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Research Paper

Experimental investigation on mass flow rate measurements and feeding characteristics of powder at high pressure

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HIGHLIGHTS

- IMM can be used to measure mass flow rate of powder fuel in firing condition.
- Two ways can be used to adjust powder mass flow rate in powder motor.
- Pipe cross sectional area affects more than pressure when adjusting thrust.
- Differences between experimental and equilibrium gas–solid flow theoretical results.

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ABSTRACT

The powder fuel feeding system is the key component of powder engine with multiple ignition capability and thrust modulation function. In cold state, the experiments of powder fuel mass flow rate measurement and powder feeding characteristics at high pressure were carried out. By comparing two measuring methods, the veracity of indirect measuring method was verified, which shows that can be applied to flow rate monitoring in the process of engine ignition. Otherwise, there are two main approaches to adjust powder mass flow: changing initial fluidized pressure or changing the cross sectional area of pipe. The powder mass flow rate is linear with these variable parameters. The experimental results were also compared with theoretical values calculated by gas–solid choking theory, which turns out that the theoretical values are higher than experimental results. It shows the gas solid choking theory needs to be corrected based on nonequilibrium gas–solid flow model.

1. Introduction

Powder engine is one kind of new concept engines, which takes metal powder as fuel, and the oxidizer can be solid or gas materials. For powder engine owns numerous underlying advantages. The American Bell Aerospace Company was the first to test the ignition of aluminum powder (AL)/ammonium perchlorate (AP) powder rocket engine as early as the 1960s, and test results verified the feasibility of powder engine [1–3]. At that time, because of research work limited by the technologies of powder fluidization and particle combustion organization, the powder rocket engine project was shelved with less published papers. Since then, the research field of deep-space exploration heats up, researchers presented magnesium powder (Mg)/carbon dioxide (CO_2) powder rocket engine for Mars exploration [4–8]. Since the Martian atmosphere is rich in carbon dioxide resource, the Mg/CO2 powder rocket engine does not need to carry oxidizer from Earth, which is benefit to increase delivery efficiency and reduce launch costs. Meanwhile, some similar engines such as Mg/CO2 ramjet and Mg/CO2 turbine engine have also been conducted [9–10]. Modern aircraft is developing to high speed and large firing range, which requires engine must be under supersonic combustion condition; however, the traditional hydrocarbon fuels will be dissociated easily at that condition, which leads to decrease the combustion performance. Nevertheless, metal powder fuel is more stable compared to hydrocarbon fuel at the same condition, so Goroshin presented powder fuel hypersonic ramjet, and the combustion performances of varieties of powder fuel were compared through thermal calculation [11]. The powder fuel hypersonic ramjet with combustor diameter of 200 mm has been ground-tested successfully in France, which verified the feasibility of powder ramjet [12]. Other ramjets such as powder/water ramjet are also under study [13].

On account of the specificity of powder fuel, the powder engine owns some functions of liquid rocket engine, like multiple-ignition capability and thrust modulation function. Moreover, thrust

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Nomenclature

ρ_P	particle density (kg/m^3)
$\dot{m}_{ti}$	instant powder mass flow rate of *ti* (g/s)
A_{piston}	cross sectional area of piston
$\dot{m}_P$	powder mass flow rate
$\rho_{packing}$	powder loading density
v_{piston}	piston velocity
$m_{packing}$	initial total mass of powder
V	total volume of powder tank
A	pipe cross sectional area of pipe (mm^2)
M	powder mass flow rate (g/s)
C_P	valid heat capacity of particle (J/(kg K))
$C_{P,g}$	heat capacity of gas at constant pressure (J/(kg K))
R_g	gas constant (J/(mol K))
R_m	two-phase mixture constant (J/(mol K))
T_0	temperature in stagnation state (K)
P_0	stagnation pressure (Pa)
γ_g	specific heat ratio of gas
γ_m	specific heat ratio of gas solid mixture
ϕ	mass fraction
ε	volume fraction

control of powder engine can be achieved by adjusting powder mass flow rate in cold condition, that makes the powder engine resulting in better security and operability than other engines such as solid rocket engine. The performance of powder engine is affected directly by powder feeding characteristics; therefore, feeding system is commonly regarded as the key point naturally.

