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

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:

$$\dot{m}_P = \rho_{packing} v_{piston} A_{piston} \quad (1)$$

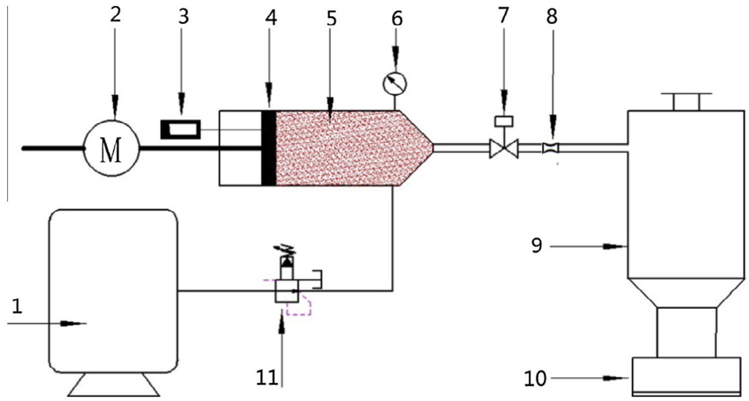

Fig. 1. Experimental system. (1 – nitrogen tank, 2 – electrical motor, 3 – displacement transducer, 4 – piston, 5 – powder, 6 – pressure transducer, 7 – pneumatic ball valve, 8 – pipe with minimum area, 9 – cyclone separator, 10 – electronic balance, 11 – pressure reducing valve).

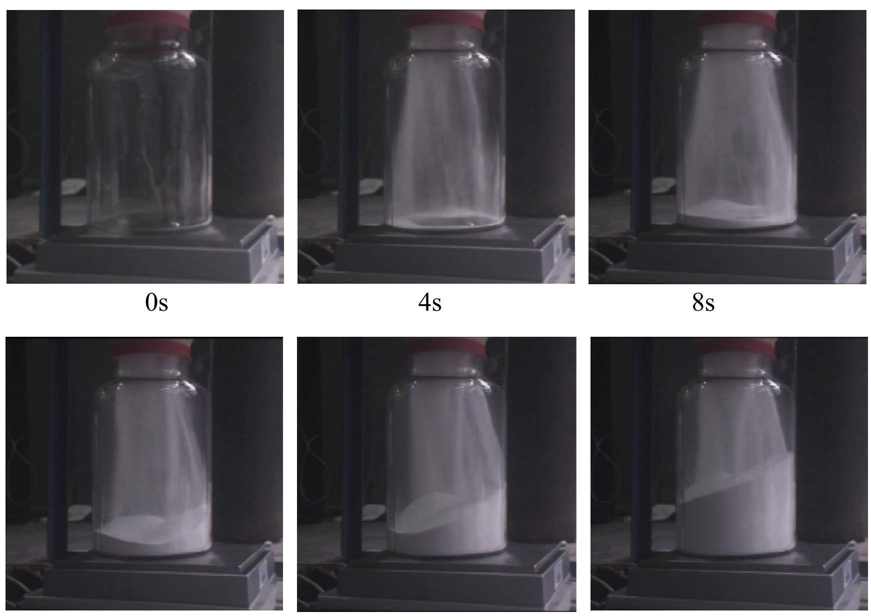

Fig. 2. The progress of powder collection.

$$\rho_{packing} = \frac{m_{packing}}{V} \tag{2}$$

where
$\dot{m}_P$ is powder mass flow rate
$\rho_{packing}$ represents powder loading density
v_{piston} represents piston velocity
A_{piston} represents cross sectional area of piston
$m_{packing}$ represents initial total mass of powder
V represents the total volume of powder tank

A linear relation is found between powder mass flow rate and piston velocity according to formula (1). So the instant mass flow rate of powder can be calculated by piston velocity.

Considering that there may be a dust explosion if micro aluminum powder disperses into air, so neutral aluminum oxide powder (AL_2O_3) is used to replace aluminum powder as experimental powder. Details of experimental condition are shown in Table 1. Case 1 to case 3 are verification and replication experiments for IMM, in which powder mass flow rate is controlled by fluidized gas mass flow rate. Because the performance of powder transportation is mainly affected by gas pressure and cross sectional area in industry [23], case 4 to case 7 are the experiments of different initial pressure in powder tank and minimum exit cross sectional area, in which powder mass flow rate is controlled by gas pressure. The pipe with different cross sectional area is installed behind the pneumatic ball valve, as shown in Fig. 3.

