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Primary Research on Theoretical Performance and Powder Supply Characteristics of Powder Rocket

Deng Zhe[1,†], Hu Chun-bo[1], Hu Song-qi[1], Xu Yi-hua[2]
[1]*National key laboratory of combustion, flow and thermo-structure, Northwestern Polytechnical University, Xi'an 710072, China,*
[2]*School of Aircraft Engineering , Nanchang Hangkong University, Nanchang 330063, China*

Abstract : The powder propellant rocket which uses micron-sized particles as fuel is storable and costly. Functions like thrust control and multiple-ignition can be realized by changing powder mass flow rate. In this paper, we discuss the theoretical performance of bi-propellant and mono-propellant powder rocket. When used as the fluidization gas, helium can improve specific impulse dramatically. The stability of the powder feeding device is preliminarily quantified through metal/N2O powder rocket hot fire tests.
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Key Words : Powder rocket, gas-solid two-phase flow, specific impulse, combustion oscillation.

1. Introduction

The Development of military technology and space launch forms a broad and increasing demand for new propulsion technology. The powder rocket engine which uses micron-sized propellant particles fluidized with a small quantity of gas can realize thrust control by varying particles mass flow rate in cold state[1]. Powder propellant without binders would not crack under strain in very cold weather or at high overloading, and it is more storable and costly than LRE(Liquid rocket engine). It is also attractive for air-ramjet[2] and water-ramjet[3]. Researchers studied the ignition and combustion characteristics[4] of several metal particles like Mg, Al, B, Be and their hydrides(AlH3, B2H6). The particles packing density and feeding method are critical technology for rocket performance. Bell Aerospace Company[5] has proceeded lots of work to investigate Al/AP powder rocket engine which uses Aluminum particles as fuel and ammonium perchlorate particles as oxidizer. Specific impulse efficiency of 87% was achieved with coaxial injector. Fluidized powder injector design is more critical than that of LRE. Their tests exhibited low frequency combustion pressure oscillations with frequencies of 45 to 85Hz and amplitudes of up to ±88% of mean combustion pressure.

This paper discusses the bi-propellant energy performance of traditional metal fuels (Al, B), potential fuels(AlH3,B2H6) with oxidizers as AP, ammonium nitrate(AN), HNIW(CL-20), N2O, and mono-propellant as RDX, HMX, HNIW. In order to obtain some preliminary data on powder rocket low combustion oscillations, Al/N2O powder rocket fire tests have been processed.

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†Corresponding Author
Tel:+ 86-029-88493406,
E-mail: 231645154@qq.com

2. Theoretical Performance

The schematic diagram of conventional bi-propellant powder rocket engine is shown in Fig.1A. Driver and fluidization gas could be air, nitrogen and helium in gas phase stored in high pressure gas cylinder, or in liquid phase form likes carbon dioxide stored in self-pressurization cylinder, or in solid phase form by using low temperature solid gas generator. It is obvious that use pyrotechnic gas generator to extrude powder propellant(fuel and oxidizer) can be storable and reduce structural mass. The Mono-propellant powder rocket(Fig.1B) employs RDX, HMX or HNIW as propellants. Its advantages are no condensed phase deposition and simpler structure. But there is no adequate security for applying account for the high explosive of RDX,HMX. High energy component must be passivation before research.

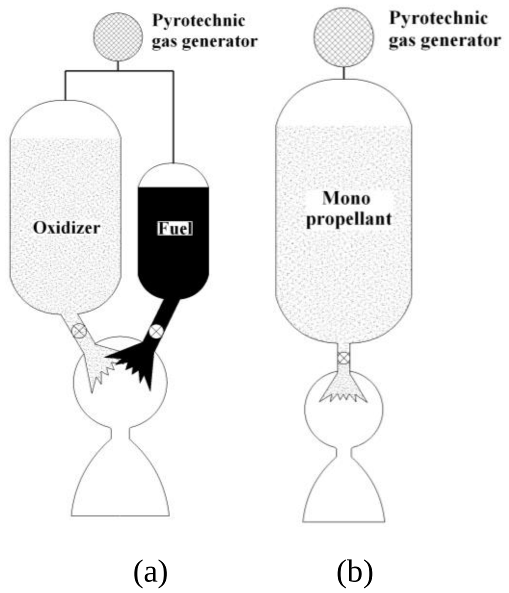

Fig. 1 Powder rocket scheme

Powder propellant Specific impulse performance varies with oxidizer fuel mass ratio is shown in Fig2. The mass fraction of fluidization gas is only 1.5%[6]. It is clear that AlH3 and B2H6 improve specific impulse extremely because hydrogen can decrease average molecular weight of products. The best oxidizer fuel mass ratios of hydride fuels are all less than 1, so combustion products deposition would also increase. The best oxidizer fuel mass ratios of fuels without hydrogen are generally above 2, and their specific impulse are lower than those containing hydrogen.

