Experimental Investigation on
Powdered Fuel Ramjet Combustion Performance

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(Received August 7th, 2012)

To investigate the ignition and combustion performance of the powdered fuel ramjet, an experiment is conducted on a connected-pipe ramjet test system. A computer code is developed to assist the design of the experimental powdered fuel ramjet. Based on the results of the parametric studies, an experimental powdered fuel ramjet is designed. The magnesium powder is pneumatically injected with ram-air. The flux of a two-phase mixture of solid powder suspended in the carrier air is measured with a Coriolis mass flow meter. Both cold-flow evaluation of the fuel feed system and hot-fire engine tests are performed. Ignition is realized successfully with a high-temperature combustion gas and high-energy spark plug. The feasibility of self-sustaining combustion of powdered fuel is demonstrated by introducing different flame holding techniques into the combustor. The multiple start-ups of the engine are also successfully performed using the spark plug as the ignition source. Methods for optimizing the combustion characteristics of the powdered fuel ramjet are put forward.

Key Words: Powdered Fuel Ramjet, Combustion, Connected-Pipe Ramjet Test, Multiple-Start, Combustion Efficiency

Nomenclature

- $m_{\text{fuel}}$: powdered fuel mass flow rate (kg/s)
- $\bar{m}_{\text{fuel}}$: average mass flow rate of the powdered fuel (kg/s)
- $\Delta M_{\text{fuel}}$: total powdered fuel mass change amount (kg)
- $t$: working time of engine (s)
- $\eta_c$: combustion efficiency of the engine (%)
- $e_{\text{ch}}$: theoretical characteristic exhaust velocity (m/s)
- $e_{\text{exp}}$: experimental characteristic exhaust velocity (m/s)
- $P_c$: chamber pressure (Pa)
- $P_{\text{ch}}$: chamber pressure of igniter (Pa)
- $A_t$: nozzle throat area (m$^2$)
- $\theta$: ejection efficiency (%)
- $M_{\text{dep}}$: mass of deposition in the chamber (kg)
- $m_{\text{air}}$: mass flow rate of ram-air (kg/s)
- $m_{\text{CMF}}$: mass flow rate of two-phase mixture measured via CMF (kg/s)

1. Introduction

The specific impulse of the ramjet engine is remarkably high compared with conventional rocket engines; therefore, liquid fuel ramjets and solid propellant ducted rockets have been investigated. Some of the new-generation supersonic missiles have been equipped with ramjets despite both liquid and solid fuel ramjets have some inherent shortcomings which are difficult to overcome.1–3) The liquid fuel ramjet has disadvantages of low volumetric specific impulse, system complexity and low security. It is difficult to regulate the thrust and multiple starts for ducted rockets.4)

To achieve long range, high speed, high volumetric energy and maneuverability of missiles, the direct use of metal powder as the fuel of ramjet was put forward.5) Powdered fuel ramjet, which employs high energetic powder as fuel and ram-air as oxidizer and working gas, is a new concept propulsion system.6,7) The powdered fuel ramjet combines the attractive characteristics of ducted rockets and liquid fuel ramjets. It has the advantages of high energy, high volumetric specific impulse, high safety, flexible trust management and multiple start-ups, which make it a perfect propulsion device for next-generation supersonic missiles.8)

As early as the late 1940s, investigation of the feasibility of powdered metals acting as the fuel of ramjet propulsion had been initiated.5) However, some disadvantages reduced the performance of the engine, such as ineffective fuel feeding technique, low combustion efficiency and deposition of the condensed metal oxides. Soon, the research programs were abandoned. With the development of supersonic missiles, investigation on engines which directly burn metal powders re-emerged. The technology of ramjets burning metal powders was successfully demonstrated at middle scale (ø 200 mm) by ONERA in France.8) Since condensed products of metal powder are stable in high-temperature environments, even the feasibility of a hypersonic ramjet using metal powder as fuel was examined by Goroshin et al.5)

Considering the above literature survey, the present study has the primary goal of demonstrating the propulsion system, and both cold-flow evaluation of the fuel feed system and hot-fire engine tests are performed. Many kinds of metal can be used as the fuel of powdered fuel ramjets, such as Mg, B, and Al.9–11) Though magnesium has the lowest performance of the metals that can be used, its main advantages

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is that it ignites easily.\textsuperscript{12,13} Magnesium powder is adopted for the study to demonstrate self-sustaining combustion and multiple start-ups of the powdered fuel ramjet. The effects of flame holding technologies on the performance of the engine are investigated. The multiple start-ups of the experimental engine are also carried out using a high-energy spark plug as the igniters.