Table 1
Experimental conditions.

Case	ρ_P, kg/m^3	Size range, mm	Gas flow rate, g/s	Initial pressure, MPa	Pipe diameter, mm
1	3900	0.15–0.25	2.3	/	0.5
2			2.8	/	0.5
3			2.8	/	0.5
4			/	0.5	3.0
5			/	1.0	3.0
6			/	2.0	3.0
7			/	3.0	3.0
8			/	3.0	4.0
9			/	3.0	2.5
10			/	3.0	2.0

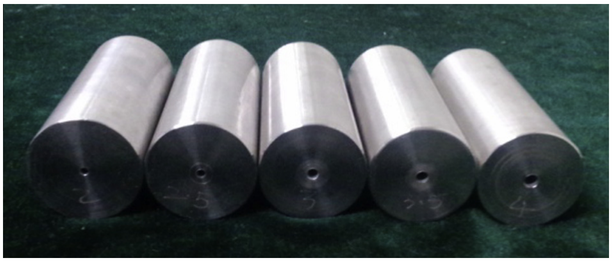

Fig. 3. Different diameter pipes.

3. Results and discussions

IMM is based on the assumption that powder loading density is constant. To verify the veracity of IMM, the results measured by CMM and IMM respectively are compared.

The curves of powder mass over time are shown in Fig. 4. The measuring moment of electronic balance is later than IMM because the gas–solid flow needs some time to transport and separation in the duct and the separator. The starting points of two curves are overlapped to make contrastive analysis conveniently. In Fig. 4, there is a good agreement between two curves on the whole. In primary stage, the value of IMM is a little higher than CMM. At the moment of 20 s, the piston and fluidized gas stop together, but the curve of CMM still rises. That is because the pressure in powder tank needs seconds to drop to the atmospheric pressure value, while the pneumatic ball valve is still open at that moment. The remainder powder is carried to cyclone separator continually, contributing to the mass increase, which is weighted by electronic balance.

To make it easy to analyze results, the sampling frequency of displacement sensor is set to 10 HZ, which is as same as that of the electronic balance. There are two calculation methods of powder instant mass flow rate based on 10 HZ sampling frequency. The method I is based on direct calculation, which is given by the following:

$$\dot{m}_{ti} = \frac{m_{ti} - m_{t(i-1)}}{0.1} \quad i = 2, 3, 4, 5, \ldots \tag{3}$$

and the method II is based on average calculation, which is given by the following:

$$\dot{m}_{ti} = \frac{m_{ti} + m_{t(i-1)} + m_{t(i+1)} + m_{t(i+1)} + m_{t(i+1)}}{0.5} \quad i = 1, 2, 3, 4, \ldots \tag{4}$$

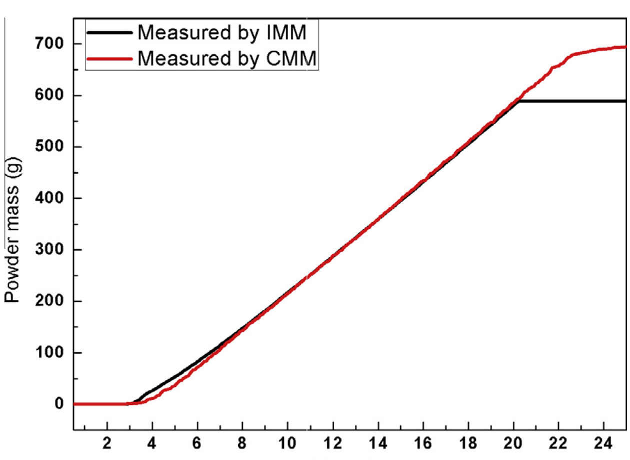

Fig. 4. Comparison of two mass curves over time.

