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Influence of Structural Parameters on the Performance of Vortex Valve Variable-Thrust Solid Rocket Motor

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Abstract: The vortex valve solid variable thrust motor is a new solid motor which can achieve Vehicle system trajectory optimization and motor energy management. Numerical calculation was performed to investigate the influence of vortex chamber diameter, vortex chamber shape, and vortex chamber height of the vortex valve solid variable thrust motor on modulation performance. The test results verified that the calculation results are consistent with laboratory results with a maximum error of 9.5%. The research drew the following major conclusions: the optimal modulation performance was achieved in a cylindrical vortex chamber, increasing the vortex chamber diameter improved the modulation performance of the vortex valve solid variable thrust motor, optimal modulation performance could be achieved when the height of the vortex chamber is half of the vortex chamber outlet diameter, and the hot gas control flow could result in an enhancement of modulation performance. The results can provide the basis for establishing the design method of the vortex valve solid variable thrust motor.

Keywords: solid rocket motor, thrust modulation, vortex valve, numerical calculation

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Introduction

Many thrust control methods for solid propellant rocket motors have been investigated. Among these, the vortex valve method in an effective way to achieve thrust control for solid propellant rocket motors. The unique feature of the vortex valve method is its fluidic element without moving parts, which enables a tangential control flow in the vortex chamber. This mechanism causes the gas to rotate, increases the flow resistance of the main flow, changes the pressure in the main combustion chamber and adjusts the motor flow to achieve thrust control. The vortex valve variable –thrust method has gained increasing attention among researchers Blatter et al. developed a vortex valve variable that can control a hot gas flow at 0.454 kg/s at 5.2 MPa for up to 50 s. The final vortex valve had a flow modulation range of 3.46 to 1 at a controlled pressure to achieve a pressure ratio of 1.7 [1]. Walsh et al. conducted a theoretical and sub-scale experimental study of solid propellant combustion that is controlled by a vortex valve. A small expenditure of the control flow could yield a wide variation in the thrust. An experimental 25.4 mm vortex valve which was used to modulate an ammonium perchlorate base composite propellant had a 550% variation in the chamber pressure. This variation is 230% higher than the theoretical value using straight mass augmentation [2]. Greenberg et al. developed a parameter calculation method that involves a cold flow test to predict the results of the solid motor test using a vortex valve. Published experimental data satisfactorily correlate with the results of this method [3]. Brodersen R. K. et al. performed analytical and experimental investigations on a number of vortex valve design configurations. A test fixture was designed and fabricated that contained one back-to-back pair of vortex valves, and tests were conducted with cold gas, warm gas, and hot gas as supply fluid, using cold gas, or liquid as control fluid. A maximum turn-down ratio of 9:1 was realized for helium control of cold high pressure nitrogen. The selected vortex valve configuration had a chamber to nozzle radius ratio of 3:1 and was found to be effective in achieving rapid cutoff of the hot supply gas without significant erosion problems [4]. Natan et al. investigated the performance of a vortex valve variable-thrust motor using a mixture of nitrogen and oxygen as the control flow. They investigated the influence of the amount of oxygen in the control flow and the ratio between the

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mass flow rates of the control flow and the main flow on motor modulation performance [5]. Zhang W. H. et al. conducted a theoretical research the design parameters of the vortex valve solid variable-thrust motor using steady analysis [6]. Guo J. et al. investigated the influence of control flow attributes on the modulation performance of vortex valve solid variable-thrust motors that uses three kinds of control flow, namely, high temperature gas, nitrogen, and air. Their result indicated that the modulation performance of high temperature control gases is better than that of low temperature control gases [7]. Lin R. S. et al. used a CFL3D code developed in the NASA Langley Research Center to simulate numerically the performance of two groups of vortex valves. Their result indicated that the structure of a vortex valve greatly influenced modulation performance [8]. Yu X. J. et al. used a three-dimensional numerical model investigated the flow process of vortex valve controlled SRM [9]. Holten T. V. et al. studied the swirl flow in nozzle and found the whole velocity could reach sound velocity in the upstream of nozzle throat when swirl flow exists. Axial velocity reached sound velocity at the throat of nozzle. The mass flow rate through Laval nozzle depended on the intensity of swirl flow, and mass flow rate decreased with increasing strength of vortex flow. By comparing predicted results, experimental results and calculated results, it was found that the model can well characterize the flow rule [10]. Martinelli F. et al. carried out experimental studies about instability of vortex core in free injection under atmosphere using laser Doppler anemometer and particle image velocimetry. The influence of swirl flow parameters and the variation of Reynolds number on flow field were mainly studied. The results show that real turbulence intensity is not dependent on swirl flow parameters [11].

