The Performance of Dual Combustion Ramjet Based on Free-jet Experiments

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Abstract
The thrust and specific impulse of the full-size dual combustion ramjet (DCR) in Ma4/17km and Ma6/25km flight conditions were investigated through free-jet experiments. The pressure distribution reveals that there is purely supersonic flow at Mach 6, while partly subsonic flow (about 1m) at Mach 4. The thrust coefficient is large enough for accelerating and cruising of missile powered by the DCR. The specific impulse is 11.0~11.9 kN.s/kg at Mach 4, and 8.6 ~ 9.0 kN.s/kg at Mach 6. Thus, the DCR shows good performance during the range of Mach 4 to Mach 6, which is important for a robust engine and worth further investigation. This paper obtained the performance of the DCR for the first time, and the data is fundamental to design of hypersonic missile.

1. Introduction

Hypersonic vehicle attracts great attention in recent years and is considered as one of the best ways to realize single stage to orbit [1] (SSTO) or two stage to orbit (TSTO) because of several advantages, such as high specific impulse and high lift drag ratio [2]. However, considering risks and technology readiness levels, hypersonic missile is the first and practical step. The difference between hypersonic missile and hypersonic plane mainly lies in two aspects: (1) the fuel used in the former is carbon-hydrogen for rapid response, while hydrogen is usually used in the latter for high performance and high Mach number; (2) lift-body vehicle is widely adopted for the plane, while axisymmetric body (HyFly [3]) and lift-body (X-51A [4]) are suitable for the missile.
In hypersonic flight condition, scramjet shows good performance and is prosperously investigated all around the world [5], while dual combustion ramjet (DCR) attracts very little attention. In fact, DCR combines the best features of ramjet and scramjet, and has several merits [6]: wider range of operating Mach number (3.5~6.5), more stable combustion, higher performance at low Mach number, and easier thermal protection. One disadvantage is that it becomes deficient when the flight Mach number exceeds 6.5 or 7.
DCR is mainly composed of a subsonic preburner and a supersonic combustor. Because liquid kerosene is difficult to combust in supersonic flow, the subsonic preburner is used to preheat the spray of the liquid kerosene and to crack it as small-molecular species such as ethylene, carbon-monoxide or hydrogen. The high-temperature fuel-rich gas is then mixed with the peripheral air, and combusts in the supersonic combustor.
DCR was firstly proposed by Billig et al. [3] of John Hopkins University (JHU) in 1980s. Stockbridge et al. [7] investigated the interaction between the intake and the combustor based on experiments and 1-D numerical analysis. Waltrup [8] studied the application of the DCR in hypersonic tactical missile, and concluded that it was the only hypersonic propulsion system to satisfy the requirement of both air force and navy. Although John Hopkins University conducted hundreds of experiments, and Boeing conducted 5 flight test of HyFly powered by the DCR, there were very few literatures about the DCR [9]. Although HyFly failed several times, and X-51A reaches its acme this year when it cruises 240s at a Mach number of 5.1, the merits of DCR has not explored thoroughly, including wide-range capability, passive thermal protection possibility.
In order to accurately evaluate performance of the DCR, flight test is the most reliable way. But flight test is thwarted by many factors, not only great expense but also other technologies such as booster rocket and dispenses system. Hyshot in Australian is one of the cheapest projects to conduct hypersonic experiments. Free-jet experiment duplicates the flight condition, thus the results from free-jet experiment are credible and accurate enough (there does exit some discrepancies because of vitiated air coming from combustion). Free-jet experiment is much cheaper and safer than flight test. Therefore, free-jet facility is an indispensable experimental facility for developing air-breathing engine. Tan et al. proposed a method to calculate performance according to free-jet experimental data and numerical results.