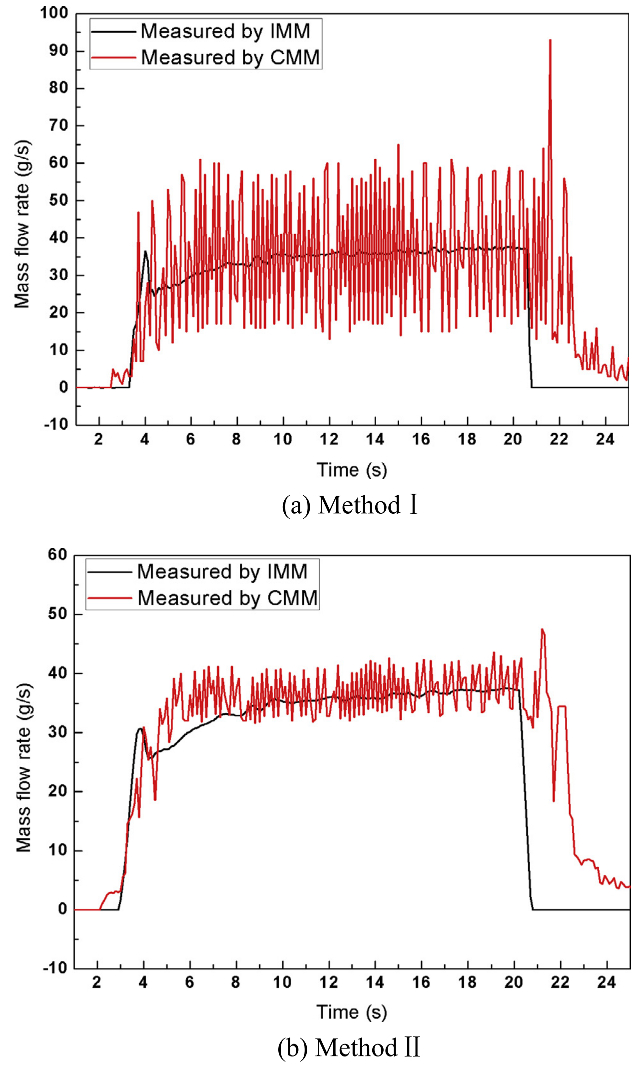

Fig. 5. The results of two computational methods.

where $\dot{m}_{ti}$ is the powder instant mass flow rate at the moment of *ti* second, m_{ti} is the powder instant mass at the moment of *ti* second, and *ti* represents the sampling instant.

The contrastive results of two calculation methods are shown in Fig. 5. The calculation method of mass flow rate makes a greater impact on the CMM results than the IMMs. The curve of CMM shows obvious violent oscillation. That is because the non-continuous powder flow will impinge on the electronic balance after gas solid separation, forming one acting force which is similar to spring force on the electronic balance, so the data curve shows oscillation.

Analyzing the results of case 2, the curves of powder mass and mass flow rate over time are shown in Figs. 6 and 7. The CMM curve and IMM curve are all in a good agreement in both Figs. 6 and 7. That indicates the measurement accuracy of IMM is equal to CMMs. Furthermore, the operation of IMM is easier than CMM, and IMM has a wider application because the velocity of piston can be measured at any time in progress of ignition.

To avoid the influence of experimental contingency, the repeatability of same experimental condition needs to be verified. Case 2 and case 3 are the repetitive tests, whose results are shown in Figs. 8 and 9. The curves of powder mass over time are in a good agreement except slight differences at the beginning and the ending of curves. The curves of mass flow rate over time have good coherence on the whole as well, but the values are different at

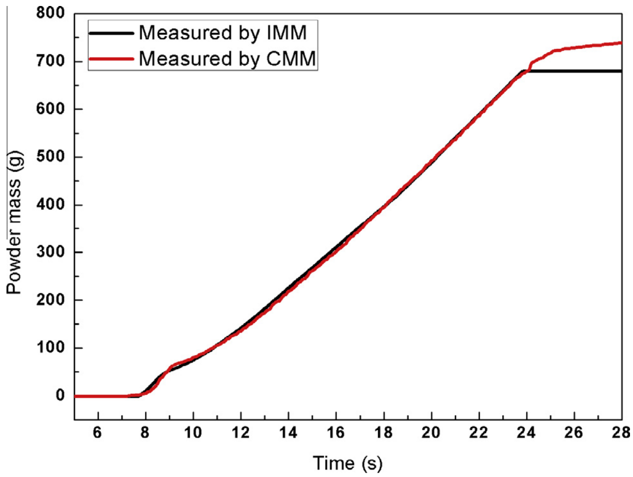

Fig. 6. Powder mass over time with case 2.

