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Research of the burning rate coefficient on the interior ballistics of gas ejection power system

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Abstract. According to the characteristics of the gas ejection power system, the interior ballistics mathematical model of the combustion chamber and the canister was established and calculated. The results were in good agreement with the experimental results. Then the gas ejection interior ballistics of four burning rate coefficients was calculated. The results show that the burning rate coefficient directly influences flow parameters of the combustion chamber and the canister and the launch ballistic parameters. It can provide a theoretical reference for the design of gas ejection system.

Introduction

The ejection power system is a device that uses the external power to eject missile out the canister. At present, according to different power sources, the methods of gas ejection and compressed air ejection and gas-steam ejection are widely used [1, 2]. Among these ejection methods, the gas injection system is using high pressure and high speed gas as the power source to move the missile. This method can eject heavier missile and the weight of power source is smaller and it is easier to meet the requirements of internal ballistics. With the advantages of simple structure, high missile speed and long range, it is widely used in weapon launch system.

The gas ejection was proposed originally by McKinnis [3]. Yuan zengfeng [4] used the classical interior ballistics theory to predict the change of the combustion chamber and the canister pressure of gas ejection. Rui Shouzhen [5] introduced and compared several different missile ejection power systems. Bai Junhua [6] studied the influence of different launching depth and charge quantity on no-cooling launch power system ballistics. Many achievements had been obtained in the calculation of the internal ballistics of gas ejection. However, the effect on the burning rate coefficient of propellant has not been studied.

The burning rate coefficient of propellant is a decisive factor in the combustion rate. The change of combustion speed will affect the pressure of the combustion chamber and ultimately affect the ballistic parameters of the missile. In this paper interior ballistics calculation model for the combustion and the canister was established and calculated. At the same time the influence of burning rate coefficient on the flow parameters and interior ballistics was studied. The results can provide reference for the development of ejection device.

Gas Ejection Process

The gas ejection power system is mainly composed of a combustion chamber, a gas generator, an elbow and the canister. The combustion chamber generates high pressure and high speed gas which is the power source of the whole launch system. The elbow is a connecting part which transfers the energy of the combustion chamber to the canister. The missile to be launched is equipped in the canister and the missile is connected with the canister by the adapter which can provide the guidance function. Fig. 1 shows the structure of the gas ejection device. The working process of the ejection system is as follows: the propellant combustion in combustion chamber generates high pressure gas that enters the canister by the connecting elbow and the missile overcomes the resistance under the action of the gas and moves until the missile is out of the canister.

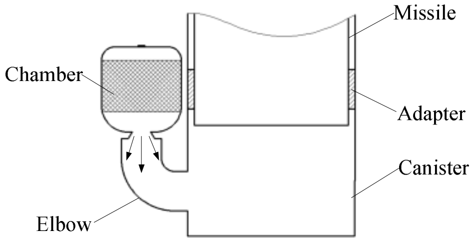


Fig. 1 Schematic diagram of gas ejection power system.

The missile ejection process is a complicated and unsteady process. Some assumptions are made in the modeling process and the model is simplified. The basic assumptions are as follows:

(1) The gas flow parameter change in the axial direction is not taken into account.

(2) The combustion of the propellant is complete. Don’t consider the change of the components of the combustion products. The gas and air are regarded as ideal gas.

(3) The flow rate correction coefficient and the heat loss correction coefficient are introduced to correct the loss of energy.

Interior Ballistic Modeling

Through the analysis and simplification of the ejection system, the calculation of gas ejection system interior ballistics can be regarded as the combustion chamber working process and the canister chamber working process. These two processes constitute a whole thermodynamic system. The calculation model can be established on the basis of the energy conservation equation of the whole system.

The Combustion Chamber Modeling. The launching interior ballistics index indicates that the missile needs to be accelerated uniformly in the canister. With the movement of missile, the free volume increases. In order to ensure the stable change of the canister pressure, the combustion chamber needs to use the progressive combustion powder to maintain constant thrust at the bottom of the missile. In this paper, the calculation of the combustion chamber is made by using the tubular powder with cladding in both ends and outer face.

Mass conservation equation

$$\rho_1 V_1 = m_b - m_g \tag{1}$$

where, ρ_1 is the density of gas in the combustion chamber, m_b and m_g represent the total gas quality of propellant combustion and the gas quality of flowing into the canister, $V_1 = V_{10} - \frac{\omega}{\rho_p}\left(1 - \frac{m_b}{\omega}\right)$ is the free volume of the combustion chamber and V_{10} is the initial volume of the combustion chamber, ρ_p is the powder density, ω is the charge quantity.