However, there are very few facilities in the world which have the possibility to run full-size DCR or scramjet free-jet experiment. Typically, when the diameter of a full-size missile is 400~700mm, only NASA Langley Research Center's 8-foot HTT [10] and AEDC's APTU can meet the size and Mach number requirements.
National University of Defense Technology of China has developed a series of high temperature wind tunnel for hypersonic experiments. Both the scramjet and the DCR are investigated through direct connected and free jet experiments. Ignition and combustion efficiency are mainly investigated in direct connected experiment, to obtain proper injection scheme and flow path of the combustor. However, only free-jet experiment can explore thrust performance, intake/combustor interaction, effect of attack angle and yaw angle, ignition feasibility in non-uniform flow field.
This paper presents the free-jet experimental results of the DCR in Ma4/17km (flight Mach number of 4.0 and flight altitude of 17km) and Ma6/26km flight conditions. Thrust, specific impulse and pressure distribution are taken into consideration for different flight conditions and equivalence ratio.

2. Experimental setup

2.1 The dual combustion ramjet

The full-size dual combustion ramjet is composed of intakes, preburner, combustor and nozzle (shown in Figure 1). The intakes include 4 supersonic intakes (blue sectors in top figure) and 2 subsonic intakes (red sectors in top figure; here, subsonic means the exit of the intake connected with subsonic ramjet, not the same meaning as conventional definition). The 4 sectors of the supersonic intakes combine into one annular passage before connecting the supersonic combustor. The sector angle θ1 is 38 degree for each supersonic intake, 19 degree (θ2) for each subsonic intake. Totally, 52.8% windward area air flows into the intakes and combust with the kerosene. However, the angles which determined the total air flow rate should satisfy thrust and volume requirements. The area ratio of the subsonic intakes to the supersonic intakes is crucial. 1:3 and 1:4 were investigated in previous experiments. Generally speaking, the larger the area ratio is, better performance at low Mach number while worse performance at high Mach number becomes.
Bottom figure of Figure 1 shows internal flow path and key sections of the DCR. Section 0~5 is far field, minimum section of the intakes, inlet of the preburner, inlet of the combustor, exit of the combustor and exit of the nozzle, respectively. It should be noted that the flow paths of the subsonic intake and supersonic intake are designed according to different rules. The preburner is a convergent pipe with the same generatrix as inner-wall of the supersonic intake and the shape seems have little effect on the total performance. The combustor is a subtle divergent pipe to allow the increasing of boundary layer.
There are 3 positions for the injectors of the liquid kerosene injects. The kerosene injected into the 2 subsonic intakes (B) is at stoichiometric ratio for reliable ignition; the kerosene injected into the circumference of the preburner (C) is mainly used to cool the preburner wall; the kerosene injected into the center of the preburner (D) is cracked into small molecular. Then the fuel-rich product flows into the supersonic combustor at section 3 (shown in the bottom figure). Because there is a throat at the exit section, subsonic combustion occurs in the preburner.
Air from the supersonic intakes is then mixes and combusts with the fuel-rich gas along the mixing-layer. Since combustion and high compressibility may suppress the increasing of the mixing-layer, mixing enhancement device or long combustor is needed to ensure high combustion performance. The combustion product ejects to ambient atmosphere through a maximum thrust nozzle. Main geometrical parameters are shown in Table 1. The maximum diameter of the DCR is set as d for the sake of secrecy.