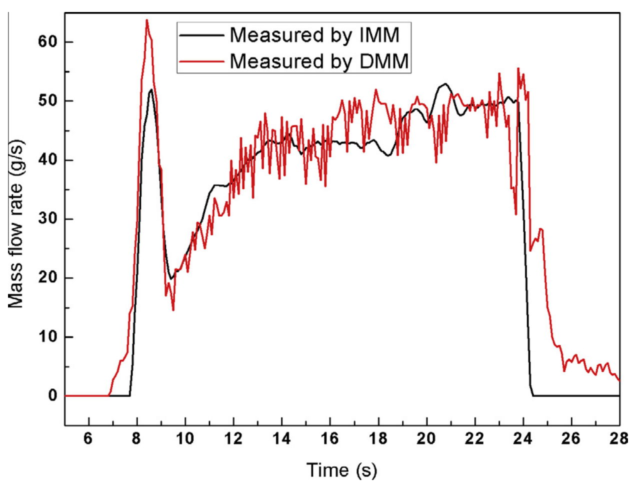

Fig. 7. Powder mass flow rate over time with case 2.

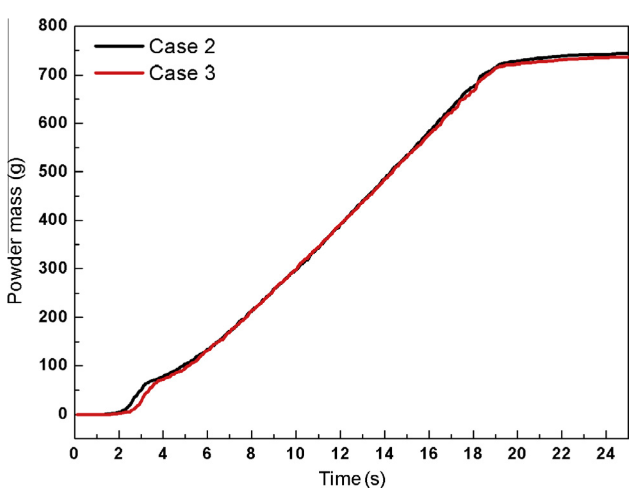

Fig. 8. Repetitive experiments: powder mass comparison.

some points. That is attributed to the volatility of balance measuring and the mass flow rate calculation method. Because the overall repeatability is not influenced by instantaneous value, so there is no need to concern about the difference that is produced by

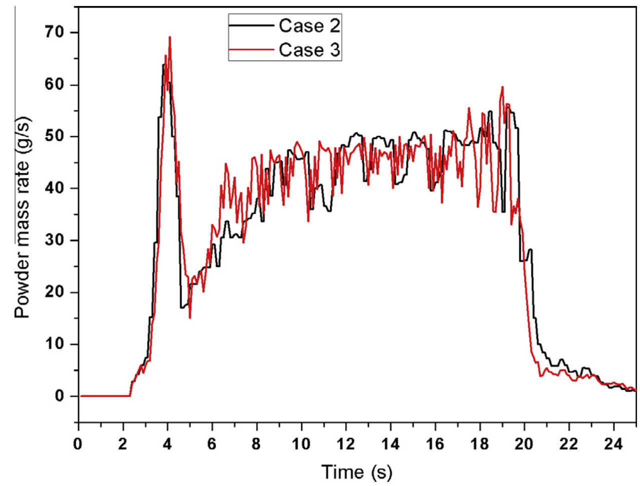

Fig. 9. Repetitive experiments: mass rate comparison.

instantaneous value. Thus it is reasonable to indicate that the feeding device owns a good repeatability.