Flow equation

$$\dot{m}_b = \rho_p S_b u \tag{2}$$

$$\dot{m}_g = \varphi_1 K_0 \frac{P_1 S_{t1}}{\sqrt{R_g T_1}} \tag{3}$$

where, φ_1 is the flow correction coefficient, S_{t1} is the nozzle throat area, R_g is gas constant, T_1 is the temperature of the gas in combustion chamber. $K_0 = \sqrt{k}\left(\frac{2}{k+1}\right)^{\frac{k+1}{2(k-1)}}$ is gas constant which is related to specific heat ratio *k*. $S_b = N\pi(d+2e)L$ ($e \le \frac{D-d}{2}$) is combustion area, where *N*, *L*, *D*, *d* and *e* respectively represent the powder number, length, external diameter, internal diameter and thickness. $u = b_0 P_1^n$ represents the combustion rate of propellant, where b0 is the propellant burning rate coefficient and *n* is pressure index.

State equation

$$P_1 = \rho_1 R_g T_1 \tag{4}$$

Where P_1 is pressure of the combustion chamber and the following interior ballistics equation can be obtained.

$$\begin{cases} \frac{dP_1}{dt} = \frac{R_g T_1}{V_1}\left(\rho_p S_b u - \varphi_1 K_0 \frac{P_1 S_{t1}}{\sqrt{RT_1}}\right) \\ \frac{de}{dt} = u = aP_1^n \end{cases} \tag{5}$$

The Canister Modeling. Gas state equation

$$P_2 = \frac{x_p (R_g m_g + R_a m_a) T_2}{S_t (l_0 + l)} \tag{6}$$

Motion equation

$$\begin{cases} \frac{dv}{dt} = a = \frac{P_2 S_t - F}{M} \\ \frac{dl}{dt} = v \end{cases} \tag{7}$$

Resistance equation

$$F = (1+z)Mg + \rho g h S_t + P_0 S_t \tag{8}$$

Energy conservation equation

$$T_2 = \frac{x_e m_g C_{vg} t_g + m_a C_{va} t_a - (\frac{1}{2}Mv^2 + \int_0^l F dl)}{m_g C_{vg} + m_a C_{va}} + 273.15 \tag{9}$$

where, P_2 and T_2 are pressure and temperature of the canister. S_t is the Sectional area of canister. l_0 is the initial height of the canister. R_a, m_a represent air constant and air quality of the canister. x_p, x_e represent the pressure coefficient and energy coefficient. C_{vg}, C_{va} represent the constant volume specific heat of gas and air. t_g, t_a represent temperature of the gas and air. M, a, v, l represent the quality, acceleration, velocity and displacement of missile. *F* is resistance of missile and ρ is the density of water, h is the launching depth. *g* is the acceleration of gravity and P_0 is atmospheric pressure and *z* is the friction coefficient of adapter.

The interior ballistic parameters including P_1, P_2, T_2, a, v, l can be obtained by the formula (1) ~ (9) .

Results and Discussion

Verification of Results. The interior ballistic model of combustion chamber is calculated and the calculated pressure is compared with the experimental data as shown in Fig. 2.

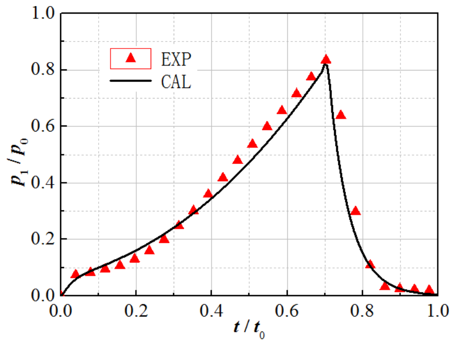
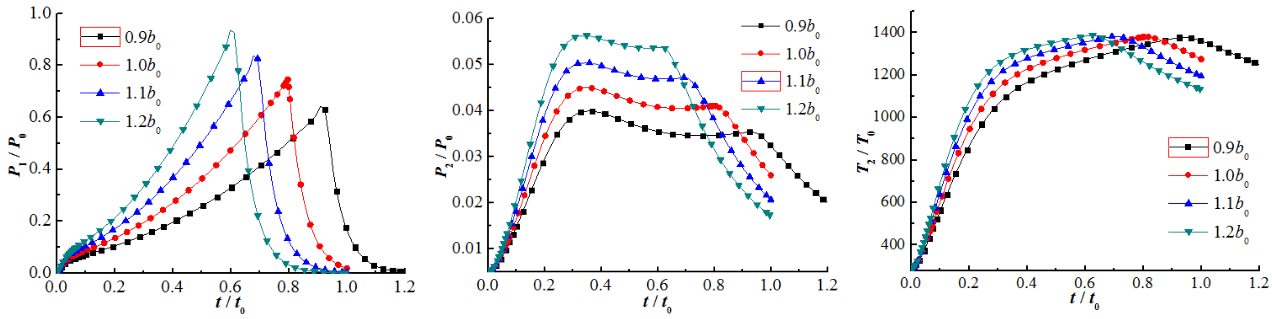


Fig. 2 Comparison of pressure in combustion chamber.