The early feeding manner is similar to fluidized bed in industry. Fluidized gas is utilized in bed to form gas solid two-phase flow and take powder into combustor. But the feeding system is too large and complex to integrate [2]. Delionback invented one powder feeding device, powder mass flow of which is controlled by rotary valve [14], but riding position is limited. Goroshin set up one device with a piston driven by an electric motor. The powder fuel was pushed ahead by the piston and taken into combustor by fluidized gas. With the help of Goroshin's feeding method, some combustion and flow experiments of powder engine were carried out [15–17].

To make powder engine work steadily, the stable transportation of powder fuel should be ensured primarily no matter which feeding system be used, so it is essential to monitor mass flow rate of powder fuel. Although there can be used many kinds of apparatuses to measure the mass flow rate presently, such as Coriolis mass flowmeter, most of them can only be applied to dilute flow. It is hard to measure mass flow rate of dense gas solid flow. To solve the above problem, we bring forward a new direct measuring approach by making use of cyclone separator and electronic balance, and with that, large number of cold state tests have been carried out in previous studies. But the separator and balance combined approach can just be appropriate for cold state, and on the other hand, there is no space to install large measuring apparatus between powder fuel tank and combustor for integrated engine. Considering that powder fuel is driven by a piston, we present an indirect method through measuring piston displacement [17], which can be applied in both cold condition and ignition condition. The veracity of the combined approach and the indirect method was verified by comparing the results of them.

Because of the combustor with quite high pressure when powder motor is in firing condition, the pressure of powder tank must be higher than that in combustor to ensure powder fuel can be taken into combustor. So the powder fuel feeding system is working at high pressure. Presently the studies of gas solid flow in high pressure condition are mainly concentrated on long distance transportation [18], and there is rare report on powder transportation at high pressure of powder motor. According to Refs. [15–17], the control of powder mass flow rate depends on the fluidized gas flow rate, which needs to be inflated into feeding system when the motor begins to work. It indicates that there will be a progress of pressure building in powder tank. The mass flow rate of powder is unstable during this progress. And the increase of pressure in combustor is faster than that in powder tank after ignition, which may easily lead to backfire phenomenon. To solve the backfire problem, the original control manner of powder mass flow rate must be replaced to pressure control manner, which keeps the powder tank in high pressure condition firstly. And there will be a pressure difference between powder tank and combustor to avoid the backfire. Additionally, researchers have found that “chocking phenomenon” exists in gas solid flow just like pure gas [19–22], which demonstrates that the mass flow rate of powder will be constant when certain specified conditions of powder tank are satisfied, that is beneficial to stable combustion. Thus it can be observed that the high pressure condition of powder tank does not only meet working requirement of powder feeding device, but can keep powder mass flow rate steady.

In this paper, two mass flow rate measuring methods were studied to verify feasibility of powder fuel mass flow rate monitoring under the combustion condition. And experiments of powder feeding characteristics in high pressure condition were also carried out to explore the adjusting method of powder mass flow rate.

2. Experimental

The experimental system mainly consists of high pressure tank, powder feeding device, cyclone separator, and displacement transducer as shown in Fig. 1. Fluidized gas is supplied by nitrogen tank. The piston is driven by an electrical motor. The cyclone separator is used to collect powder. Under the collector there is a precise electronic balance, XP8002S, produced by Mettler Toledo company in Switzerland, whose measurement accuracy is 0.01 g, and the functions of sampling frequency adjustment and real time data transmission are supported. Firstly, the powder tank is inflated by fluidized nitrogen until the pressure rise to one designed value. After that, the pneumatic ball valve and electrical motor begin to work at the same time. Fluidized gas carries powder from powder tank to cyclone separator. Then the powder drops into the collector and be weighted by electronic balance. The progress is shown in Fig. 2. Because the total mass of powder changes over time, we get instantaneous values of mass flow rate by differentiating the mass-time curves.

Although the combined measuring method (CMM) can solve the problem of powder mass flow rate measurement in cold condition, the application in firing condition is more concerned. So the indirect measuring method (IMM) was put forward. In the indirect method, the loading density of powder is assumed as a constant in progress of powder feeding. So there exists a mathematic relation between powder mass flow rate and piston velocity, which is given by the following:

$$\dot{m}_P = \rho_{packing} v_{piston} A_{piston} \tag{1}$$