hydrogen supply and the ethylene fuel supply.

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