Structure Optimization of Natural Gas Engine’s Intake Pipe Based on One-Dimensional and Three-Dimensional Coupled Simulation

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Abstract. A one-dimensional and three-dimensional coupled simulation model of a natural gas engine was established by using GT-POWER and FLUENT software based on the one-dimensional and three-dimensional coupling simulation method, and the structure of the intake pipe pressure-stabilized cavity was optimized by numerical simulation. Firstly, the veracity of the above model was verified according to the engine bench test results. Then, the average intake air flow and non-uniformity of intake air at different engine speeds were simulated and analyzed by using the above model. According to the simulation results, a multi-objective optimization model was established, and a single objective evaluation function was established by using the linear weighted sum method. The results show that when the inclination angle of the stabilized cavity is 15 degrees, the comprehensive intake capacity of the intake pipe will get the best. In which the average intake air flow rate is increased by 4.3%, and the maximum air inlet non-uniformity is reduced by 10.98% compared with the original machine.

Keywords: natural gas engine, structure of pressure-stabilized cavity, one-three dimensional coupled simulation, multi-objective optimization.

1. Introduction

The natural gas has the outstanding advantages of rich resources, lower price and less pollution, which is favored by people and plays an important role in the energy consumption structure of the world [1]. Natural gas engine uses the natural gas as the fuel, which has high economic and social benefits. Intake pipe is one of the main components of natural gas engine. Its main function is to provide uniform and stable intake air for the engine. If the volume of intake pipe pressure-stabilized cavity is not big enough, then the fuel and air will not be mixed sufficiently, and the combustion quality or the power density of the engine will be decreased. Besides, unevenness of intake air will cause unstable torque output, engine vibration and emission deterioration [2]. Therefore, reasonable design of intake pipe can not only reduce intake pressure loss, increase intake flow rate, but can also ensure the air intake uniformity of each cylinder. It is one of the key technologies to ensure engine power, economy, reliability and emission quality [3].
Many scholars have done a lot of work in improving the engine intake system, and studied the influence of different factors on the flow characteristics of the engine intake pipe. W. Du et al. built an one-dimensional simulation model of a multi-cylinder diesel engine to analyze the influence of engine load, rotating speed and ignition sequence on the intake flow rate and intake inhomogeneity of each cylinder [4-5]. H. Wang et al. built a three-dimensional numerical simulation model based on the software of FLUENT, and analyzed the influence of intake pipe installation position on the air intake inhomogeneity of each cylinder [6]. Nowadays, one-dimensional and three-dimensional coupled simulation has been proved to be an effective simulation method, it do not only have the high efficiency of one-dimensional simulation, but also have the accuracy of three-dimensional simulation [7]. W. Du et al. compared the intake inhomogeneity of two different intake pipes based on the one-dimensional and three-dimensional coupled simulation, and analyzed the causes of different intake inhomogeneities [8]. M. H. Ye and L. Huang constructed an one-dimensional and three-dimensional coupled simulation model based on the software of BOOST and FIRE. Based on the model, the flow resistance and uniformity of intake manifold were analyzed, the length and valve phase of the intake manifold were optimized [9]. Y. E. Yin and F. Z. Ji built an one-dimensional and three-dimensional coupled simulation model by using the software of STAR-CD and GT-POWER. Based on the model, the effects of pressure-stabilized cavity volume and inlet direction on the flow were analyzed [10-11].

Nowadays, the influence of pressure-stabilized cavity’s inclination angle on the engine intake performance has not been studied. In this paper, a one-dimensional and three-dimensional coupled simulation model of an in-line six-cylinder natural gas engine was established. Seven kinds of intake pipes with different pressure-stabilized cavity’s inclination angles were simulated, and the outlet flow of each manifold and the inhomogeneity of each cylinder were compared under five different engine speeds. Finally, a suitable evaluation function was established by using the multi-objective optimization algorithm, and the inclination angle of the pressure-stabilized cavity was optimized.