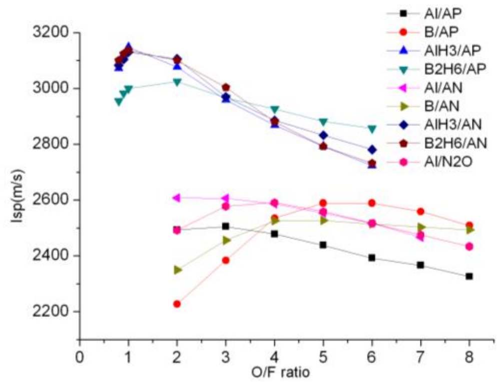

Fig. 2. Specific impulse vary with O/F ratio

RDX, HMX, HNIW have high enthalpy of formation. They are widely used as high-energy component in solid propellant. The smooth and controllable combustion in SRM makes them probably to be used in mono-propellant powder rocket. The application of high-energy component in mono-propellant powder rocket requires passivating treatment and study on ignition and flame propagation to prevent backfire explosion. Although the security of high-energy components is not good enough, their excellent performance likes pure gas phase combustion products and no condensed phase deposition is obvious. Two-phase loss are reduced in the nozzle, moreover, there is no melt ablation caused by bi-propellant. Fluidization gas is essential for carrying powder propellant to combustor. Function of Fluidization gas is fluidifying powder propellant and carrying particles into combustion chamber. So fluidization gas inevitable affects specific impulse as a part of input quantity in the nature of things. Specific impulse would decrease as fluidization gas proportion increasing in use of air and nitrogen for their high molecular weight. On the contrary, helium improves specific impulse for its low molecular weight reducing average molecular weight of products. Specific impulse vary with helium mass fraction increasing is shown in Fig.3. The thermodynamic calculation is proceeded under best O/F ratio for bi-propellant. The Specific impulse enhancements of bi-propellants are higher than mono-propellants account for their higher energy and more condensed phase. However, the proportion of helium is not the more, the better. It cools gas and makes the combustion efficiency lower.

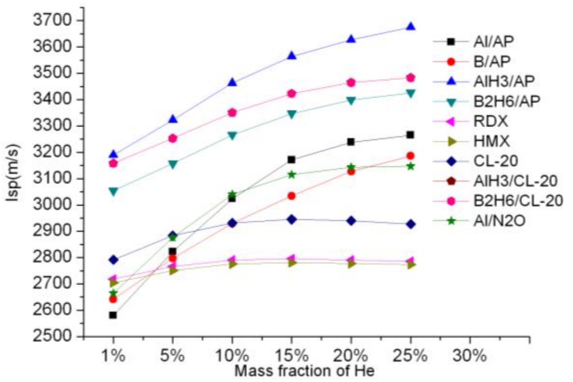

Fig. 3 Specific impulse vary with mass fraction of Helium

3. Experimental Research

The powder feeding device in this paper refers to Ref.[5]. The schematic diagram is shown in Fig.4. Its fundamental is fluidifying powder particles by fluidized gas imported through hollow rod which connect with the hollow piston. Driver gas pushes the piston moving in order to extrude fluidized powder propellant into combustion chamber. ε is calculated by Equ.1. ρ_g is calculated from The standard gas state equation. v is calculated by Equ.2 with ignoring the kinetic energy loss of two phase flow due to particle collisions and friction to pipeline internal wall. Fluidization gas blow into powder cylinder through the gas distributor. Pneumatic ball valve controls on-off state. 40μm diameter spherical magnesium and aluminum particles are employed. The natural packing densities are 0.726g/ml and 1.112g/ml, respectively. The fluidization cavity is a diminishing cone, accelerating the two phase flow with its 50mm inlet diameter to 4mm diameter outlet. The angle of convergence of fluidization cavity is 80°.

Mass flow rate of fluidization gas is 2g/s. Gas velocity at inlet and outlet of fluidization cavity are 0.28m/s and 44m/s under 0.5MPa combustion chamber pressure, assuming that ε in fluidization cavity is constant (Ma<0.3). Permeation flow at the inlet is transferred to fluidization flow(v>10m/s) at the outlet theoretically. It would not change powder packing state until gas flowing into fluidization cavity. Combustion oscillations is obviously in Ref.[5]. It may be caused by two-phase flow pulsation or AP combustion oscillation. Two phase flow stability in pipeline could not be confirmed. So we use N2O instead of AP to process fire tests on metal/N2O powder rocket in order to certify two phase stability.