Although many studies on vortex valve variable-thrust motors have been done, only a few initial conclusions on the performance, plan demonstration, and influence factors are obtained. Moreover, only a few research materials that discuss the specific achievement and design method of a vortex valve exist. The structure of a vortex valve greatly influences modulation performance [4–8]. However, existing studies can-not further explain the kind of influence a vortex valve structure has on modulation performance. Existing studies do not also expound on the design of a vortex valve structure to achieve good modulation performance. Thus, investigating the design basis of vortex valves is very important because the structural design of the vortex valve is related to the modulation capability and modulation performance of motors. Investigating the influence of the structure of the vortex valve on modulation performance using numerical simulation means that the design basis of its geometric parameters must be determined.

Vortex valve variable-thrust motor

A vortex valve variable-thrust motor is constructed by installing a vortex valve composed of an airflow modulation device and a control – flow spraying structure in front of the nozzle of an ordinary solid-propellant rocket motor. Its schematic diagram is shown in [1, 3] and [5]. The gas generated by the master motor enters into the vortex chamber after it is circularly modulated through the center body and mixed with the control flow, which comes from control flow supply system and enters the vortex chamber in a tangential direction. The control flow is injected in an angular momentum to induce airflow rotation, which builds pressure gradient, increases flow resistance, increases the operating pressure in the master motor combustion chamber and changes the mass flow rate. All these processes are performed to change the motor thrust. The structure of the vortex valve shows that the valve has two important structure parameters: diameter and height. The vortex valve radius influences the energy of the vortex valve because thrust modulation in variable-thrust motor is required to cause airflow rotation. On the other hand, the vortex valve height is an important parameter that checks if the angular energy can be sufficiently developed in a radial direction. These two parameters determine the structure and modulation capability of a vortex valve. The schematic diagram of vortex valve and structural parameters are shown in Figure 1. This paper aims to determine the influence of vortex chamber diameter, height, and vortex chamber shape on modulation performance.

Numerical calculation method

Numerical calculation model

Numerical calculations were performed using FLUENT 6.3.26, which is a commercial fluid simulation software (ANSYS Co). Three-dimensional Reynolds-Averaged Navier-Stokes equations were used in the numerical model, and SST k-ω turbulent model was adopted to ensure that the governing equations are closed. Upwind biasing was used to determine the convection terms and

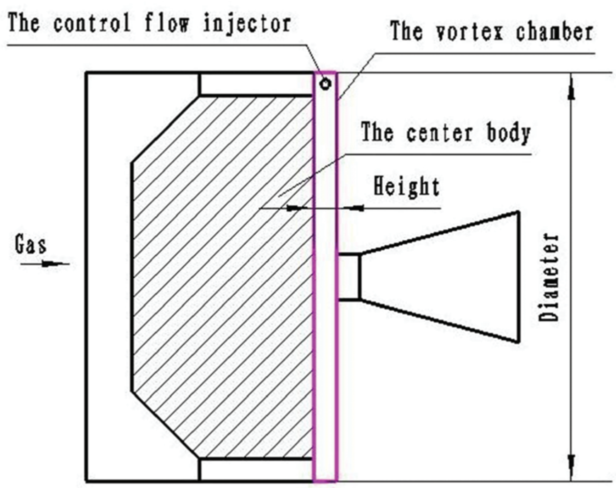

Figure 1: The schematic diagram of vortex valve and structural parameter.