From the above we know that the IMM can be utilized to measure the mass flow rate of powder in both cold condition and ignition condition. And there is linear relation between piston velocity and powder mass flow rate. So IMM is applied in the following experiments. For convenience, we do not convert piston velocity to mass flow rate. The curves of pressure and piston displacement in powder tank are shown in Fig. 10. The piston moves forwards and backwards in the progress of pressure building up and returns to its normal position after the pressure tends to stable. The total mass of powder and the total volume of tank do not change before the pneumatic ball valve opens, because the feeding device is in a closed state. So the piston motion at the very beginning will not influence on the experimental results gained afterward. When feeding device starts to work, there exists obviously a progress of pressure drop. And after that the pressure tends to be stabilized. The piston velocity changes with the pressure in powder tank. Two obvious periods are divided: (1) The piston velocity is unstable during the pressure drop progress while the mean value of velocity is higher than that with stable pressure; (2) The piston velocity becomes stable when the pressure tends to be stabilized. The cause of pressure drop lies in the change of gas solid flow state. Before the opening of pneumatic ball valve, the measured static pressure by sensor is total pressure, after that the total pressure

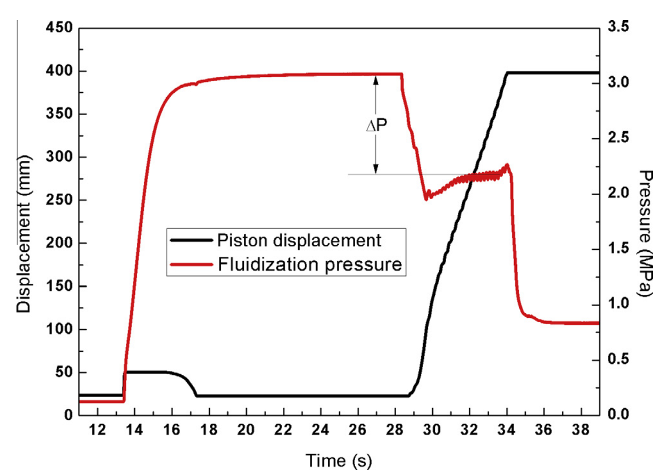

Fig. 10. The curves of displacement and pressure over time at high pressure.

consists of static pressure and dynamic pressure. Powder transporting with the action of moving gas, that results in a drop of static pressure is shown in Fig. 10. Besides, the mass flow rate of powder is higher in the progress of pressure drop because the powder gets more kinetic energy from the fluidized gas. The pressure change at the stage of initialization will impact on the mass flow rate of powder, which concerns the ignition of engine directly. The related research will be carried out in the future.

The curves of piston displacement over time with different initial pressure are shown in Fig. 11. It can be observed that piston velocity becomes higher with initial pressure after the stage of initiation, which indicates that rising initial pressure will increase the mass flow rate of powder. Moreover, when the initial pressure is lower, the piston velocity is not steady enough. Like the conditions of 0.5 MPa and 1 MPa, an obvious shake can be seen from both of the two curves. So it follows that high initial pressure is beneficial to stable transportation of powder. It is also found that slopes of the curves increase firstly and then decrease during the period of initiation. But the changing range of piston velocity caused by pressure drop decreases with the rise of initial pressure. It presents that the gas solid flow transits smoothly with higher initial pressure, which also demonstrates the high pressure can make the powder feeding more stable.

For further discussion, average value of the piston velocity in stable period is obtained. And the pressure drop is also calculated averagely. The average values of piston velocity and pressure drop are shown in Fig. 12. There is an approximate linear relation between the piston velocity and initial fluidized pressure. The pressure drop is climbing with initial pressure too.

Changing the diameter of pipe is a way to study the influence of minimum sectional area on piston velocity. The curves of displacement over time are shown in Fig. 13. Similar to Fig. 11, the slope of curve increases with pipe diameter. On the other hand, the pressure drop becomes faster because of rising exit area, which leads to the transit of velocity smoother. There is also an approximate linear relation between piston velocity and pipe diameter. And the pressure drop follows the rules in Fig. 12 too, which is shown in Fig. 14.

Because initial fluidized pressure and pipe sectional area are irrelevant, both of them can induce the pressure drop and change of powder mass flow rate in different degrees independently. Based on the experimental points of Figs. 12 and 14, the linear fitting is carried out, and the slopes of fitting lines represent the changing rates.

The fitting line slope of piston velocity with initial pressure is 21.16 [mm/(s MPa)]. And for another fitting line, the piston velocity changes with pipe diameter concerned, and the slope is 50.31 [mm/s mm]. It is clear that the effect of pipe cross sectional area on powder mass flow rate is greater than that of initial pressure. In addition, the slopes of pressure drop fitting lines of Figs. 12 and 14 are 0.216 [MPa/(MPa)] and 0.162 [MPa/(mm)], respectively.