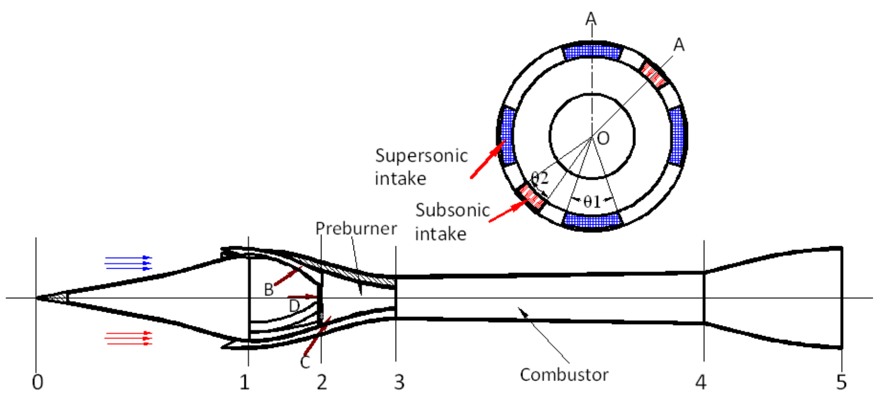

Figure 1: Schematics of the dual combustion ramjet

Typically, combustion exists in both subsonic zones in the preburner and supersonic zones in the combustor. Subsonic combustion is helpful for sustainable flame in various conditions, while supersonic combustion keeps the merits of entropy loss and thermal protection. Thus, DCR is not so sensitive to flight altitude and flight Mach number as dual mode scramjet does because there is a stable torch, which satisfies the requirement of robust scramjet proposed by US Air Force.

Table 1: Geometrical parameters of the DCR

Item	Unit	Value
Diameter of the DCR	mm	d
Diameter of the combustor inlet (3)	mm	0.43d
Diameter of the nozzle	mm	0.95d
Total angle of the intakes	deg.	190
Ratio of subsonic to supersonic	null	0.25
Total length of the DCR (1-5)	mm	9d
Length of the combustor (3-4)	mm	4d

2.2 Free-jet experimental setup

The free-jet experiments were conducted in a continuous hypersonic wind tunnel [11] (shown in Fig. 1). The wind tunnel can works up to several minutes, limited only by volume of high-pressure vessels.

The free-jet experimental setup is composed of vitiated air heater (VAH), hot-gas ejector and test cabin. The VAH generates high-temperature gas to duplicate the actual free stream stagnation conditions, including total pressure, total temperature and oxygen concentration of 23%. A convergent-divergent nozzle then brings the gas into the test cabin with the same static pressure and Mach number as that of free stream. In order to maintain the static pressure in the cabin, an exhauster system is located downstream to eject the gas into the ambient atmosphere. A unique ejecting technology of is adopted in this wind tunnel to reduce the size and running cost.

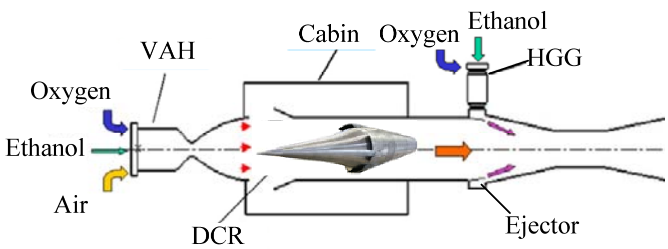

Figure 2: Free-jet experimental setup

The VAH burns oxygen, ethanol and air simultaneously to avoid the difficulty of thermal protection and to generate uniform gas. The mass flow rates of the three propellants can be adjusted to simulate different flight altitude and flight Mach number. Qualitatively speaking, air is used to control total pressure, ethanol is used to control total temperature, and oxygen is used to keep the concentration of oxygen. For example, as for Mach number 4 at 20 km altitude, the flow rate of air, oxygen and ethanol is 47.62kg/s, 3.64kg/s, 1.208kg/s respectively. After flowing through the nozzle, Mach number of the gas becomes 4 and static pressure becomes 8.79kPa, corresponding to the static pressure at 17km.

The hot gas ejector includes two parts: hot gas generator (HGG) and ejector. HGG burns ethanol and oxygen to generate hot gas. The higher the temperature of the gas is, the stronger the ejecting ability becomes. But the strength of material limits the temperature, usually lower than 1000K. The hot gas flows through the ejector, an annular nozzle with water cooling. Although the static pressure at the exit plane of the nozzle is very low, the kinetic energy of the gas is large enough to entrain the gas of the VAH into the ambient circumstance. To maintain low pressure in the cabin, the flow rate of HGG is usually 2~3 times of that of VAH.