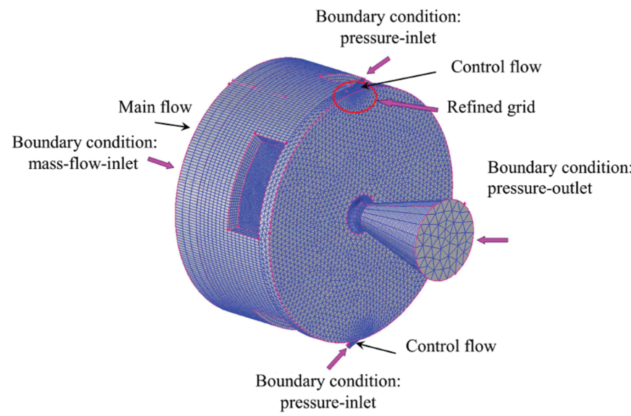

Figure 2: Calculation structure schematic diagram and the boundary condition.

central differencing to determine the viscosity terms. The temporal term was discretized using the second-order backwind form. The finite volume computational frame is based on this model. Hybrid grids were introduced in the computational zone, and the meshes near the controlling gas injection orifice were refined. The boundary condition was set according to the structure and the working character of the vortex valve variable-thrust motor: the master motor inlet adopts the mass flow inlet, the control flow injector adopts the pressure inlet, and the nozzle outlet adopts the pressure outlet. In the mass flow inlet boundary of the master motor, the mass flux is related to the propellant ignition speed, which is used during the calculation using UDF. The flow rate is determined using the formula

$$\dot{m} = \rho_p A_p a p_m^n \tag{1}$$

with $\rho_p = 1.567\ \text{g/cm}^3$, $A_p \approx 24.88\ \text{cm}^2$, $a = 2.267$, $n = 0.6$, $\dot{m}$ is the master motor mass flow rate, ρ_p is the solid propellant density, A_p is the propellant burning area, $a$is the burning rate coefficient in the burning rate formula in exponential form, n is the burning rate pressure exponent, p_m is pressure in the master motor combustion chamber. And in the master motor the combustion gas temperature was 1,789 K. The calculation structure sketch map and the boundary conditions are shown in Figure 2.

Calculation model checking

The results of the numerical calculation were verified with experimental results to determine the applicability and accuracy of the calculation model. The numerical calculation model was verified by comparing the pressure in the combustion chamber with those of experimental data. The experimental system is shown in [12]. The experimental system based on vortex valve includes four parts: the system supplying control flow, test motor, ignition and scheduling device and data acquisition system, as shown in Figure 3. The system supplying control flow, mainly made up of gas source, pipeline and valve, can provide necessary control flow for the experiment motor which is researched here. The ignition and scheduling device is responsible for the ignition of the rocket motor, the opening and closing of the solenoid valve and the time scheduling of the experiment. The data acquisition system is responsible for the acquisition of the pressure and the flow signal during the experiment. The chamber pressure are measured in the test. The end burning propellant which used in the tests was

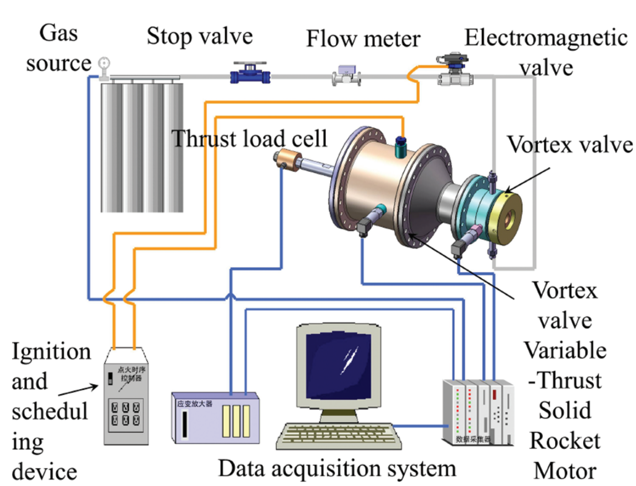

Figure 3: The experimental system schematic diagram.

