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Experimental study on the operation characteristics of aluminum powder fueled ramjet

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ABSTRACT

A new powder fueled ramjet configuration is put forward based on the previous studies on ramjet, and an experiment investigation is conducted to study the working process of the engine. A series of tests are conducted to investigate the combustion efficiency of the engine by changing the ram air flow inlet interface position and the fluidization gas mass flow rate. It is found that the engine achieves 24 s self-sustaining combustion and worked stably during fire tests. In addition, the powder feed system provides aluminum fuel particles continuously and steadily during the tests, and the piston velocity can be used as a function of the fuel mass flow rate. Optimized ram air flow inlet interface position is 250 mm to the combustion chamber front end. Furthermore, as the mass flow rate of fluidization gas rises from 5 to 15 g/s, the combustion efficiency of the engine significantly increases. The best combustion efficiency reaches 73.05% on the condition that the ram air flow inlet interface position is 250 mm to the combustion chamber front end and the mass flow rate of fluidization gas is 15 g/s.

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1. Introduction

The powder-fueled ramjet makes use of micro-sized metal particles (B, Al, and Mg) and incoming air as propellants. It offers a combination of high impulse, security, thrust modulation, simple structure and low cost that are not completely achieved by liquid and solid ramjet. In addition, Metal powder fuels also have excellent storage characteristics. They do not require thermal protection either on the ground or in hypersonic flight.

For these attractive characteristics, many researchers have conducted experimental investigations directly on the use of metal fuels for ramjet since the late 1940s' [1]. Branstetter investigated the combustion properties of a high-speed aircraft fueled with aluminum experimentally and obtained stable combustion with aluminum injected in powder form. Meanwhile, he pointed out that the solid deposits in the combustion chamber present an obstacle to the utilization of aluminum as a ramjet fuel in 1951 [2], which discouraged the researchers in the later investigations on metal powder fuel for ramjet [3].

However, the research work of metal powders as fuel for air craft never stopped. In the next decades, Researchers focused on the use of metal fuel for powder rocket moto and metal/CO_2 rocket. American researchers of Bell Aerospace Company made extensive efforts on testing ammonium perchlorate/aluminum powder rocket motor [4]. With the development of powder technology [5,6], moreover on the background of Mars exploration, the Mg/CO_2 powder rocket and Al/CO_2 powder rocket [7] have always been the research hotspots. With the support of NASA, the investigation on Mg/CO_2 powder rocket has been conducted by Wickman Spacecraft and Propulsion Company [8], Applied Research Laboratory [9] and Marshall Space Flight Center [10] since 1970s. Recently, Northwestern Polytechnical University conducted experiments on ammonium perchlorate/aluminum powder rocket motor and achieved multiple-pulse ignition, of which the result is unpublished.

Researchers have been working on the use of metals as fuel for air craft more than half a century. Based on the theoretical calculation of specific impulse performance of different fuels, Goroshion reexamined the possibility of using metal powders for hypersonic ramjet propulsion in 2001, and proposed the conception of hypersonic ramjet fueled by powdered metals. In addition, he measured the fundamental combustion characteristics of aluminum powder suspensions in air and put forward a conceptual design of a hypersonic ramjet fueled by powdered metals [11]. Based on the previous investigations, France ONERA completed Φ 200 mm engine fire test and pointed out the transport of powder fuel and precisely control of fuel mass flow rate were the key technologies to the engine in 2002 [12]. Jesse presented a preliminary design of a powder fuel ramjet used in the Martian atmosphere and obtained a feasible ramjet design which had an

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operational speed of Mach 4–5 [13]. National University of Defense Technology achieved quick ignition and multiple-impulse work of powder ramjet [14]. Maria Smirnova analyzed a concept of Mars planet propulsion vehicle, which uses aluminum or magnesium combustion with CO_2 as the main energy production cycle, also she demonstrated that lift force increase on approaching rigid surface could guarantee reliable flights in Martian atmosphere, finally she proposed a conceptual design of Mars vehicle in 2014 [15]. Recently, Xi'an Aerospace Propulsion Institute of China analyzed the solid power fuel ramjet through the method of 3D two-phase flow field simulation, and they investigated the effect between the combustion performance and the big speed difference combustion stabilization device. They found that the combustion efficiency of the engine reached 89.3% [16].

On the basis of previous investigations, a new powder ramjet configuration is put forward in this paper. Then an experiment investigation is conducted to study the working process of the engine. Metal aluminum is chosen as the powder fuel with the consideration of ignition and combustion performance as well as availability. The combustion efficiency of the engine under different circumstances is analyzed by changing the ram air flow inlet interface position and the fluidization gas mass flow rate.

2. Approach

2.1. Powder selection

Without consideration of the condensation energy loss, the specific impulse of the powder ramjet with different metals can be calculated by Eq. (1) [11]:

$$I_{sp}^{RJ} = I_{sp}^{R}(1+\phi) - \phi V_0 \tag{1}$$

where ϕ is the air-to-fuel ratio, V_0 is the velocity of the ram air flow, and I_{sp}^{R} is the rocket specific impulse for the air-fuel mixtures, which can be calculated using the thermodynamic software package "CEA" developed by NASA [17,18]. The specific impulse as a function of air-to-fuel is calculated for the three most cited elemental metal fuels: Al, B, and Mg. The relationship between the specific impulse of different metals and air-to-fuel ratio is shown in Fig. 1. Unless otherwise mentioned, the design condition of the prototype engine in this paper is: flight speed Ma=3, flight altitude H=10 km, combustion chamber pressure P_c=0.4 MPa.

