Simulation Study on Flow Rate Regulation of Pasty Propellant in Lateral Extrusion Pipe

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Abstract-The resistance structure was introduced to design a new paste propellant lateral extrusion supply channel, and a Python script-controlled solution process based on CFD software was established to achieve the optimization design and optimization goals of the resistance structure.

1. Introduction
As a new type of adjustable energy device, the paste propellant engine has received attention from many countries. The United States, Russia, Ukraine, etc. are relatively mature in the research and application of paste propellants. They conducted a lot of experimental research and made substantial technological breakthroughs, and even reached the practical level[1].

Domestic research on the power system of pasty propellant began in the 1990s, and there have been certain results in the research of various key technologies. Many units, including Nanjing University of Science and Technology, Northwestern Polytechnical University, and Institute of Aeronautics, have conducted theoretical, experimental, and simulation research on paste propellant engine technology.[2-4]

Liang Cai[5] of Zhengzhou Institute of Mechanical and Electrical Engineering proposed a solid-paste propellant engine. Using solid gas generators as the propellant supply power source, compared with common electric cylinders, hydraulic cylinders, high-pressure gas sources, etc., it is easy to achieve miniaturization, reduce the demand for external energy, and improve the environmental adaptability of the equipment.
Figure 1. Schematic diagram of solid-paste engine.

The fuel supply channel is composed of several groups of monomer pipes, and each group of fuel supply pipe monomer presents a single-outlet and multiple-outlet lateral extrusion shape. The single pipeline structure is shown in Figure 2.

Figure 2. Supply pipeline schematic.

The pipeline structure from the inlet 3 to the outlet 4, 5, 6 is different, so the flow resistance is also different. This leads to different fuel supply rates at each outlet, which in turn leads to differences in the working conditions at each outlet. This paper uses simulation methods to study the improvement of the consistency of the propellant supply rate by changing the inner wall structure of the pipeline without changing the main structure of the pipeline.

2. Materials and Methods

2.1. Constitutive model

In the research of many scholars, the paste propellant is regarded as a power law fluid. Studies have shown that the description of the paste propellant in the power law model is sufficiently accurate, and its expression is [6]:

$$\eta = K\gamma^{n-1}$$

Where K is the fluid viscosity coefficient, the unit is Pa•s; n is a parameter that measures the deviation between the fluid and the Newtonian fluid, called the viscosity index, and its value determines the type of fluid; when n=1, it is a Newtonian fluid, and when n<1 it is a shear thinning fluid, n>1 is a shear thickening fluid, for paste propellant n<1; it is a shear rate, the unit is 1/s. Figure 3 shows the viscosity curve of a certain paste propellant, where K is 20000 and n is 0.45.
2.2. Analysis
Observing the pipeline structure in Figure 2 and studying the pressure curve of the laterally squeezed supply channel (Figure 4), it is not difficult to find that the resistance coefficients of the outlet channels are close, and the outlets are distributed along the axis of the main channel. There is a big difference in the resistance coefficient of the outlet, which causes a big difference in the flow rate of each outlet.

According to the split ratio, \( \frac{Q_1}{Q_2} > \frac{Q_2}{Q_3} \), a resistance structure is added to the first and second outlet passages to increase the total resistance of the passage, thereby changing the flow distribution ratio. The structure is shown in Figure 5. By optimizing the parameters of the two resistance structures, the same flow target for each outlet can be achieved.

2.3. Iterative solution
This problem is to find the optimal structural parameters of the resistance section, so that the flow of each outlet is as consistent as possible. The local resistance of the resistance result is positively
correlated with its height, that is, increasing the height of a resistance structure can reduce the outlet flow; at the same time, it can be known from the flow distribution law that reducing the flow of one of the outlets will cause the other two outlets to increase accordingly; vice versa. Rationale. Therefore, according to the flow distribution ratio of the current iteration step, the direction of change of the height of the two resistance structures can be easily determined. After analysis, it is concluded that the flow distribution change approximately satisfies the following linear relationship under the condition that the change range of structural parameters is small:

$$ -[A]^{-1}[\Delta h_i] = [\Delta \delta_{qi}] $$

(2)

Among them, $i=1, 2$; is the flow adjustment relationship matrix, which describes the relationship between the change in the height of the resistance node in a small range and the change in the flow distribution ratio; is the increment of; is the increment of the current outlet diversion ratio; minus sign Indicates that the direction of change is opposite. Construct the following iterative formula:

$$ [h_{i,n+1}] = [h_{i,n}] + [A][\delta_{qi,n}] $$

(3)

This relationship establishes the relationship between the new structural parameters and the current structural parameters and the process simulation results, and gives the predicted values of the structural parameters. Among them, $\delta_{qi} = \frac{Q_{out,i}}{Q_{in}} - \frac{1}{3}$ is the difference between the current outlet diversion ratio and the target diversion ratio.

The solution process is controlled by the Python script to control the flow direction and input and output. The CFD software is used for the flow field calculation and the flow field result statistical solution process. The Python script is used to control the flow direction and input and output, and the CFD software is used for the flow field calculation and flow field results. The statistical grid structure and grid are as shown.

Enter the inlet flow rate, give it, and use it as the initial value, write it into the simulation process and start iterative solution. After multiple iterations of optimization, a solution that satisfies the condition can be obtained. Set as the monitoring value of the iterative process, the maximum value is
set as the iterative characteristic value, if it is small enough, it is considered that the export consistency meets the requirements. The iteration stop condition is set as this condition can satisfy the maximum difference of each outlet flow not exceeding 0.002% of the inlet flow.

3. Results & Discussion

The calculation results of the flow field draw a cross-sectional cloud diagram as shown in the figure. Compare the velocity cloud diagram and streamline diagram before and after optimization. The changes mainly occur in the vicinity of the resistance structure and the corner. After optimization, the velocity contour near the resistance structure is closed at the center of the resistance node, where the maximum value appears here, and there is a gradient along the axis from the resistance node to the exit direction, and there is radial flow. Analyzing the optimized cloud map at the end of the outlet channel, its velocity distribution contours are parallel, indicating that the radial flow has gradually disappeared, and the flow field distribution near each outlet tends to the ideal circular pipe flow.

![Comparison of speed cloud images before and after optimization.](image)

**Figure 8.** Comparison of speed cloud images before and after optimization.

![Monitoring value and characteristic values.](image)

**Figure 9.** Iterative monitoring values and characteristic values.

The monitoring value and characteristic value of the iterative process are shown in Figure 9 a and b. The monitoring value of the iterative process is the difference between each flow distribution ratio and the target value, reflecting the magnitude and direction of the difference between each outlet flow and the target value; the iterative characteristic value is each The maximum value of the difference between the outlet flow rate and the target value. Under different input flow conditions, the solution convergence speed is basically the same.
4. Conclusions
In this paper, a new lateral extrusion supply channel for paste propellant is designed by introducing a resistance structure; a Python script is used to control the simulation solution process based on CFD software, and the optimization design of the resistance structure is realized; through this solution method, a multi-outlet type is realized. The flow rate of each outlet of the supply channel is adjusted, so that the flow difference of each outlet is rapidly reduced, and the result of meeting the expected goal can be obtained with fewer iteration steps. Of course, while this method improves the consistency of each outlet flow, there is also the problem that the total pressure loss of the entire supply channel has increased compared to before the improvement.

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