non-metallized propellant with $n = 0.6$, $T_f = 1{,}789$ K. T_f is the combustion chamber stagnation temperature. The diameter of burning area was 178 mm. The control flow used in the test was nitrogen with a temperature of 293 K. These parameters of vortex valve used in the test include the following: vortex chamber diameter of 90 mm, and control flow injector of 2-Φ2 mm ("2" represents two control flow injectors using, "Φ2" represents that the control flow injector diameter is 2 mm), and control flow injector of 1-Φ2.4 mm in the test6. The diameter of throat used in the test was 10 mm. Four tests were done with the results shown in Table 1. Table 2 shows the comparison results between experimental value and numerical value of chamber pressure. The comparison results show that the results of the numerical calculation are slightly higher than that in the experimental data with a maximum error of 9.5%. Because the thermal loss of mixed airflow, heat transfer to shell, and flow loss are not considered in the numerical calculation. Moreover, the experimental motor has a thick wall without insulation, which caused an increase in the heat loss. However, the numerical calculation result is consistent with the trend of experimental results. Thus, the numerical calculation can be completely applied in investigating vortex valve variable-thrust motors. The result also shows that the calculation result is credible within an acceptable calculation accuracy.

Table 1: Experimental parameters.

	Test1	Test2	Test3	Test4	Test5	Test6
Height of vortex chamber/mm	3	5	8	3	3	5
Pressure of control flow/MPa	9.08	10.24	10.32	8.84	10.63	11.8
Mass flow rate of control flow/kg/s	0.109	0.118	0.127	0.104	0.13	0.113

Table 2: Comparison results of chamber pressure.

	Test1	Test2	Test3	Test4	Test5	Test6
Numerical result/MPa	8.42	8.83	7.54	8.03	8.96	8.27
Experimental result/MPa	7.69	8.56	7.28	7.38	8.44	8.12
Relative error	9.49%	3.15%	3.57%	8.81%	6.2%	1.8%

Calculation result and discussion

Performance parameter definition

Several parameters that reflect the thrust modulation performance need to be defined to ensure a better comparison of the influence of various factors. Theoretically, a higher thrust change with less control flow, lower control flow pressure, and lower pressure change in the combustion chamber can be obtained in a vortex valve variable-thrust motor with excellent performance. Therefore, parameters that reflect motor performance, such as pressure ratio and thrust ratio, mass flow rate ratio before modulation between the control flow mass flow rate and the master motor mass flow rate before modulation, mass flow rate ratio between the control flow mass flow rate and the total mass flow rate after modulation, pressure ratio between the control flow pressure and master motor combustion chamber pressure before modulation, and modulation performance efficiency, need to be defined.

Pressure ratio in the combustion chamber

$$\varepsilon = \frac{P_{m2}}{P_{m1}} \tag{2}$$

Where P_{m1} is the pressure in the master motor combustion chamber after modulation, P_{m2} is the pressure in the master motor combustion chamber after modulation.

Thrust ratio

$$\lambda = \frac{F_2}{F_1} \tag{3}$$

Where F_1 is the thrust before modulation, F_2 is the thrust after modulation.

Mass flow rate ratio before the control flow

$$\alpha = \frac{\dot{m}_c}{\dot{m}_1} \tag{4}$$

Where $\dot{m}_c$ is the mass flow rate of the control flow, $\dot{m}_1$ is the master motor mass flow rate before modulation.

Mass flow rate ratio

$$\varphi = \frac{\dot{m}_c}{\dot{m}_2 + \dot{m}_c} \tag{5}$$

Where m_2 is the master motor mass flow rate after modulation.

The ratio between the control flow pressure and motor combustor pressure before modulation is

$$\gamma = \frac{P_{cf}}{P_{m1}} \tag{6}$$

Where P_{cf} is the pressure of the control flow.