$$\varepsilon=\frac{\rho_s \dot{m}_g}{\rho_s \dot{m}_g+\rho_g \dot{m}_s} \tag{1}$$

$$v=\frac{\dot{m}_g}{\varepsilon \cdot \rho_g A_p} \tag{2}$$

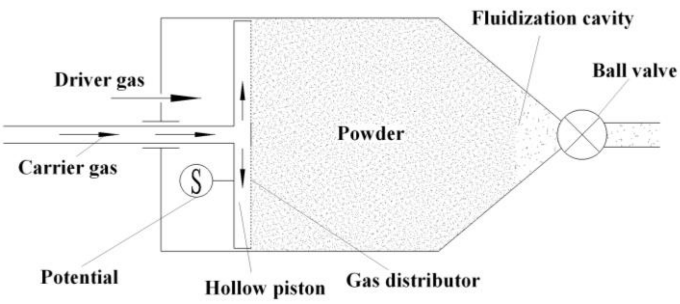

Fig. 4 Schematic diagram of powder feeding device

Schematic diagram of combustion chamber is shown in Fig.5. Using nitrogen as fluidization gas rather than nitrous oxide is to establish a non-premixed combustion form. It can avoid backfire in pipeline. Annular gas cavity and oxidizer vents make N2O well-distributed at radial direction. Diameter of single oxidizer vent is 3.6mm and total sectional area of all vents is 564mm2. N2O flow velocity is 30m/s at 0.5MPa. High inlet velocity of N2O prevents condensed phase deposition blocking up vents. Use small size SRM to ignite. Metal/N2O powder rocket fire test summary is shown in Tab.1.

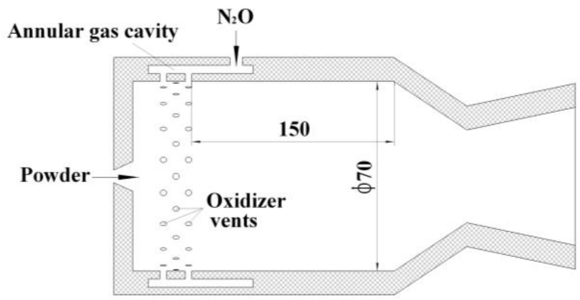

Fig. 5 Schematic diagram of combustion chamber

Table1 fire test summary

fuel	Pipeline		Chamber Pressure	
	ε	Flow velocity [m/s]	amplitude	frequency [Hz]
Mg	0.973	26.8~27.0	±0.36%	10.72
Al	0.978	26.5~27.3	±1.45%	10.55
Al	0.972	14.3~15.0	±2.46%	5.11

Exhaust plume and typical function curves are shown in Fig.6 and 7. Initial pressure peak is about twice as high as stable period. Ending pressure peak is due to nitrogen blowoff. High ε of all tests, exceeding 0.9, declare that the two-phase flow is lean phase before entering combustion chamber. Oscillation frequency and flow velocity approximately presents linear relationship. LF(frequency<100) combustion usually aroused from propellant supply. two phase flow concentration amplitude would not be bigger than combustion amplitude. Although working conditions of case1 and case2 are same and magnesium particles and aluminum particles diameter are all 40μm, chamber pressure oscillation amplitude of case1 is smaller. The reason may be lower density of Mg or more combustion sensitivity of Al depending on pressure oscillation[5]. Oscillation frequency and flow velocity of case3 drop to 48% and 54% respectively in Contrast with case2. The result indicates that flow velocity decreasing makes particles reuniting effect increasing[7], and solid phase concentration pulsation becomes more severe. It makes bigger oscillation amplitude and lower frequency of case3 than that of case2. The powder feeding device can afford probably stable mass flow rate of solid-phase. Concentration pulsation depends on flow velocity and particle characteristics.

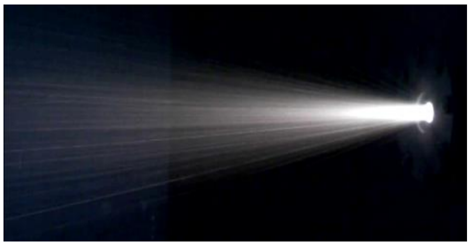

Fig. 6 Exhaust plume

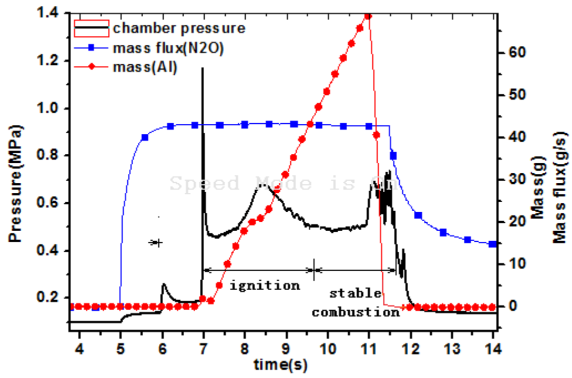

Figure 7. Chamber pressure curves

4. Conclusions

As a result of performing this work, the following conclusions were obtained:

(1)Fuels as AlH3 and B2H6 have higher specific impulse because hydrogens reduce the average molecular weight of products.

(2)RDX, HMX, HNIW(CL-20) can be mono-propellants due to their excellent energy performance and pure gas phase products if their security could be improved. They would be desired powder propellants.

(3)Increasing the mass fraction of helium can enhances specific impulse, but cooling effect of much helium may cause low combustion efficiency.

(4)Results of metal/N2O powder rocket fire tests indicate that powder supply device has high flow stability. The combustion chamber pressure influences the two phase flow velocity in the pipeline. It changes the solid phase concentration pulsation characteristics.

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Author

Deng Zhe
PhD Candidate.
Mainly engaged in space propulsion technology