Design and optimization of air intake system based on FSC

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Abstract. Based on the requirements of Formula Student China racing rules, the maximum diameter of the restrictor valve is 20mm in the intake system. In order to improve the engine charge coefficient and reduce the impact on performance caused by uneven air intake of each cylinder, it is quite necessary to redesign and analyse the air intake system under. Firstly, we calculate the volume of the pressure stabilizing chamber and the length of the intake manifold applied theoretical knowledge. Secondly, we redesign the model of intake system using UG software, which includes the parameter of the throttle angles for inlet and outlet, the intake manifold length, the volume of the pressure stabilizing chamber. By comparing and analysing the different data of inlet-outlet angles for the restrictor valve and the height of the baffle located in the stabilizing chamber, we can came to a conclusion after using CFD software that it is the optimal value when the inlet angle for throttle is 14 degree, the outlet angle is 22 degree and the height of the baffle is 10mm, the intake unevenness of each cylinder is 1.4%, and the total intake air is increased by 5.5%.

1. Introduction

The Formula Student China (FSC is called for short, same as below) is a racing competition participated by teams of students from Chinese colleges and universities majoring in automotive and automotive related majors, which requires them to independently design, process and assemble a racing car by themselves. The FSC racing rules require all the intake airflow into the engine must flow through a restrictor valve which is set at the diameter of throttle less than 20mm. In this paper, we use UG to design new air intake system for the new vehicle of FSC of Guilin University of Aerospace Technology. After that we perform CFD simulation on the model by using the Fluent software. We mainly engage in the research which is the structural parameter design and optimization analysis for the inlet-outlet angle of restrictor valve and the height of the baffle, so that to the purpose the uniformity of the intake air of each cylinder, and the charge coefficient is further improved to achieve the purpose of improving engine performance.

2. FSC racing air intake system

Because the driving direction of the car is inconsistent with the direction of air flow, at the same time consider the problems of uniformity of air intake and uniform force, the intake system of this engine adopts the arrangement of front intake. Use UG software to complete the design of the air intake system, including: air cleaner, throttle, intake manifold, pressure regulator chamber, intake manifold and other geometric models, As shown in Figure 1.
2.1. Air intake system structure design

The design of air intake system for the FSC racing mainly includes the design of the inlet-outlet angle for restrictor valve, the determination of the volume of the pressure stabilizing chamber, the design of the intake manifold length. The structure of the restrictor valve is similar to the structure of the venturi tube. In order to understand the structure of the inlet-outlet restrictor valve, it can be divided into some parts, which include cylindrical section, tapered section, throat section and gradually expanded section, As shown in Figure 2. This article focuses on the angle parameter of the tapering and expanding segments that cause huge throttling losses. We can use the Mesh module in Workbench to mesh the intake manifold and import the finite element mesh file into Fluent for numerical simulation calculation. The optimal value is selected after performing multiple sets of simulation analysis on the intake manifold by controlling a single variable.

2.2. Simulation analysis of intake manifold

The FSC racing competition rules require that the intake system needs to be equipped with a 20mm diameter restrictor valve behind the throttle. Therefore, the change of the geometric diffusion shape before and after the intake manifold has a great influence on the gas flow and the charge coefficient. Refer to previous design data, the structural parameters of the intake manifold are initially determined as follows: the inlet diameter as 28mm which is determined by the outlet diameter of the throttle valve, the length of the cylinder section as 20mm, length of tapered angle as 21.5, angle of tapered angle as 22°, length of restrictor valve as 5mm, length of tapered section as 213.5mm, total length: 260mm. We conduct a comparative analysis, mainly about the intake pressure, flow rate and outlet mass flow at different angles of the diffusion angles for the degree 6°, 7°, 8°.

2.3. Boundary condition setting

Since the analyzed air is considered as compressible fluid, the gas is easily converted from laminar flow to turbulent flow, so we do the simulation analysis using turbulence model as analysis mode. The pressure inlet is used as the inlet boundary condition, be set to an atmospheric pressure (101325Pa), the pressure outlet is used as the outlet boundary condition, be set to 97870Pa. The calculation process is using SIMPLE algorithm based on the pressure solver.
Figure 3. Pressure cloud and Velocity cloud at a diffusion angle of 6°

Figure 4. Pressure cloud and Velocity cloud at a diffusion angle of 7°

Figure 5. Pressure cloud at a diffusion angle of 8°

Table 1. Pressure cloud and Velocity cloud at different diffusion angle

| Diffusion Angle (°) | Lowest Pressure (×10^4 Pa) | Maximum Velocity (×10^-2 m/s) |
|---------------------|-----------------------------|-------------------------------|
| 6°                  | 7.34                        | 2.068                         |
| 7°                  | 7.133                       | 2.134                         |
| 8°                  | 7.01                        | 2.179                         |

At the same time, the mass flow rate at the outlet of the diffuser at 6°, 7° and 8° of the intake manifold was monitored, as shown in Table 2.

