Study on Multi-Objective Simulation Optimization of Flow Characteristics of Solenoid Valve Injector

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Keywords: Solenoid valve injector, Static traffic, Dynamic flow range, Multi-objective optimization.

Abstract. A one-dimensional simulation model of AMESim solenoid valve injector was established. The key structural parameters of the injector were simulated and analyzed. The influence of structural parameters on the flow characteristics of the injector was analyzed. Based on the response surface test design method, Design-Expert software was used. The regression equations of static flow and dynamic flow range and key structural parameters are sought. The multi-objective simulation optimization design of key structural parameters of electronically controlled injectors is based on static flow and dynamic flow range. The multi-objective simulated annealing MOSA optimization algorithm was used as the optimization strategy. The optimized injector static flow increased by 2.3\% to 0.135L/min; the dynamic flow range increased by 6.1\% to 5.2.

Introduction

In the initial development stage of the solenoid valve injector, researchers often need to use the experimental design to produce injectors with many different parameters. Through a large number of tests, the performance data of the sample injectors are collected and the spray is summarized. According to the experimental data, the fuel injection law and characteristics of the oil injector are proposed. After a series of tests, the optimal solution is obtained\textsuperscript{[1-2]}\textsuperscript{.} This research method has a long development cycle and high cost, and is not suitable for the technical requirements of the rapidly developing automotive industry.

In this paper, a ball valve electromagnetic injector independently developed by a factory in Wenzhou is taken as the research object, and a one-dimensional simulation model of AMESim is established. Through simulation analysis, several key parameters are selected as the optimization parameters of the fuel injector structure parameters, based on the response surface test design. The regression equation of optimization target is sought. The multi-objective optimization model is established with the static flow and dynamic flow range as the objective function. The multi-objective simulated annealing MOSA algorithm is used as the optimization strategy to optimize the flow characteristics of the electromagnetic injector.

Establishment of Simulation Model of Electromagnetic Injector

The injector simulation object is a fuel injector independently developed by a factory in Wenzhou. The purpose of the injector is to synthesize various structural parameters of the injector and predict the performance of the injector to guide the production of domestic automobile injectors. To improve the fuel injection performance of the injector, the overall model is shown in Figure 1. However, whether the simulation model can achieve the intended guidance purposes depends on the test data for verification and calibration. Therefore, it is necessary to verify the correctness of the simulation model by testing the dynamic flow characteristics of the injector\textsuperscript{[3]}.  

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Figure 1. The overall model of the electromagnetic injector.

Figure 2 is a comparison diagram of the simulated dynamic flow rate of the injector and the dynamic flow rate obtained by the test when the injection pressure is 300 kPa, and Figure 3 is a comparison of the static flow rate under each injection pressure.

Figure 2. Dynamic flow comparison chart when the injection pressure is 300kPa.

Figure 3. Comparison of static flow rates under different injection pressures.

It can be seen from the comparison curves of Figure 2 and Figure 3 that the one-dimensional model of the injector obtained by simulation using AMESim, whether in the unit pulse width or the static flow rate, under different control injection pressures, The simulation results and the test results are basically the same, and both increase linearly. From the comparison results, although there is a certain error, the error is stable in the range of 5% to 10%, which is in line with the error range allowed by the project, so the accuracy of the injector model is verified.

In summary, the one-dimensional simulation model of the injector built by AMESim has been verified by experiments. The simulation calculation error is within the engineering allowable range, and the calculation accuracy of the model meets the optimization requirements. The model can be used to analyze the injector flow characteristics. And the simulation work of the fuel injector structural parameter optimization.
Optimization Target Regression Equation

Response Surface Test Design

According to the optimization parameters selected by the parameter analysis results, three horizontal levels of the maximum stroke of the ball valve, the mass of the ball valve assembly, the preload of the ball valve spring, and the total area of the injection hole are respectively set within the allowable range of the production capacity. Therefore, the four-factor three-level response surface design scheme is used for the simulation test. The influencing factors and levels of the test are shown in Table 1.

Table 1. Test factors and levels.

| Levels | Test factors                          |
|--------|--------------------------------------|
| 1      | ball valve maximum lift /mm | 0.06 | 0.5 | 2 | 0.18 |
| 2      | ball valve assembly quality /g     | 0.11 | 1.5 | 3 | 0.75 |
| 3      | spring preload /N                 | 0.16 | 2.5 | 4 | 1.32 |
| 4      | total orifice area /mm²            |      |      |   |      |

In this paper, the Design-expert software is used to design the test based on the BBD test design method. Input the fuel injector parameters in the test design table into the AMESim model, obtain the test results, and record the test values. The final result is shown in Figure 4.

Regression Analysis

The ANOVA function in the software is used to fit the static flow data and the dynamic flow range data obtained from the simulation test, and the maximum and minimum values of the 95% confidence
interval parameter estimation values are averaged as the coefficient of the final regression equation parameter estimation.

Further verifying the accuracy of the regression model, it is also necessary to compare the actual value with the predicted value according to the inherent residual distribution, as shown in Figure 5 and Figure 6. In the figure, the abscissa and the ordinate represent the predicted value and the actual value respectively. The closer the scatter distribution is to the straight line, the better the consistency between the predicted value and the actual value. The points in the graph are basically distributed around the straight line, indicating static flow and dynamic flow. The regression prediction is reliable.

![Figure 5](image1.png)  ![Figure 6](image2.png)

**Figure 5.** Comparison of the predicted and residual residual values of static traffic.  **Figure 6.** Comparison of residual residuals and actual values in the dynamic flow range.

### Multi-objective Parameter Optimization based on MOSA Algorithm

The regression equations obtained from the experimental design were solved and verified using the genetic algorithm toolbox in MATLAB software\(^5\-\)\(^6\). The optimized solution set data is displayed in a graphical form, as shown in Figure 7.

![Figure 7](image3.png)

**Figure 7.** Multi-objective optimization Pareto frontier.

In Figure 7, point B is the optimization parameter design point of static flow, and point C is the optimization parameter design point of dynamic flow range. In order to achieve the better overall design requirements of the flow characteristics, the point A closest to the origin is selected as the optimal solution for this optimization. Table 2 lists the design parameters before and after optimization. Table 3 shows the values of the static flow and dynamic flow range before and after optimization.
Table 2. Parameters before and after optimization.

| aims                         | ball valve maximum lift/mm | ball valve assembly quality/g | spring preload/N | Total orifice area/mm² |
|------------------------------|-----------------------------|------------------------------|-----------------|------------------------|
| before optimization          | 0.08                        | 1.5                          | 3               | 0.8                    |
| after optimization           | 0.072                       | 0.55                         | 3.635           | 0.5                    |

Table 3. Multi-objective optimization results.

| aims                         | static traffic /L • min⁻¹ | dynamic flow range |
|------------------------------|-----------------------------|--------------------|
| before optimization          | 0.132                       | 4.9                |
| after optimization           | 0.135                       | 5.2                |
| degree of improvement        | 2.3%                        | 6.1%               |

Conclusion

1) Taking the electromagnetic injector produced by a factory in Wenzhou as the research object, the AMESim simulation software is used to physically model the electromagnetic injector to prepare for the in-depth study of the flow characteristics of the electromagnetic injector.

2) Using the Design-expert software to design the surface response test, the regression equations of static flow and dynamic flow range are established, which lays a foundation for optimizing the performance of the injector.

3) Using the multi-objective simulated annealing algorithm MOSA in MATLAB to optimize the flow characteristics of the gasoline injector electromagnetic injector, the experimental results show that the static flow rate is increased by 2.3% and the dynamic flow range is increased by 6.1%.

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