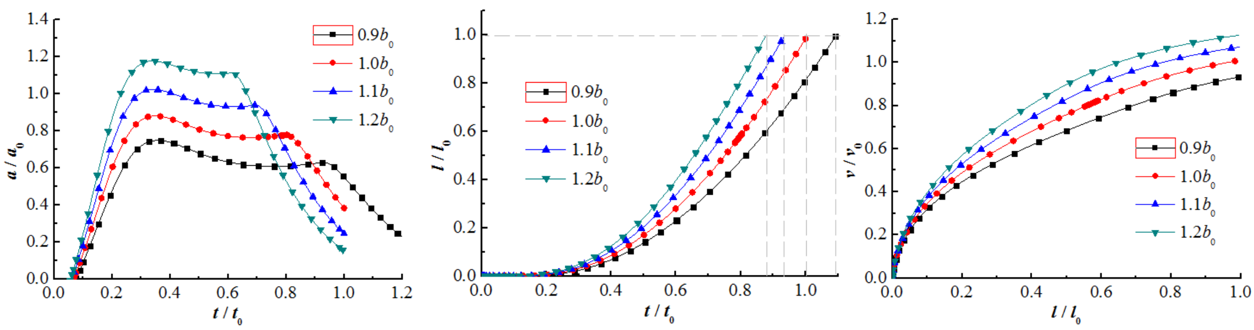
It can be seen from the figure that the pressure of the combustion chamber is consistent with the experimental value and the time point is in good agreement with experiment. The pressure error controls within 5% so the calculation model can be used for interior ballistics calculation.

Effect of Different Propellant Burning Rate Coefficient on Ballistic. The combustion chamber pressure and initial temperature will cause the change of the burning rate coefficient. In the paper, the chamber and canister flow parameters and the interior ballistic rules can be obtained under $0.9b_0$, $1.0b_0$, $1.1b_0$ and $1.2b_0$ four burning rate coefficient conditions see Fig. 3 and Fig. 4. In the figure, t_0, P_0 and T_0 respectively represent the reference time, reference pressure and reference temperature. a_0, l_0 and v_0 represent the acceleration, displacement and velocity.



(a)Combustion Chamber pressure (b) Canister pressure (c) Canister temperature

Fig. 3 Flow parameters in chamber and canister.



(a)Acceleration (b) Displacement (c) Displacement-velocity

Fig. 4 Interior ballistic parameters of missile.

The results can be seen from the calculation as follows

(1) The pressure of the canister is kept rising, stable and decreasing due to the increase of surface burning powder. The combustion chamber gas flows into the canister so that canister pressure increases and the missile moves and the canister free volume increases. After the canister pressure decreasing, the pressure keeps stable. At last the canister pressure has seen a steady decline when the powder is complete combustion.

(2) The higher the propellant burning rate coefficient is, the faster the pressure increase rate of the combustion chamber is, the higher the peak value is, the earlier the pressure peak value time in

combustion chamber and the earlier the missile movement time is.

(3) The higher the propellant burning rate coefficient is, the higher the canister temperature is during initial launch. However, because of the total energy conservation, the temperature rising rate is faster in later. Under the four conditions, the temperature peak is similar, but the temperature peak duration is longer when the burning rate coefficient is larger

(4) According to the displacement curve of the missile, it can be seen that the larger the burning rate coefficient is, the shorter the barrel time is and the larger the missile speed is when the length of canister keeps constant.

(5) When the burning rate coefficient is 1.2 b_0, the acceleration peak value is 1.2 a_0 which exceeds the ballistic target. When the burning rate coefficient is 0.9 b_0, the missile out tube speed is 0.93 v_0 which is less than the ballistic target. So these two conditions don’t meet the design requirement. Therefore, in the four working conditions, the conditions of burning rate coefficient are $1.0b_0$ and $1.1b_0$ meet the interior ballistic index, so meet the design requirements.

Conclusion

In this paper, the ballistics model of combustion chamber and canister is established and the calculation results are verified with experimental. Results show that the error is small and the reliability is high. The combustion chamber and the canister pressure and temperature and the interior ballistics of missile under conditions of four burning rate coefficient are studied. The research results show that the burning rate coefficient affect the combustion chamber pressure directly, thus affecting the canister flow parameters and ballistic of missile. The gas ejection device should be designed based on the ballistic index.

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