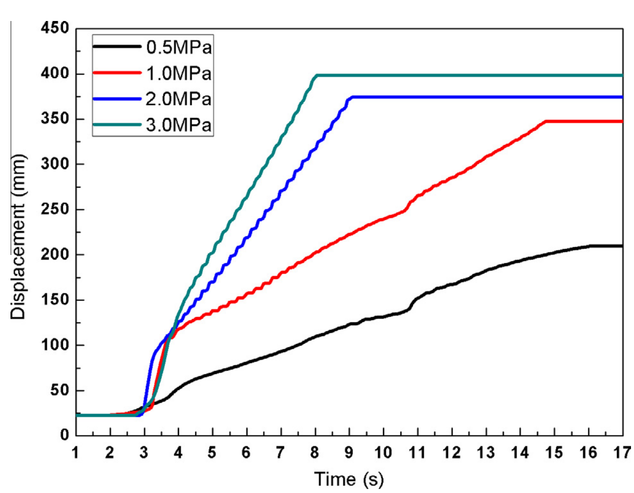

Fig. 11. The curves of piston displacement over time with different initial pressure.

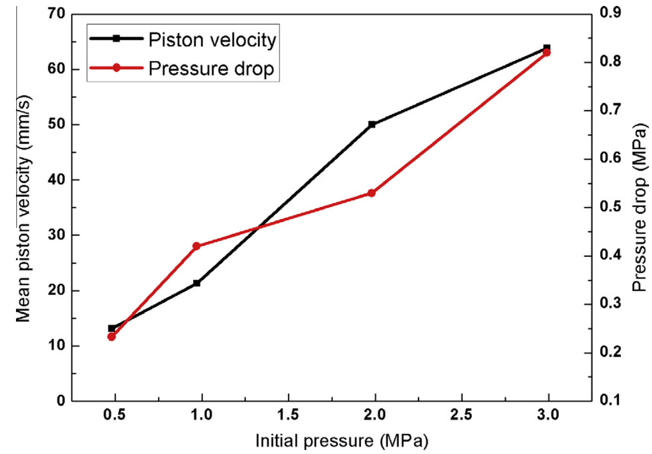

Fig. 12. The curves of average piston velocity and pressure drop with different initial pressure.

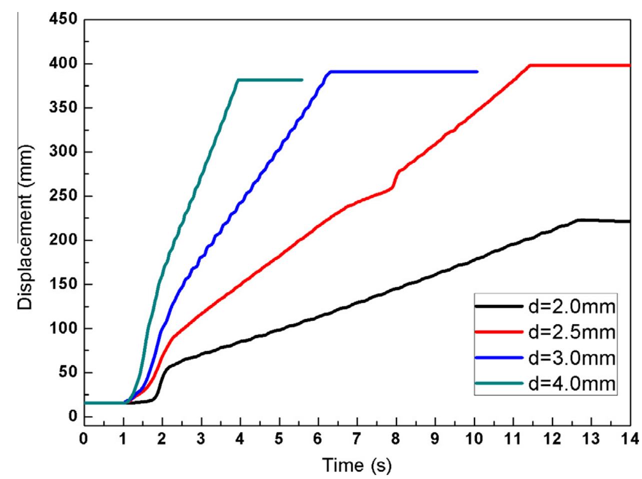

Fig. 13. The curves of displacement over time with different pipe diameter.

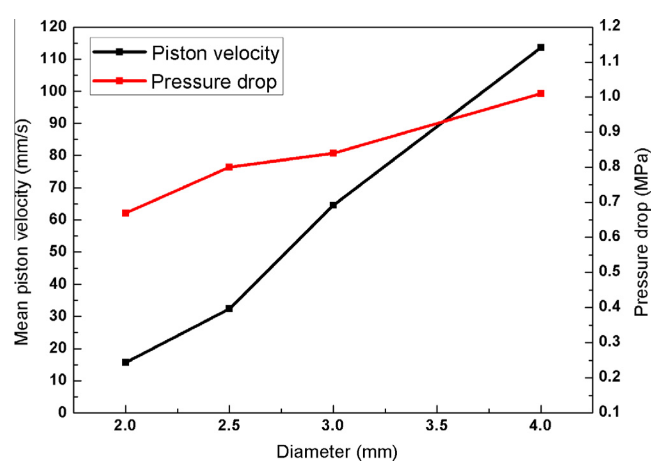

Fig. 14. The curves of average piston velocity and pressure drop with different pipe diameter.