A control flow with less flow and lower pressure must be used to ensure that the vortex valve variable-thrust motor has an excellent performance (i.e., greater thrust modulation ratio).

Influence research on vortex chamber shape

The figures in [1] and [5] show that a vortex chamber shape is not completely consistent. The kind of vortex chamber shape can ensure good motor modulation performance must be determined. Furthermore, the influence of the vortex chamber shape on modulation performance needs to be determined to optimize the vortex valve design. Thus, numerical simulations are performed to investigate the six possible shapes of a vortex chamber. These shapes are shown in Figure 4. Other construction parameters also need to be kept constant during the calculation. These parameters include the following: vortex chamber diameter of 90 mm, vortex chamber height of 5 mm, and control flow injector of 2-Φ2 mm.

The vortex chamber in Figure 4 is the basic vortex chamber shape. Figure 4(b)–4(e) have an additional convergent section compared with that of Figure 4(a). The convergence angle in Figure 4(b)–4(d) is 90°, and the

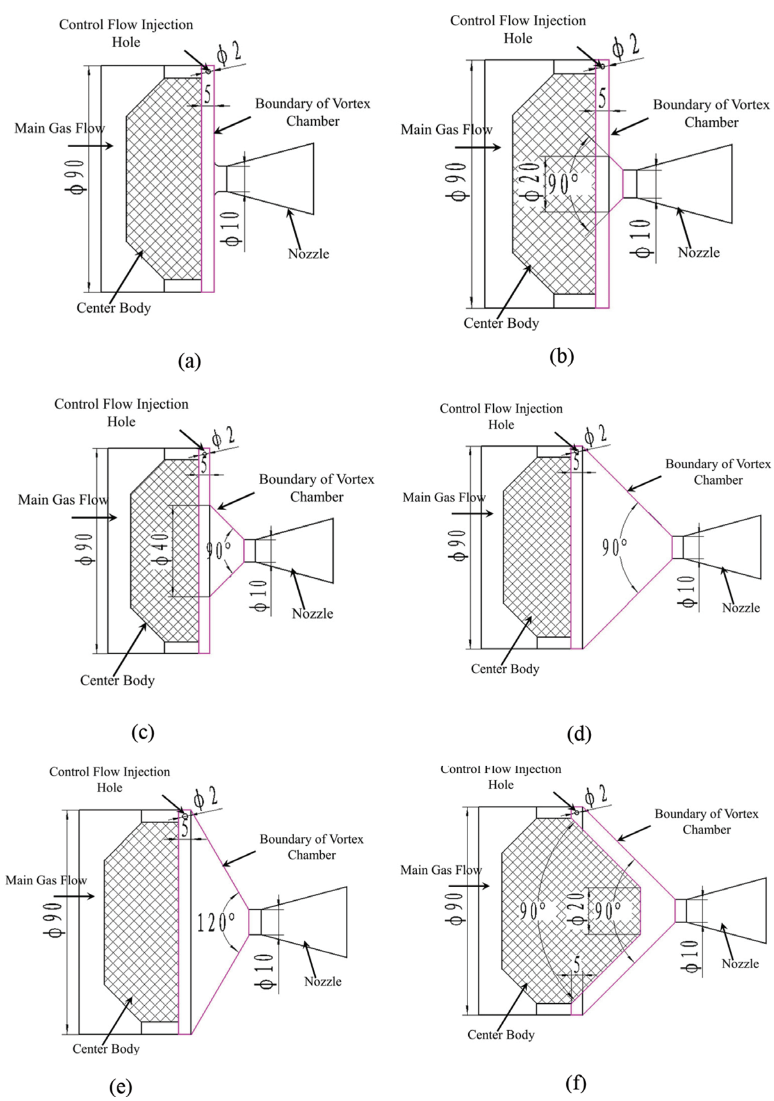

Figure 4: Vortex chamber structures.

diameters of the entrance are 20, 40, and 90 mm, respectively. The convergence angle in Figure 4(e) is 120°, and the diameter of the entrance is 90 mm. The vortex chamber in Figure 4(f) has an additional internal cone compared with that in Figure 4(d).