Several piping systems transmit air, oxygen, ethanol and kerosene from high-pressure (up to 20MPa) vessels to the VAH, the HGG and the ramjet. Nitrogen is used as pressurizing gas for liquid. There are pilot-controlled pressure regulator, filter, flow meter and pneumatic valve for each piping system, which results in an accurate and scheduled supply of the propellant.

2.3 Measurement apparatus

There are three types of parameters to be measured: mass flow rate, pressure and thrust.
Mass flow rates of liquid and gas through small pipes (<50mm) are measured by turbo flow meters, but the flow rates of gas through large pipes (>50mm) can only be measured by orifice flow meters. The accuracy of the flow meters is about ±0.2%FS.
Forces and torques are measured by a six-component strain gauge balance. The measurement error for the balance is about ±50 N and the balance can be calibrated in-situ.
High pressures (>2MPa) in the VAH, the HGG and the piping system are measured by independent piezoresistive pressure sensors. But low pressures (<400kPa) along the ramjet are measured by intelligent pressure scanners (Model 9116, Pressure System Incorporation). The maximum sampling frequency of the pressure scanner is 500Hz, and the accuracy is about ±0.05%FS.
All the data from the sensors transmit to a PXI measurement system through high speed Ethernet. And the PXI system connects with the control system to diagnose the real-time status of the wind tunnel.
The DCR is installed in the cabin of the free-jet experimental system. A rack located on the thrust balance, in which there are fuel pipelines, igniter, and pressure scanners. However, the rack causes large drag, which is difficult to separate from drag of the DCR.

3 Results and discussion

3.1 Pressure distribution

Figure 3 and Figure 4 show the pressure distribution at Mach 6 and Mach 4 condition, respectively. The pressure is divided by atmospheric pressure of the flight altitude. And the pressure ratio p_r is defined as:

$$p_r = p_m / p_{st} \tag{1.}$$

Where, p_m is the measured pressure, and p_{st} is the static pressure at the flight altitude.
There are 3 lines for the pressure distribution: one along the centerline of the combustor (triangle shape), one along the subsonic intake (round shape), and one along the supersonic intake (square shape). The maximum pressure locates at the inlet of the combustor, and then decreases. The maximum pressure ratio is about 108 at Mach 6 and 40 at Mach 4. And it almost reaches the limit of the intake because the pressure at the minimum section of the intakes is almost disturbed. This means that the DCR reaches the maximum performance.
However, the pressure distribution at Mach 6 is different with that at Mach 4. At Mach 6, the pressure decreases rapidly from 108 to 72 within 0.2m, and then continually decreases to 28 at the exit of the combustor. This means that the flow is almost entirely supersonic, since heat release causes the loss of the total pressure. Further numerical results show that the pressure at the wall just reflects the peripheral supersonic flow and part of the core flow is subsonic. At Mach 4, there is a long zone with almost isotonic pressure (about 1m), which means that the flow in this zone is subsonic, as is attested by simulation [12].