2. Research objects and methods

2.1. Research objects

The main technical parameters of the engine are shown in Table 1, and the structure of engine intake pipe which is studied in this paper is shown in Figure 1. The intake pipe is mainly composed of three parts, which is named as the intake main pipe, the pressure-stabilized cavity and the intake manifold. The original intake pipe’s inclination angle of the pressure-stabilized cavity is 5°. In order to study the effect of pressure-stabilized cavity’s inclination angle on the engine intake performance, seven kinds of intake pipes, whose pressure-stabilized cavity’s inclination angle is 0°, 5°, 10°, 15°, 20°, 25° and 30°, are established. During the simulation, because the pipe temperature is not very high during the intake process, so the stress deformation of the inlet pipe due to the temperature change is not considered. In this paper, only the gas basin in the intake pipe, that is, the inner cavity of the intake pipe, is calculated. The intratracheal cavity of the original machine is shown in Figure 2. In the process of modeling, the method of control variates is used to make sure the total volume of the pressure-stabilized cavity remains the same when the angle changed. The inlet pipe geometry model of other structures is no longer displayed due to the layout limitation.

| Items             | Parameters                   |
|-------------------|------------------------------|
| Engine type       | In line six cylinder turbocharging |
| Bore/mm           | 128                          |
| Stroke/mm         | 155                          |
| Compression Ratio | 11.5                         |
| Firing order      | 1-5-3-6-2-4                  |
| Displacement/L    | 12                           |
| Power/kw          | 312                          |
| Speed/(r·min⁻¹)   | 2100                         |
In the simulation, the quantity and quality of the grid directly affect the efficiency and accuracy of the calculation results. Therefore, the method of grid sensitivity was used to analyze the influence of grid size. In this paper, four different basic grid sizes were applied for meshing, and the outlet flow of intake manifold was simulated at the speed of 1400 r/min. The results, including the average outlet flow and the computing time, were shown in Table 2. From the table we can see, after the scheme 2, the decrease of basic grid size do not have significant effect on the simulation results, but obviously increased the total number of grids. The increasing number of grids will greatly increase the calculation time and lead to computing resources waste. Therefore, considering the calculation accuracy and simulation time, scheme 2 was chosen as the basic grid size.

| Scheme | Grid number | Rate of outlet/(kg·h⁻¹) | Computing time/h |
|--------|-------------|-------------------------|-----------------|
| 1      | 78,543      | 194.2                   | 0.8             |
| 2      | 121,383     | 195.9                   | 1.7             |
| 3      | 213,669     | 196.5                   | 3.6             |
| 4      | 359,136     | 196.8                   | 5.8             |

In this paper, the three-dimensional geometry is constructed by the software of SOLIDWORKS, the geometry is meshed by the software of HYPERMESH, and finite element model is constructed by the software of FLUENT. The mesh model of the intake pipe with the inclination angle of 20° is shown in Figure 4, where the tetrahedral mesh is used to divide the inner cavity. The grid refinement is adopted at the connection between the pressure-stabilized cavity and each intake manifold, and the grid of the boundary layer near the wall is divided into three layers.

According to the main performance and structural parameters of the natural gas engine, the natural gas engine was simplified into a system consisting of an air inlet system, a combustion system, an oil injection system, an exhaust system, an environmental boundary and a corresponding connecting...
pipeline. The complete simulation model of natural gas engine constructed by the GT-POWER and FLUENT is shown in Figure 4.

![Figure 4](image-url)

**Figure 4.** One-dimensional and three-dimensional coupled simulation model.

In order to verify the accuracy of the model, the engine bench test was carried out. The comparison of in-cylinder pressure under the standard working condition between the test and the simulation was shown in Figure 5. The diagram shows that the test and simulation curves are basically consistent, and the maximum error is within 2%. Therefore, it can be considered that the simulation model has high reliability and can accurately simulate the actual working process of the engine.

![Figure 5](image-url)

**Figure 5.** In-cylinder pressure check curve.

2.2. Research method

In this paper, the one-dimensional and three-dimensional coupled method was used to simulate the intake performance of different pipe structures. The results of one-dimensional calculation (such as temperature, velocity, pressure, etc.) were provided as boundary conditions for the three-dimensional model through the one-dimensional and three-dimensional interface. Besides, k-ε turbulence model was used in the three-dimensional simulation, and the turbulence intensity was set as 0.01 and the turbulence scale was set as 0.1.

In this paper, the purpose of structure optimization is to maximize the average intake flow and minimize the intake nonuniformity. Therefore, a multi-objective optimization model was established based on the simulation results, and the optimal inclination angle of the pressure-stabilized cavity was calculated. The process of intake pipe optimization based on the one-dimensional and three-dimensional coupled simulation is shown in Figure 6.
Engine bench test  
Model Verification  
GT-Power Model  
Fluent CFD Model  
1D-3D Coupling calculation  
Analysis of simulation results  
Establishment of evaluation function  
Come to conclusion

Figure 6. Flow chart of intake pipe optimization.