The control flow used in the calculation was nitrogen with a temperature of 293 K and a total pressure of 11.19 MPa. The control flow parameters at various working conditions are shown in Table 3. The calculation result of various working conditions is shown in Table 4.

Table 3: Control flow parameters that influence the vortex chamber shape.

	Shape	Pressure/MPa	Mass flow rate/kg/s
Case1	a.	11.19	0.118
Case2	b.	11.19	0.120
Case3	c.	11.19	0.139
Case4	d.	11.19	0.148
Case5	e.	11.19	0.132
Case6	f.	1,119	0.127

Table 4: Calculation result that influence the vortex chamber shape.

	ε	λ	ϕ	γ	β
Case1	2.82	2.56	0.255	3.422	1.173
Case2	2.83	2.54	0.259	3.464	1.173
Case3	2.91	2.75	0.304	4.025	0.826
Case4	2.44	2.51	0.332	3.793	0.778
Case5	2.35	2.28	0.286	3.091	1.101
Case6	2.67	2.26	0.274	3.381	0.978

Table 3 shows that the control flow significantly differs among various shapes. Moreover, the control flow increases as the space in the vortex chamber is increased.

Table 4 shows that as the diameter of the entry point is increased for four kinds of vortex chamber shapes, namely Figure 4(a)–4(d), the modulation performance appears to decrease. When the diameter of the entry point is decreased, the modulation performance increases. Comparing the results of Figure 4(d) and 4(e), increasing the convergence angle caused an increase in the modulation ratio and the impulse change rate. The calculation results of Figure 4(d) and 4(f) reveal that increasing the rear cone in the vortex chamber can improve the modulation performance, but also results in great loss. Thus, the vortex chamber in Figure 4(a) is the reasonable choice in the calculation model.

Influence research on vortex chamber diameter

In investigating the influence of the vortex chamber diameter on modulation performance, the basic parameters used are as follows: vortex chamber height of 5 mm and control flow injector of 2-Φ1.2 mm. These values are working conditions used for the vortex chamber diameters of 60, 70, 80, 100, 110, and 120 mm. The control flow used during the calculation was nitrogen with a temperature of 293 K, a total pressure of 11.19 MPa, and a control flow and mass flow rate of 0.05 kg/s. The calculated thrust modulation ratio and pressure modulation ratio are shown in Figure 5. The calculated mass flow rate ratio is shown in Figure 6.

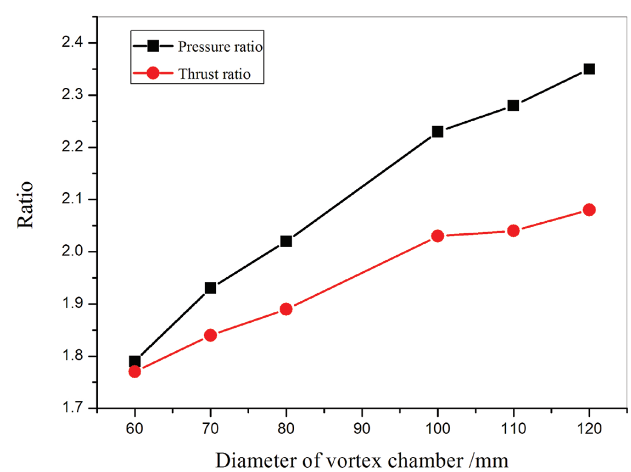

Figure 5: Influence of diameter on the thrust ratio and pressure ratio.