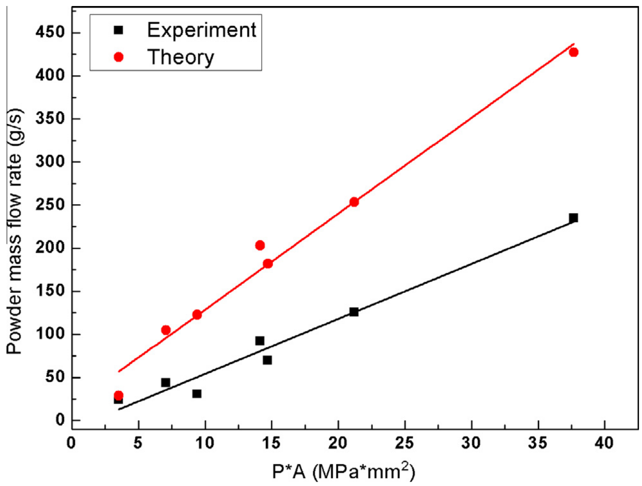

Fig. 15. Comparison of theoretical and experimental results.

It demonstrates that the stability of powder feeding will be more affected by changes of initial fluidized pressure. On the whole, changing the pipe cross sectional area is a better way for large-range adjustment of powder mass flow rate.

It is well known that the gas state will not be influenced by back pressure under some special situations, so the gas mass flow rate can be calculated by special formula, which is called the "gas choking" phenomenon. Researchers have found that there also exists the "choking" phenomenon in gas solid flow [19–22]. According to Ref. [22], when gas–solid flow is in "choking" condition, the mass flow rate of solid phase can be calculated by formula, which is given by

$$M = \frac{P_0 A}{\sqrt{R_m T_0}} \sqrt{\gamma_m} \left[\frac{2}{\gamma_m + 1} \right]^{\frac{\gamma_m + 1}{2(\gamma_m - 1)}} \tag{5}$$

$$\gamma_m = \gamma_g \left(1 + \frac{\phi}{1 - \phi} \frac{C_P}{C_{P,g}} \right) \Big/ \left(1 + \frac{\phi}{1 - \phi} \frac{C_P}{C_{P,g}} \gamma_g \right) \tag{6}$$

$$R_m = (1 - \phi)/(1 - \varepsilon) R_g \tag{7}$$

where

M represents powder mass flow rate
P_0 represents stagnation pressure
A represents cross sectional area of pipe
R_m represents two-phase mixture constant
T_0 represents temperature in stagnation state
γ_m represents specific heat ratio of gas solid mixture
γ_g represents specific heat ratio of gas
C_P represents valid heat capacity of particle
$C_{P,g}$ represents heat capacity of gas at constant pressure
R_g represents gas constant
ϕ is mass fraction
ε is volume fraction

Because the powder feeding experiments with high fluidized pressure meet the condition of gas solid "choking", powder mass flow rate can be calculated by Eq. (5). On the other hand, it is known from formula (5) that the powder mass flow rate is mainly decided by stagnation pressure and minimum pipe cross sectional area. So, the stagnation pressure and minimum pipe sectional area are taken together to obtain a new parameter, $P * A$, as the independent variable when analyzing. The contrastive results of experiment and theory are shown in Fig. 15. The qualitative result agrees with Refs. [19–22]. There is a linear tendency of the experimental values, as the same trend with the theoretical calculation values. But the theoretical values are higher than experimental values. And the fitting curve slope of theoretical values is higher, too, indicating that the value calculated by theoretical formula is always bigger than experimental value. The obvious difference is mainly attributed to the theoretical model regarding the gas–solid flow as equilibrium flow where the parameters of particle velocity, particle temperature, etc. are as same as the parameters of gas. Actually, there is little possibility to form equilibrium flow when considering the influence of inter phase coupling and particle–particle collision. So the theoretical model is not very correct. Meanwhile, there exists relative error between the experimental results and real values limited to experimental conditions, which may enlarge the difference of comparison.