Table 2. Mass flow rate corresponding to the diffusion angle of each intake manifold

| Diffusion Angle (°) | Mass Flow at the Outlet of the Intake Manifold (g/s) |
|---------------------|-----------------------------------------------------|
| 6°                  | 73.36 g/s                                           |
| 7°                  | 76.71 g/s                                           |
| 8°                  | 75.33 g/s                                           |

By comparing the pressure cloud diagram and velocity cloud diagram corresponding to the three different expansion angles of 6°, 7° and 8°, it can be seen from Table 1 that when the divergence angle is 7°, the mass flow is the largest, and the diffusion angle is finally determined to be 7°. The structure parameters of the intake manifold are finally determined as follows: the inlet diameter is determined by the outlet diameter of the throttle valve as 28mm, the length of the cylinder section as 20mm, the tapered angle length as 21.5, the tapered angle as 22°, the restrictor valve length as 5mm, length of gradually expanding section as 213.5mm. The taper angle 7°, the total length as 260mm.

The volume of the pressure stabilizing cavity will also affect the intake air volume. According to other paper, the volume of the pressure stabilizing chamber is generally 5~5.5 times of the total displacement of the engine. The displacement of the CBR600 engine is 0.6 L, the volume of the pressure stabilizing chamber is determined to be 3 L.
3. Determination of intake manifold structure parameters

After we make sure the pressure-retaining cavity of a certain volume, we should determine the length and diameter of the intake manifold. In order to increase the intake air volume, we can use the gas's wave effect and inertial effect to generate large value pressure wave at specific speed stage. The calculation of the length of the intake manifold is based on the fluctuation effect.

\[ q = \frac{30 \times c}{n \times L} \]

After calculation, the tube length is finally determined to be 270mm. Since the calculated intake manifold length \( L \) includes the engine intake port length, the CBR600 intake port length is 110mm, the original engine throttle length is 75mm, and the final intake manifold length is

\[ L = 270 - 110 - 75 = 95 \text{mm} \]

According to the above calculation data, the structural parameters of the engine after intake air flow limitation are as follows.

| Structure name                                      | Numerical value |
|----------------------------------------------------|-----------------|
| Intake (mm)                                        | 260             |
| Inner diameter of the inlet of the restrictor valve (mm) | 28              |
| Tapered angle (°)                                  | 22°             |
| Length (mm)                                        | 21.5            |
| Taper angle (°)                                    | 14°             |
| Length (mm)                                        | 213.5           |
| Regulator chamber (L)                              | 3               |
| Intake manifold (mm)                               | 95              |

4. Three-dimensional model of the intake system

According to the above simulation analysis and calculation results, the three-dimensional model of the intake system is established using the UG three-dimensional modeling software. And by designing two baffles at the inlet of the intake manifold of the 2 and 3 cylinders, diversion of the regulated internal airflow through the adjustment of the height of the baffle to achieve the effect of uniformity of each cylinder, As shown in Figure 6.

(a) Front view of restricted-flow intake system   (b) Side view of restricted-flow intake system

![Figure 6. Three-dimensional drawing of the structure of a restricted-flow intake system](image)

We use the pressure inlet as the inlet boundary condition, set the inlet pressure to an atmosphere (101325Pa). The pressure outlet is used as the outlet boundary condition, set the outlet pressure as 88000 Pa, the outlet temperature is set to 301.45K (Corresponding to 28.3 degrees Celsius), the intake system wall adopts a non-slip boundary condition, and the temperature of wall is set to 301.45K too. The calculation process is based on the pressure solver, we use SIMPLE algorithm as the calculation method.
Figure 7. Vector line and mass flow chart with baffle height of 25mm

Figure 8. Vector line and mass flow chart with baffle height of 20mm

Figure 9. Vector line and mass flow chart with baffle height of 10mm

Table 4. Comparison table of mass flow rate at different baffle heights

| Baffle Height (mm) | Each Cylinder Mass Flow (g/s) | Unevenness (%) |
|-------------------|-------------------------------|----------------|
|                   | No.1  | No.2  | No.3  | No.4  |                |
| 25 (a)            | 36.46 | 39.51 | 39.38 | 36.86 | 8              |
| 20 (b)            | 36.74 | 39.29 | 38.89 | 37.02 | 6.7            |
| 10 (c)            | 40.02 | 40.47 | 39.9  | 40.82 | 1.4            |

As it can be seen from Figure 7(a), 8(a) and 9(a), when the airflow flows along the wall surface of the pressure stabilizing chamber through the baffles with a height of 25mm, 20mm and 15mm, the baffles can prevent the airflow from flowing directly into the cylinders 2, 3. It can be seen from Table 4 that when the height of the baffle is 25mm, the intake unevenness of each cylinder reaches 8.0%. When the height of the baffle is reduced to 20mm, the intake unevenness of each cylinder of the engine reaches 6.7%. Compared with the (a) model, the total intake air has increased by 0.21%. When the height of the baffle is reduced to 10mm, the intake unevenness of each engine cylinder reaches 1.4%, and the total intake air is increased to 5.5%. Under the premise of the requirements ensuring, the intake air volume of the engine is greatly improved, the purpose of increasing the charge coefficient is achieved.

5. Conclusion
First, in this paper, after comparing the flow field changes of multiple groups of inlet manifolds with the size of the outlet mass flow, which is calculated Numerical Simulation through Fluent, the inlet manifold with a taper angle of 7° and outlet mass flow of 76.71 g/s is selected. Second, from the numerical
simulation analysis, it can be seen when the height of the baffle is 10mm, the pressure distribution of the four manifolds is balanced, the intake unevenness of each cylinder reduce to 1.4%, the internal flow resistance of the air intake system is also reduced, the total intake air is increased by 5.5%, and the charge coefficient is significantly improved.

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