3. Results and analysis
Based on the one-dimensional and three-dimensional coupled simulation model, the intake performance of seven pressure-stabilized cavity with different inclination angles were calculated under the speed of 800 r/min, 1100 r/min, 1400 r/min, 1700 r/min and 2000 r/min. The simulation time step was set to be a crankshaft angle, and the intake flow was obtained by integrating the mass flow of each manifold according to the crankshaft angle. The results are shown in table 3. Intake nonuniformity is used to evaluate the intake nonuniformity of each cylinder. The calculation method is shown in Formula (1) and Formula (2).

\[ Q_m = \frac{\sum_{i=1}^{N} Q_i}{N} \quad (1) \]

\[ \sigma = \frac{Q_{\text{max}} - Q_{\text{min}}}{Q_m} \quad (2) \]

In the formula, \( Q_m \) is the average outlet flow of 6 manifolds, \( N \) is the number of manifolds, \( Q_i \) is the outlet flow of the \( i \)-th manifold, \( Q_{\text{max}} \) is the maximum outlet flow of all manifolds, and \( Q_{\text{min}} \) is the minimum outlet flow of all manifolds. Table 3 shows the average outlet flow of the intake pipe with different pressure-stabilized cavity’s inclination angles at the speed of 800 r/min, 1100 r/min, 1400 r/min, 1700 r/min and 2000 r/min. And the letters of A, B, C, D, E, F and G respectively represent the pressure-stabilized cavity with an inclination angle of 0°, 5°, 10°15°, 20°, 25°, 30°.

Table 3. Average mass flow at the outlet of each manifold of different intake pipes at different speeds.

| Engine speed/(r/min) | Average Mass Flow Rate of Intake Manifold/(kg·h⁻¹) |
|----------------------|---------------------------------------------------|
| 800                  | A=114.2 B=114.3 C=114.5 D=114.9                  |
|                      | E=114.3 F=114.3 G=114.4                           |
| 1100                 | A=155.7 B=155.4 C=155.9 D=156.5                   |
|                      | E=155.8 F=155.8 G=155.6                           |
| 1400                 | A=196.7 B=196.9 C=196.9 D=197.9                   |
|                      | E=197.0 F=196.8 G=196.5                           |
| 1700                 | A=234.5 B=235.1 C=235.4 D=236.1                    |
|                      | E=235.6 F=235.2 G=235.3                           |
| 2000                 | A=276.0 B=276.5 C=276.9 D=277.7                    |
|                      | E=276.2 F=276.8 G=276.3                           |
The data in the Table 3 shows that at the same speed, the average mass flow rate at the outlet do not change significantly with the change of pressure-stabilized cavity’s inclination angle. But when the speed increased, the average mass flow will be increased synchronously.

It can be seen from the above that the maximum intake air flow difference of the intake manifold was defined as $\Delta Q = Q_{\text{max}} - Q_{\text{min}}$. The larger $\Delta Q$ is, the greater unevenness of the intake pipe is. The maximum outlet flow difference of seven intake pipes at different speeds were shown in Figure 7. It can be seen from the figure that, at the same speed, when the inclination angle increased, the outlet flow difference trends to decrease first but then increase. The minimum difference will be got at the inclination angle of 15 °, and the data is 3, 5.5, 7.9, 10.3, 12.6 kg/h⁻¹ at the speed of 800 r/min, 1100 r/min, 1400 r/min, 1700 r/min, and 2000 r/min. Besides, the maximum outlet flow difference will be increased with the increase of engine speed.

Figure 7. Maximum intake flow difference.

Figure 8 shows the intake non-uniformity of the intake pipe with different inclination angles of pressure-stabilized cavity at different engine speeds. It can be seen from the figure that the intake non-uniformity at the same speed decreases at first and then increases with the increase of the inclination angle, and reaches the minimum when the inclination angle of the pressure-stabilized cavity is 15 °. The minimum intake non-uniformity of 800 r/min, 1100 r/min, 1400 r/min, 1700 r/min, 2000 r/min corresponding to 2.61, 3.51, 4.0, 4.35, 4.54, %, respectively. Besides, the non-uniformity of air intake increases with the increase of rotating speed.