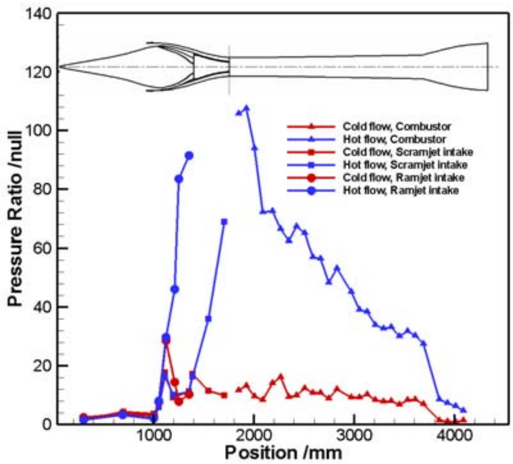

Figure 3: Pressure distribution at Mach 6

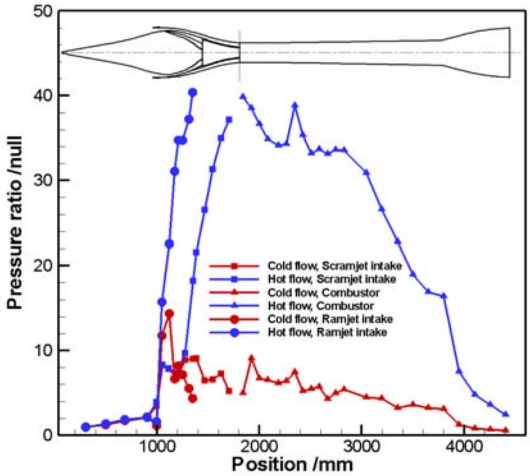

Figure 4: Pressure distribution at Mach 4

3.2 Internal thrust

Figure 5 shows the thrust coefficient at Mach 4, which is defined as:

$$C_F = \frac{F}{\frac{1}{2}\rho u^2 S} \tag{2}$$

Where, F is the measured thrust, ρ the air density, u the flight velocity, and S the reference area.

There are three stages during the free-jet experiments: (1) VAH works at 7s which simulates flight drag, and the coefficient is -0.418; (2) Only the preburner is ignited, since there is no combustion in combustor, the thrust remains negative, -0.102; (3) When the combustor is ignited, the thrust becomes positive, and the thrust coefficient is about 0.15, which means that hypersonic missile powered by the DCR can overcome the drag and accelerate in Mach 4 condition.

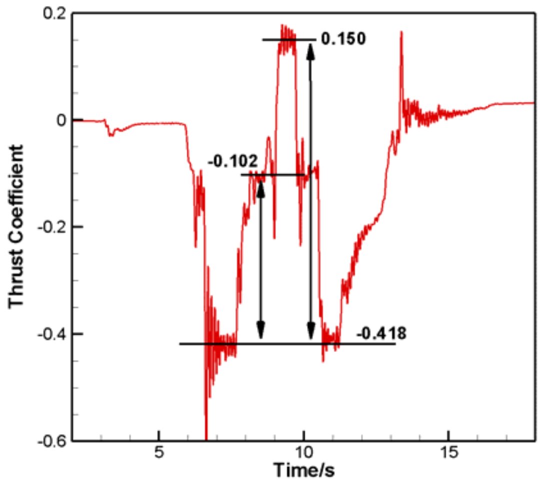

Figure 5: Evolution of thrust coefficient at Mach 4

Figure 6 shows the thrust coefficient at Mach 6. The working stage is almost the same as that at Mach 4 except that there are two injection schemes. All fuel injects into the preburner in A scheme, while part fuel (about 50%) injects into the combustor in B scheme. The thrust of the latter is slightly higher than that of the former, because the fuel is much homogenous distributed when there are both central and peripheral injections.

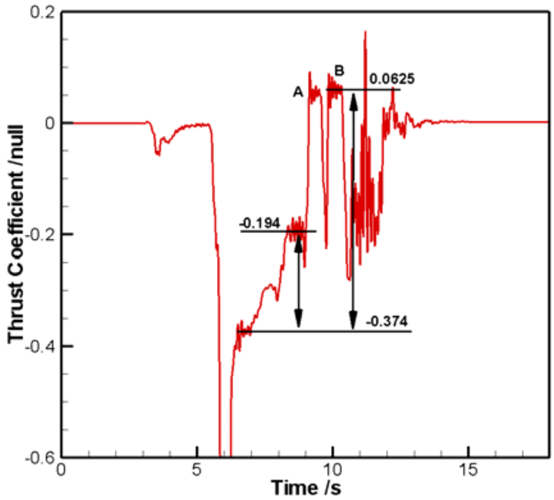

Figure 6: Evolution of thrust coefficient at Mach 6

However, the thrust obtained in free-jet experiment is not the same as that in free flight. There are wings in free flight while rack in free jet experiment which supports the DCR. The drag from the rack is quite incomparable to that from the wings. Thus, absolute thrust in free jet experiment is useless. Internal thrust rather than thrust increment is desirable for the calculation of trajectory of the missile powered by the DCR.
The thrust increment F_{inc} is defined as the difference between hot flow and cold flow.