It shows that the boron has obviously excellent specific impulse performance in the elements compared above when the air-to-fuel ratio exceeds ϕ=7. However, taking into account the terrible ignition and combustion performance, as well as the high oxygen consumption of boron, Aluminum powder is selected for use with the overall performance of moderate specific impulse, better ignition and combustion characteristic and availability. Table 1 shows the physical and chemical properties of different elements, including the melting point T_M, boiling point T_B, heat production per fuel unit mass H_W and per fuel unit volume H_V as well as stoichiometric air-to-fuel ratio $\phi_{stoic} = \dot{m}_{air}/\dot{m}_{fuel}$ when reacting with air. Table 2 shows the properties of their oxides.

Table 1
Physical and chemical properties of elements.

Element	ρ (g/cm^3)	T_M (K)	T_B (K)	H_W (MJ/kg)	H_V (MJ/dm^3)	T_I (K)	ϕ_{stoic}
B	2.34	2450	3931	57.91	135.51	1992	9.65
Al	2.70	933	2740	31.07	83.89	2300	3.86
Mg	1.74	923	1390	24.91	43.34	875	2.87

Table 2
Properties of oxides.

Chemical formula	ρ (g/cm^3)	T_M (K)	T_B (K)
B_2O_3	2.46	733	2123
Al_2O_3	3.97	2327	3800
MgO	3.58	3073	3853

Design point of the air-to-fuel ratio is mainly decided according to the specific impulse with the consideration of condensed products deposition. Study shows that the liquid form of condensed product deposition (mainly aluminum oxide) in the combustion chamber easily causes energy lose compared with that of solid form [19]. Fig. 2 shows the relationship between combustion chamber temperature and the air-to-fuel ratio, which indicates that the aluminum oxide exists in liquid form and would easily cause energy loss when the air-to-fuel ratio is less than 13, because the combustion chamber temperature is higher than the melting point of aluminum oxide (2327 K). Then, as the air-to-fuel ratio increases, the temperature would drop. Meanwhile, the aluminum oxide become solid form and there is little energy loss. For this reason, the air-to-fuel ratio is 15 in this paper. To ensure long time stable feeding of the powder fuel feed system, mass flow rate of

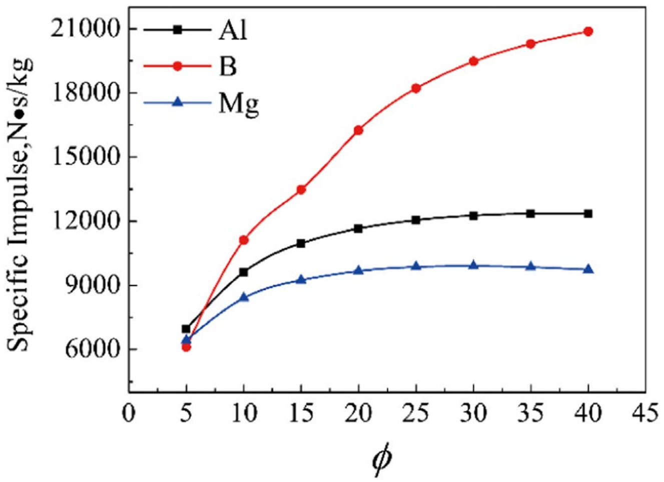

Fig. 1. Relationship between the specific impulse and air-to-fuel ratio.
Flight speed Ma=3, flight altitude H=10 km, combustion chamber pressure P_c=0.4 MPa.

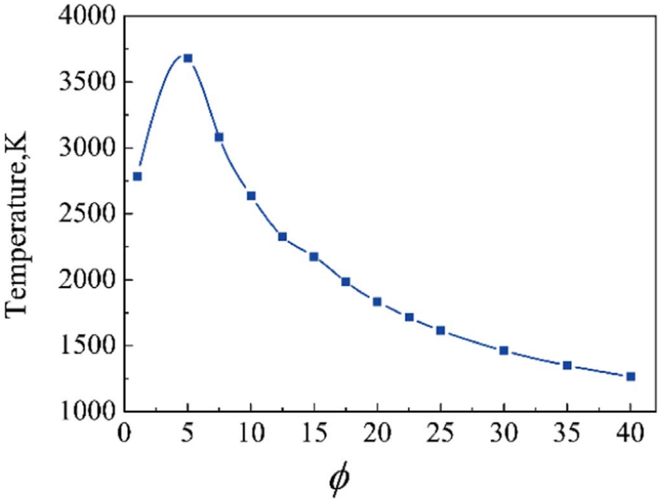

Fig. 2. Relationship between chamber temperature and air-to-fuel ratio.
Flight speed Ma=3, flight altitude H=10 km, combustion chamber pressure P_c=0.4 MPa.

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