It can be found that the existing theoretical model cannot be utilized to calculate the mass flow rate precisely. The model needs

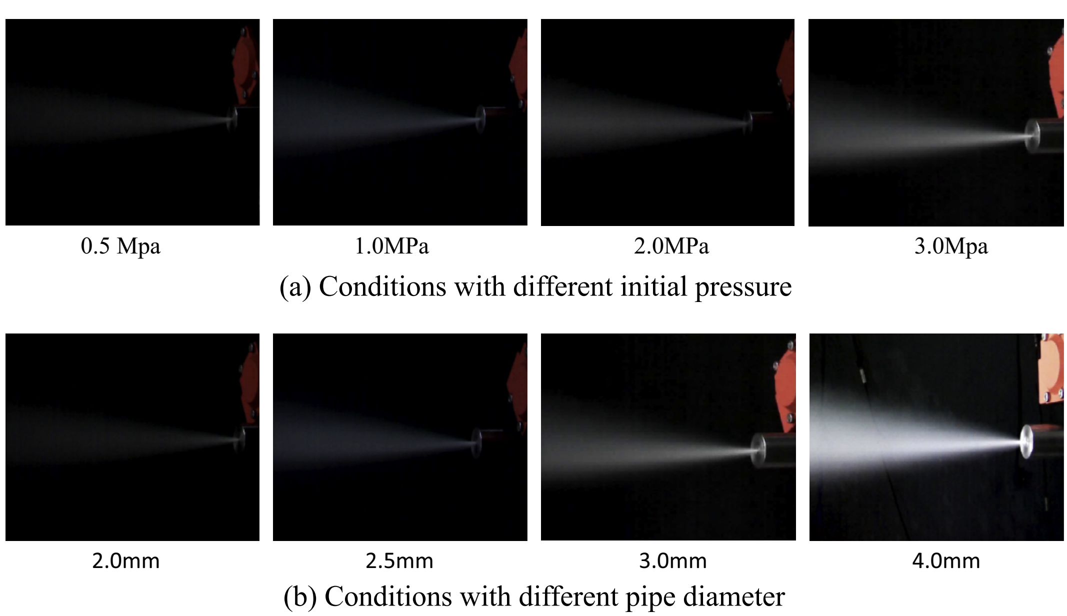

Fig. 16. Powder sprinkle.

to be constructed based on nonequilibrium gas–solid flow. Besides, the measurement accuracy of subsequent experiments needs to be improved.

Particle ignition and combustion in combustor are affected directly by powder sprinkling at high pressure. Largish sprinkling angle of powder will be benefited to improve the mixing combustion efficiency of gas–solid flow. Therefore the powder sprinkling state under various conditions when the feeding system works stably is shown in Fig. 16. The sprinkling angle increases with the initial fluidized pressure. And it also rises with pipe cross sectional area.

Mass flow rate adjustment of powder fuel is pivotal for powder engine. There exist two approaches to adjust powder mass flow rate: changing the initial fluidized pressure or the pipe cross sectional area. Overall, the second one is the better for powder mass flow rate adjustment.

4. Conclusions

In the research progress of powder engine, there exist two big challenges: the mass flow rate measurement of powder fuel under ignition condition and the mass flow rate adjustment of powder. For the first problem, the indirect measuring method (IMM) is put forward and compared with the combined measuring method (CMM). The consequence is obtained that the IMM owns higher measurement accuracy and can be used for measuring powder mass flow rate in firing condition.

For the second problem, two approaches to adjust powder mass flow rate are presented: by changing the initial fluidized pressure or the minimum pipe cross sectional area. Through comparing the experimental results, it is found that changing the pipe cross sectional area is more efficient for thrust adjustment. Additionally, there is a large difference between the experimental result and the result calculated by current theoretical model based on the assumption of equilibrium gas solid flow. It implies that the prediction needs to be corrected by nonequilibrium gas solid flow theory.

Pressure drop which arises from the feeding manner at high pressure will impinge on the powder feeding stability. In further research, the emphasis should be laid on how to make the pressure steady in powder tank during the progress of powder feeding.

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