2. Experimental Procedure

The experiments are conducted on a connected-pipe ramjet test system. Figure 1 shows a schematic diagram of the overall powdered fuel ramjet test rig, including a high-pressure air feeding system, an experimental powdered fuel ramjet, and a measuring and control system.

2.1. Experimental powdered fuel ramjet

A computer code is developed to assist the design of the experimental powdered fuel ramjet. The code utilizes a time-dependent continuity equation coupled with a chemical equilibrium code to confirm air-fuel mass ratio, chamber pressure and combustion gas temperature. In order to meet the proper range of test conditions, parametric studies are conducted to confirm the air flow rate, the powdered fuel flow rate, nozzle diameter and test time.\textsuperscript{8} Based on the results of the parametric studies, an experimental powdered fuel ramjet is designed. Figure 2 shows the powdered fuel ramjet used in this study. It consists of an injector, igniter, pre-chamber, bluff flame holder, secondary chamber and nozzle.

When the practical powdered fuel ramjet operates in flight condition (Mach number of 2.8 and flight height of 10 km), the stagnation temperature of air is 573 K, and stagnation pressure of air is 0.7 MPa. The high-pressure air is used both as oxidizer for the powdered fuel and as the carrier gas for the powdered fuel feed system. For convenience and safety, the high-pressure air is not heated during the experiment, and only the stagnation pressure and mass flow rate of air is simulated. For self-sustaining combustion and high combustion efficiency, the air to oxidize the powdered fuel is separated into two parts. The first one is injected into a prechamber, and the second one is injected into the secondary chamber. The ratio of the first and the secondary air is 1.0. Ignition is carried out by both the high-temperature combustion gas and high-energy spark plug. The temperature of the ignition gas is approximately 1800 K and is achieved by applying a gas generator, in which aluminum-magnesium fuel-rich solid propellant is used. The high-energy spark plug, whose energy discharge is 20 kW, is produced by Zhuzhou Spark Plug Factory. To realize the self-sustaining combustion of powdered fuel, different flame holding techniques are introduced into the combustor, including a bluff flame holder, sudden-expansion flow and swirl combustor. The swirl combustor is achieved by using the first air swirl injector.

2.2. Powdered fuel feed system

It is important for powdered fuel ramjets to provide a steady and controlled flow rate of powdered fuel. As first described by Goroshin et al.,\textsuperscript{5} a powdered fuel feed system is developed to deliver powdered fuel from the storage tank to the combustion chamber; its schematic is shown in Fig. 3. The powdered fuel is stored in a columnar tank and the powder bed is pushed by a moving piston driven by an electro-mechanical actuator. When the powder bed is pushed upward, it encounters the carrier gas. Carrier gas, which comes from the ram air ducted by the air inlet, is injected through a narrow cylindrical slot. The shear force created by the strong high-speed air jet removes dust particles from the bed surface layer by layer. The mass flow rate of fuel is controlled by the velocity of the piston.

2.3. Powdered fuels

Particle material, shape and size distribution of powdered fuel have an important effect on the combustion process of the engine and the powdered feed system performance.
Boron, aluminum, and magnesium can all be used as the fuel of powdered fuel ramjets. Since magnesium powder has low ignition temperature and good combustion characteristics in air, magnesium powder is often added into solid fuel-rich propellant and powdered fuel. The experimental data shown below are obtained with magnesium powdered fuel. The characteristics of the powdered fuel used in tests is shown in Table 1.

2.4. Measuring instruments

Thrust-measuring components include leaf springs, a flexible universal joint and a thrust meter. Through a flexible universal joint, the movable frame is connected to a thrust meter (model BLR-12, made by Hefei Zhongya Sensor Limited Company), with a maximum range of 100 kg. The uncertainty in the thrust measurement was 0.1%. While the experimental powdered fuel ramjet is set on the test bench as shown in Fig. 1, an in-situ calibration device on the front of the stationary frame can be used to exert standard thrusts for calibration of the thrust meter before and after the testing, which helps to maintain precision in thrust measurements. As for the pressures in the motor and along the flow passages, a maximum value of 5 MPa can be measured by piezoresistive pressure transducers (model PT301, made by Hefei Zhongya Sensor Limited Company), with an uncertainty of 0.1%.

During the tests, the flux of a two-phase mixture of solid powder and carrier air is measured with Coriolis mass flow meter (model DMF-1, made by Hefei Zhongya Sensor Limited Company), with a maximum range of 0.1 kg/s. The uncertainty in the Coriolis mass flow meter is 0.2%.