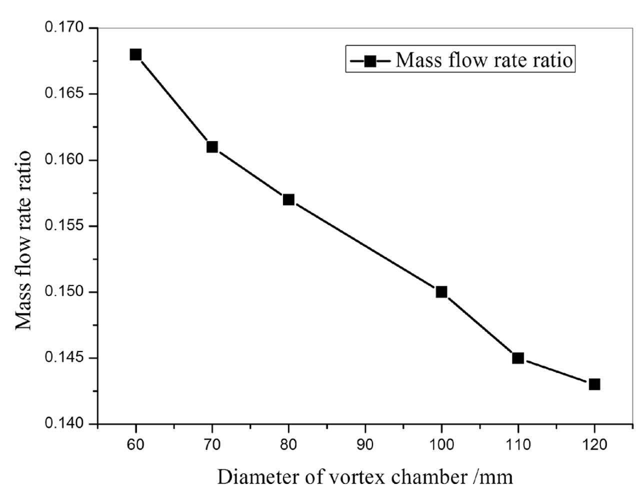

Figure 6: Influence of diameter on the mass flow rate ratio.

Figure 5 shows that the pressure ratio and thrust ratio continuously increase as the vortex chamber diameter is increased. The pressure ratio increases faster than the thrust ratio. On the other hand, Figure 6 shows that the mass flow rate ratio continuously decreases as the vortex chamber diameter is increased. These trends conclude that increasing the vortex chamber diameter caused an increase in the momentum required to rotate the air flow into the vortex chamber using the same control flow. This phenomenon increases the modulation capability of the motor.

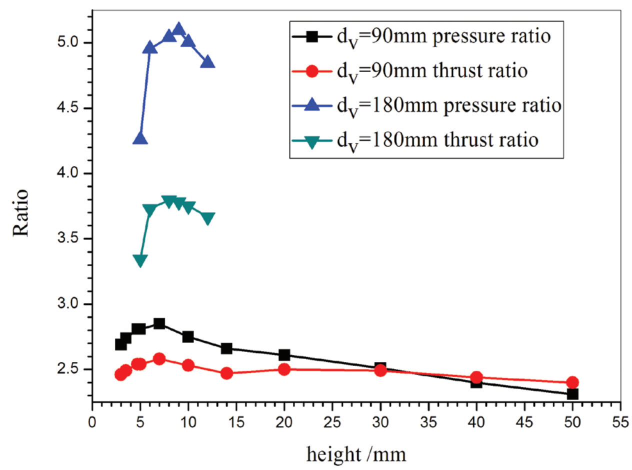

Figure 7: Influence of height on the thrust ratio and pressure ratio.

Influence research on vortex chamber height

The influence of vortex chamber height with varying diameters on modulation performance was also investigated. When the vortex chamber diameter is 90 mm, the control flow injector is 2-Φ2 mm. The control flow used during the calculation was nitrogen with a temperature of 293 K. When the vortex chamber diameter is 180 mm, the control flow injector is 2-Φ4 mm. The control flow used during the calculation is a gas with a temperature of 1,560 K. The control flow pressure and flow parameter used during the calculation are shown in Table 5. The calculated thrust ratio and pressure ratio using various working conditions are shown in Figure 7. The calculated mass flow rate ratio is shown in Figure 8.

Figure 7 shows that the thrust ratio and pressure ratio with two different diameters follow the same trend: the modulation ratio first increases, then decreases as the height is increased before reaching the maximum. The two maximum values of vortex valves are 7 mm for 90 mm and 9 mm for 180 mm. The diameter of the vortex chamber outlet is 14 mm when the vortex valve diameter is 90 mm, whereas the outlet diameter is 18 mm when the vortex valve diameter is 180 mm. Thus when the vortex chamber height and the outlet radius are half of the vortex chamber outlet diameter, the thrust ratio and pressure ratio of vortex valve reach maximum values. Figure 7 also shows that the modulation ratio for a vortex chamber diameter of 180 mm is much higher than that when the diameter of the vortex chamber is 90 mm.

Table 5: Influence of vortex chamber height on the mass flow rate of the control flow during numerical calculation.