Figure 8. Intake non-uniformity statistics.
4. Multi objective optimization algorithm

4.1. Model for multi objective optimization of inclination angle of the stabilized cavity

The multi-objective optimization mathematical model of the pressure-stabilized cavity’s inclination angle can be expressed as follows.

\[ Q_m = f_1(\theta) \]  
\[ \sigma = f_2(\theta) \]  
\[ \begin{align*} 
    \max f_i(\theta), & \quad \max f_i(\theta) \\
    \min f_i(\theta), & \quad \max(-f_i(\theta)) \\
    \theta_{\text{min}} < \theta < \theta_{\text{max}} & \Rightarrow \theta_{\text{min}} < \theta < \theta_{\text{max}}
\end{align*} \]  

The minimum value of non-uniformity \( \sigma \) can be converted into the maximum value of its inverse function. \( \theta_{\text{min}} \) and \( \theta_{\text{max}} \) determine the solution domain of the optimization problem and represent the minimum and maximum inclination angles of the stabilized cavity in multi-objective optimization, respectively.

4.2. Linear weighting method for solving multi objective optimization problems

According to the importance of objective \( f_i(\theta) \) \((i = 1, 2, 3, \ldots, k)\), the weight coefficients of \( \lambda_i \) \((i = 1, 2, 3, \ldots, k)\) were determined, and the objective evaluation function was established by summing up the product of \( f_i(\theta) \) and \( \lambda_i \). In order to get the optimal inclination angle of pressure-stabilized cavity, the single objective problem was constructed [12-13].

\[ \begin{align*} 
    \max h(f(\theta)) &= \sum_{i=1}^{k} \lambda_i f_i(\theta) = \lambda^T f(\theta) \\
    \theta_{\text{min}} < \theta < \theta_{\text{max}}
\end{align*} \]  

In the formula, \( f(\theta) = (f_1(\theta), \ldots, f_k(\theta)) \) is the each target function vector, and \( \lambda = (\lambda_1, \lambda_2, \ldots, \lambda_k)^T \in \Omega \), \( \Omega = \{ \lambda = (\lambda_1, \lambda_2, \ldots, \lambda_k)^T \mid \lambda_i > 0 \text{ and } \sum_{i=1}^{k} \lambda_i = 1 \} \).

How to determine the weight coefficient reasonably is the key to solve the linear weighting method. Generally, the weight coefficient \( \lambda_i \) is allocated according to the importance of different objective functions \( f(x) \). The more important \( f(x) \), the greater the corresponding \( \lambda_i \). There is no fixed criterion for determining the weight coefficient [14]. In this paper, the importance of average intake flow and intake nonuniformity were thought to be the same, that is, the weight coefficients of these two objective functions were set to be the same.

4.3. Establishment of evaluation function

Based on the above formulas, the following evaluation function was established by using the linear weighting method.

\[ h(f(x)) = \sum_{i=1}^{k} \lambda_i \frac{(f_i(x) - f_{i_{\text{min}}})}{(f_{i_{\text{max}}} - f_{i_{\text{min}}})} \]  

In the formula, \( \lambda_i \) is the weight coefficient of each objective function; \( f_{i_{\text{min}}} \) and \( f_{i_{\text{max}}} \) are the minimum and maximum values of each objective function, respectively. Thus, the multi objective optimization problem is normalized into the following single objective optimization problem.

\[ \max h(f(x)) = \sum_{i=1}^{k} \lambda_i \frac{(f_i(x) - f_{i_{\text{min}}})}{(f_{i_{\text{max}}} - f_{i_{\text{min}}})} \]
Figure 9 shows the corresponding evaluation function results of intake pipes with different pressure-stabilized cavity’s inclination angles at different engine speeds. From the evaluation function established above, it can be seen that the larger the value of evaluation function, the better the comprehensive intake performance of intake pipes. From the figure 9, it can be seen that when the inclination angle is 15 °, the evaluation function reaches its maximum value at all different speeds. Therefore, when the inclination angle of pressure-stabilized cavity is 15 °, the comprehensive intake performance of the intake pipe is the best.

![Figure 9. Results of evaluation function analysis.](image)

5. Conclusion
The one-dimensional and three-dimensional coupled simulation method can accurately simulate the engine working process, and is helpful to optimize the structure of pressure-stabilized cavity. In this paper, seven kinds of intake pipes with different pressure-stabilized cavity’s inclination angles were calculated and analyzed based on the one-dimensional and three-dimensional coupled simulation method at different speeds. The results show that when the inclination angle of pressure-stabilized cavity is 15 °, the intake performance of the intake pipe will get the best: the average intake air flow rate will be increased by 4.3%, and the maximum air inlet non-uniformity will be reduced by 10.98% compared with the original structure under the standard working condition. All in all, the research on the inclination angle of the pressure-stabilized cavity fills up the gap in this field and has certain engineering research value.

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