If the velocity of the piston is constant in the whole experiment, the alternative to measuring the powdered fuel mass flow rate ($\dot{m}_{\text{fuel}}$) is to measure the average mass flow rate of fuel ($\overline{\dot{m}}_{\text{fuel}}$).

$$
\overline{\dot{m}}_{\text{fuel}} = \frac{\Delta M_{\text{fuel}}}{t}
$$

where $\Delta M_{\text{fuel}}$ is the total powdered fuel mass change amounts in the storage tank and $t$ is the working time of the experimental powdered fuel ramjet.

2.5. Data reduction

With respect to time, the measured values of the thrust and the pressure at the igniter chamber and secondary chamber are available. As the flow Mach numbers at above points of pressure measurements are very low (<0.1), the values are taken as the stagnation ones.

Combustion efficiency is used to evaluate the overall motor performance here. Combustion efficiency is an important indication of the motor ability to employ heat energy. It has been defined differently by various investigators. In this study, characteristic velocity of the experimental powdered fuel ramjet is adopted to calculate its combustion efficiency. An experimental characteristic velocity and combustion efficiency is given by

$$
\eta_c = \frac{c^*_\text{exp}}{c^*_\text{th}}
$$

where $c^*_\text{th}$ is the theoretical characteristic exhaust velocity, which is obtained from thermodynamic calculation using equilibrium condition. $c^*_\text{exp}$ is the experimental characteristic exhaust velocity, which is given by

$$
c^*_\text{exp} = \frac{P_c A_t}{(\dot{m}_{\text{fuel}} + \dot{m}_{\text{air}})}
$$

where $P_c$ is the secondary chamber pressure and $A_t$ is the throat area of the experimental powdered fuel ramjet nozzle.

The particle deposition on the wall inside the secondary combustion chamber of the powdered fuel ramjet is a serious problem, which would affect the application of the engine. Using magnesium metal powder as fuel brings out more deposition in the chamber, and the ejection efficiency ($\eta_e,\text{epl}$) is used as an indication of the deposition problem.

$$
\eta_{e,\text{epl}} = 1 - \frac{M_{e,\text{dep}}}{(\Delta M_{\text{fuel}} + \dot{m}_{\text{air}}t)}
$$

where $M_{e,\text{dep}}$ is the mass of the deposition of magnesium metal powder and magnesia in the chamber and $\dot{m}_{\text{air}}$ is the mass flow rate of ram-air.

3. Results and Discussion

Both cold-flow evaluation of the fuel feed system and hot-fire engine tests are carried out on direct-connect test system. Some results are listed below.

3.1. Powdered fuel feeding experiments

Figure 4 shows the flux characteristics of the powdered fuel.
fuel feed system. It is observed that the flux of the carrier gas ($m_{carrier}$) is steady, and the curve of the Coriolis mass flow meter is also approximately steady. The result shows that powdered fuel can be fed availabley and equably by this system. The real-time mass flux of the two-phase mixture ($m_{CMF}$) can be measured with the Coriolis mass flow meter successfully. Figure 5 shows the kinescope of the powdered fuel feed experiment. $m_{CMF}$ in Fig. 4 is high at the starting times, and it is observed simultaneously from Fig. 5 that the concentration of powder is thick.

3.2. Hot-fire test with high-temperature combustion gas igniters

Table 2 shows experimental cases using high-temperature combustion gas as the igniter, and the data reduction are not carried out for the failure to ignite the magnesium particles. The igniter is shut-off when secondary combustion is achieved. The total time of igniter operation is approximately 5 s. Figure 6 shows the pressure in the secondary chamber and flux characteristics of case 1. $P_c$ is the pressure in the secondary chamber, $P_{i,c}$ is the pressure in the igniter chamber, $m_{air}$ is the summation of the first and the second air mass flow rates. In order to validate the effect of magnesium particles combustion on the pressure in the secondary chamber, case 2 with no powdered fuel in the tank of feed system is also carried out, in which the mass flow rate powdered fuel is zero and $P_{ref}$ is the pressure in the secondary chamber. Figure 7 shows the pressure in the secondary chamber and flux characteristics of case 3.

The initial jump in pressure at the beginning is caused by the start of the igniter at a time of approximately 1 s. The motor reached a quasi-steady state operating condition, during which the high-temperature combustion gas produced by the igniter and the magnesium particles mix with air in the secondary chamber and combust. After 5 s, the aluminum-magnesium fuel-rich solid propellant is exhausted and the igniter is shut-off. The pressure in the secondary chamber decreases until the motor reaches a new quasi-steady state operating condition, during which only the mag-

Fig. 4. Flux characteristics of the powdered fuel feed system.

Fig. 5. Kinescope of the powdered fuel feed experiment.

Fig. 6. Pressure and flux characteristics of case 1.

Fig. 7. Pressure and flux characteristics of case 3.