Diameter/m						**90**
No.	**Case1**	**Case2**	**Case3**	**Case4**	**Case5**	**Case6**
Height/mm	3	3.5	4.7	5	7	10
Flow rate/kg/s	0.117	0.116	0.118	0.118	0.115	0.116
Total pressure/MPa	11.19	11.19	11.19	11.19	11.19	11.19
No.	**Case7**	**Case8**	**Case9**	**Case10**	**Case11**	
Height/mm	14	20	30	40	50	
Flow rate/kg/s	0.122	0.123	0.138	0.142	0.145	
Total pressure/MPa	11.19	11.19	11.19	11.19	11.19	
Diameter/mm						**180**
No.	**Case12**	**Case13**	**Case14**	**Case15**	**Case16**	**Case17**
Height/mm	5	6	8	9	10	12
Flow rate/kg/s	0.137	0.137	0.137	0.137	0.137	0.137
Pressure/MPa	16.43	19.02	17.55	17.89	17	16.49

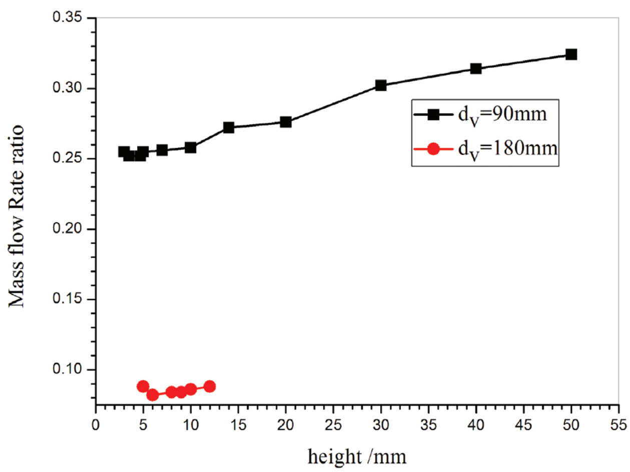

Figure 8: Influence of height on the mass flow rate ratio.

In addition, Table 5 shows that the control flow for two kinds of vortex valves is similar with a maximum error of 18%. The control flow pressure ratio of the vortex chamber with a diameter of 180 mm is higher by 5 MPa compared with that of a vortex valve with a diameter of 90 mm.

Figure 8 shows that the master motor gas mass flow rate of the control flow of the vortex chamber with a diameter of 90 mm increases after modulation. Figures 7 and 8 show that the modulation performance of the vortex chamber with a diameter of 180 mm is significantly higher than the vortex valve with a diameter of 90 mm, which indicates that the modulation performance of a vortex chamber with a hot gas control flow is higher than that with cold airflow conditioning control flow.

Conclusion

Numerical calculation was performed to investigate the influence of the chamber shape, diameter, and height of vortex valve of variable-thrust motors on modulation performance. The results obtained from the numerical calculations were verified using experimental results. The calculation results were consistent with the experimental results. The results indicate the following: the optimal modulation performance was achieved in a cylindrical cross-section of a vortex chamber, because this vortex chamber can concentrate energy, reduce dissipation; increasing the vortex chamber diameter can improve the modulation performance of the vortex valve variable-thrust motor, in the case of the same momentum, the moment of momentum increase as the vortex chamber diameter is increased, and the modulation capability is increased too; when the vortex chamber height is half of the vortex chamber outlet diameter, optimal modulation performance is achieved; and a hot gas control flow is used to achieve good modulation performance.

Nomenclature

$\dot{m}$	master motor mass flow rate
ρ_p	solid propellant density
A_p	propellant burning area
a	burning rate coefficient in the burning rate formula in exponential form
p_m	pressure in the master motor combustion chamber
n	burning rate pressure exponent
T_f	combustion chamber stagnation temperature
P_{m1}	pressure in the master motor combustion chamber before modulation
P_{m2}	pressure in the master motor combustion chamber after modulation
P_{cf}	pressure of the control flow
F_1	thrust before modulation
F_2	thrust after modulation
$\dot{m}_1$	master motor mass flow rate before modulation
$\dot{m}_2$	master motor mass flow rate after modulation
$\dot{m}_c$	mass flow rate of the control flow
d_v	diameter of the vortex chamber

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