$$F_{inc} = F_{hot} - F_{cold} \tag{3}$$

Where, F_{hot} and F_{cold} is the thrust at combustion status and at cold flow status. The internal thrust F_{int} is defined as the resultant of forces caused by internal pressure. It is related with the thrust increment according to:

$$F_{int} = F_{inc} - D_{cold} \tag{4}$$

Where, D_{cold} is internal drag force caused by the intakes and the combustor. However, it is not easy to distinguish the internal drag from the external drag in experiments, since they couple tightly and affect with each other. Numerical results are adopted to obtain the internal drag. The numerical method, mesh and validation of simulation have little relevant to the purpose of this paper. Two groups independently calculated the internal drags and obtained similar results, 0.083 at Mach 4, and 0.085 at Mach 6.
Apart from the internal thrust, another important index of the performance is specific impulse, which is defined as the ratio of the internal thrust to the mass flow rate of the fuel.

$$I_{sp} = F_{int} / \dot{m}_{fuel} \tag{5}$$

3.3 Performance of the DCR

The internal thrust coefficient and the specific impulse in different flight velocity and equivalence ratio are shown in Figure 7. The thrust increases with the increasing of the equivalence ratio, while the specific impulse decreases. The typical drag coefficient for an axisymmetric missile is about 0.25 ~ 0.35 for hypersonic flight, thus, the thrust of the DCR is enough for cruising at Mach 6 and accelerating at Mach 4. When the equivalence ratio lies in 0.8~1.0, the specific impulse is 11.0~11.9 kN.s/kg at Mach 4, and 8.6 ~ 9.0 kN.s/kg at Mach 6.
The specific impulse of DCR is a little smaller than that of ramjet [11] (<3.5%) at Mach 4, and a little smaller than that of scramjet at Mach 6. However, it works very well during the range from Mach 4 to Mach 6, which is difficult for either ramjet or scramjet. Therefore, this paper confirms the conclusion that the DCR combines the best features of ramjet and scramjet. And DCR may be the best choice when the flight velocity lies in the vicinity of supersonic and hypersonic.

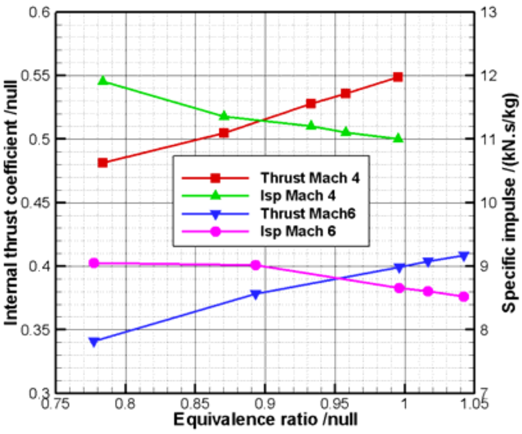

Figure 7: Internal thrust coefficient and specific impulse

SUMMARY AND CONCUSIONS

The performance of the full-size DCR in Ma4/17km and Ma6/25km flight conditions was investigated through free-jet experiments. The pressure distribution and thrust were measured, and a method to deduce the internal thrust from the thrust increment was proposed. Results show that:

(1) The maximum pressure ratio is about 108 at Mach 6 and 40 at Mach 4 for the DCR intakes. The flow is almost entirely supersonic at Mach 6, while partly subsonic (about 1m) at Mach 4.

(2) The internal thrust coefficient is 0.55 at Mach 4 and 0.4 at Mach 6, which means that the DCR powered missile can accelerates and cruises.

(3) Although the specific impulse is a little smaller (<3.5%) than that of ramjet at Mach 4, the DCR shows good performance during the range of Mach 4 to Mach 6, which is important for a robust engine.

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