Table 2. Experimental cases using high-temperature combustion gas as the igniter.

| Case | Flame holder     | $d_p$ (mesh) | $m_{fuel}$ (g/s) | $c_{exp}$ | $c_{th}$ | $\eta_c$ (%) |
|------|------------------|--------------|------------------|-----------|----------|--------------|
| 1    | Sudden-expansion flow | 80–100      | 18.0             | —         | —        | —            |
| 2    | Sudden-expansion flow | 80–100      | 0                | —         | —        | —            |
| 3    | Bluff flame holder | 80–100      | 18.8             | 511.54    | 927.88   | 55.13        |
nesium particles mix with air in the secondary chamber and combust. From Figs. 6 and 7, it is shown that the mass flow rate of air in case 1 and case 3 are almost the same. It is also shown that the pressure curves are coincident under different powdered fuel mass flow rates when adopting sudden-expansion flow as the flame holder (cases 1, 2), which indicates that the magnesium particles do not ignite and combust in the secondary chamber. At the same time, the pressure is higher when introducing the bluff flame holder into the combustor (case 3). These facts show that using a bluff flame holder is helpful to realize the ignition and self-sustaining combustion of the experimental powdered fuel ramjet, and large-diameter powdered fuel cannot be ignited when using sudden-expansion flow as the flame holding method.

3.3. Hot-fire test with high-energy spark plug igniters

Though high-temperature combustion gas is a feasible igniter, it is still desirable to find a reliable, multiple relight ignition system. The spark plug is selected for use in the demonstration multiple start-ups of the powdered fuel ramjet. Table 3 lists experimental cases using a high-energy spark plug as the igniter. Figures 8–10 show the pressure in secondary chamber and flux characteristics of experiments. After supplying the first and second air, the chamber filling process is finished and the pressure in the secondary reaches a stable state within approximately 2.5 s, after which time the carrier gas valve is opened. Then, 0.5 s later, the high spark plug begins to work. The motor reaches a quasi-steady state operating condition.

From these data the following conclusions are obtained:
1) The feasibility of using a spark plug as igniter is demonstrated.
2) When using small-diameter particle as fuel, sudden-expansion flow is still an effective flame holding method.
3) Combustion stability and efficiency are enhanced by introducing a bluff flame holder into the chamber. At the same time, ejection efficiency is reduced.
4) The highest combustion efficiency of 72.8% is achieved with a swirl flow combustor.

3.4. Multiple start-ups of the engine

Practical powdered fuel ramjet operation may include thrust modulation via powered fuel throttling and restart capability. Some tests are conducted to investigate the performance of the powered fuel ramjet for restart. During the tests, the bluff flame holder is applied, the Sauter mean diameter of magnesium particles is 67 μm, and the mass flow rate of the powered fuel is 12.7 g/s. Figure 11 shows the pressure histories at the secondary chamber and mass flow rate of air profiles for a restart test (case 7). The experimental powdered fuel ramjet is ignited and allowed to burn for 7 s, after which time the carrier gas ball valve is closed. The pressure of the chamber then begins to drop as combustion ceases. The motor is restarted by opening the carrier gas.
ball valve and activating the high-energy spark plug igniter after a shutoff time of 2 s. The burn time for the second portion of the test is still 6 s. The mass flow rate of the carrier gas is the same for both segments of the test. The pressure traces rise rapidly back to their earlier levels after restart, indicating a rapid ignition. The number of times for multiple-start and time intervals can be regulated at random. Furthermore, no pressure oscillations are measured, indicating stable combustion. It is evident that multiple start-ups are feasible with a spark plug as the igniter. There are two ignition pressure peaks. Even though the ignition energy of the spark plug is uniform, the values of pressure peaks are different. The different peak value is caused by the different mass flow rate of powdered fuel.

4. Conclusion

To investigate the ignition and combustion performance of the powdered fuel ramjet, the combustion in a cylindrical combustor for the designed engine was investigated preliminarily using a connected-pipe ramjet test system. The powdered fuel feeding system was a viable method of delivering metal fuel to the engine, and the real-time mass flux of two-phase mixture could be measured with a Coriolis mass flow meter. Hot-fire tests for the powdered magnesium fuel ramjet were completed using different igniters and flame holders. However, the combustion efficiency was low (maximum efficiency was 72.8%), and the major performance loss was an incomplete release of combustion energy. It was postulated that the incomplete release of energy was due to large diameter of fuel particles.

Acknowledgments

The support of the China Sponsorship Council (CSC) (Grant No. 51006118 and 51276194) is gratefully acknowledged. The author thanks Benveniste Natan of the Technion-Israel Institute of Technology for his help and encouragement.

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Fig. 11. Pressure and flux characteristics of case 7.