Study on Separation Characteristics of Dust and Droplet on Air Intake Pre-filtration Systems of CV Based on CFD Simulation and Test

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Abstract. In order to the problem of short life of air filter in intake system due to the harsh working conditions of commercial vehicles(CV), the computational fluid dynamics (CFD) method was used to simulate the velocity flow field of the three high inlet pipe assemblies, and the velocity cloud of different vortex fan angle were obtained. These velocity cloud diagram proves that the velocity gradient is caused by the angle of the vortex fan, and the velocity gradient can coarsely separate the dust, droplet and gas. The rack experiment method was adopted for the three high inlet pipe assemblies to evaluate its the pre-filtration performance. The test results show that the vortex fan at the front end of the tube plays a good role in the pre-filtration of dusts and droplets. And the pre-filtration efficiency reaches over 87%. Effectively extend the life of the air filter element.

Introduction

Air intake system is one of the most important parts of automobile. Its main function is to provide clean, sufficient, dry, moderate temperature air for the engine, to meet the engine fuel combustion requirements [1]. In the air intake system, the high inlet pipe (also known as the air intake pre-filtration Systems) mainly includes the vortex pipe, the dust and droplet drain valve, the shock absorption bellows, and the assembly pipeline with four parts of the transition pipe. Its main function is to lead the air from the height of the car body to the air filter, which has the high efficiency of prefiltration[2]. The efficiency of prefiltration of dust and droplet is more than 80%. The intake performance of the high inlet pipe includes the characteristics of intake resistance, intake air flow, the efficiency of pre-filtration dust and droplet, ash capacity, turbulence and velocity distribution, etc. However, the efficiency of pre-filtration dust and droplet has a direct impact on the life of the Primary filter, and also has a certain effect on the engine power and life [1, 2].

Because of the complexity of the air intake characteristics, many commercial vehicle manufacturers design the high inlet pipe assembly according to the test or imitation of the standard domestic and foreign famous enterprises, and seldom carry out deep and thorough research on the mechanism. With the wide application of computer simulation technology in engineering field, it is also an important method to optimize the design of high inlet pipe assembly by means of computational fluid dynamics (CFD) and experimental analysis. Chu [3] has studied the air filter by using the method of combining experiment and simulation, and obtained the air intake characteristic of the air filter. Professor Hao Zhiyong of Zhejiang University [4] and his students mainly studied the acoustic performance of the inlet and filter, and obtained the parameters that affect the acoustic performance. Tang Lianhua [5] has studied the separation characteristics of droplets in the inlet of commercial vehicle air filter, and obtained the structural parameters that affect the separation of inlet droplets. However, these studies mainly focus on the acoustic characteristics and droplet-gas separation characteristics of inlet and air filter. At present, there are few papers on the experimental analysis and numerical simulation of the dust-droplet-gas multi-physical flow field in the intake system of commercial vehicles.
In this paper, aiming at the problem of short life of air filter in intake air system due to the bad working conditions of a commercial vehicle. The flow field simulation of high inlet pipe is carried out by CFD software, and the analysis of inlet velocity flow field cloud map is carried out by using 45°, 65° and 85° three vortex fan angle models. The performance of pre-filtration dust and droplet in high-rise trachea is demonstrated. The performance of pre-filtration dust and droplet of high-rise trachea was analyzed by bench test, and the optimum angle of vortex fan was obtained. It provides ideas for the optimization design of pre-filtration dust and droplet in the intake system of commercial vehicles.

**Theoretical Basis of Simulation and Test**

For the calculation of the inlet flow field of the high inlet pipe assembly, the whole internal flow field of the high inlet pipe is firstly established, and the steady flow field is calculated by using the RNG turbulence model, and the vortex fan and bellows intake velocity cloud diagram is extracted.

**The Basic Formulations of CFD**

Mass conservation equation:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_i)}{\partial x_i} = 0 \quad (i = 1, 2, 3)
\]  

(1)

where \( u_i \) \((i = 1, 2, 3)\) is eachly \( x_1, x_2, x_3 \) velocity components in three directions, \( t \) is time, \( \rho \) is air density.

Momentum conservation equation:

\[
\rho \frac{\partial u_i}{\partial t} + \rho u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial \rho P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho \frac{\partial u_i}{\partial x_j} \left( \frac{\partial u_j}{\partial x_j} - \frac{\partial u_i}{\partial x_i} \right)
\]  

(2)

where \( \rho \) is air density; \( \mu \) is Hydrodynamic viscosity; \( u \) is velocity vector.

United (1) (2) vertical equation without solution. It is necessary to establish the corresponding turbulence model equation and solve it jointly. The turbulent kinetic energy of the RNG model and dissipation rate equations is similar to those of the standard \( k - \varepsilon \) model. Where:

Turbulent kinetic energy equations [6]:

\[
\frac{\partial}{\partial x_j} (\rho k u_i) = \frac{\partial}{\partial x_j} \left( \alpha_{i} \mu_{\text{eff}} \frac{\partial k}{\partial x_j} \right) + G_k + G_b - \rho \varepsilon
\]  

(3)

Turbulent kinetic energy dissipation equations [6]:

\[
\frac{\partial}{\partial x_j} (\rho \varepsilon u_i) = \frac{\partial}{\partial x_j} \left( \alpha_{i} \mu_{\text{eff}} \frac{\partial \varepsilon}{\partial x_j} \right) + C_{\text{te}} \frac{\varepsilon}{K} \left( G_k + G_{\text{a}} G_b \right) - C_{\text{te}} \rho \frac{\varepsilon^2}{K}
\]  

(4)

where: \( G_k = \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_j}{\partial x_j} \); \( G_b = \beta \varepsilon \frac{\mu}{\rho} \frac{\partial T}{\partial x}; \mu_{\text{eff}} = \mu_i + \mu_t; \mu_t = \rho C_{\mu} \frac{k^2}{\varepsilon}. \)

In those equation: \( G_k \) is turbulent kinetic energy due to buoyancy; \( G_a \) is turbulent kinetic energy due to velocity gradient; \( \beta \) is turbulent Planck number, \( \beta_T = 0.85; \) \( \varepsilon \) is turbulent kinetic energy dissipation rate, also turbulent effective viscosity coefficient; \( \beta \) is coefficient of expansion due to heat, generally 0.011-0.015; for high Reynolds number problem, generally \( C_{\mu} = 0.0845, C_{\text{te}} = 1.42, C_{\text{te}} = 1.68, C_{a} = 0.09; \alpha_i, \alpha_k \) are turbulent kinetic energy and reciprocal of turbulent Planck number of dissipation rate, usually 1.0, 0.7.
Calculation Method of Prefiltration Efficiency

Calculation method of dust and droplet efficiency of Pre-filtration in intake system reference QC/T 32-2017 Performance Test Method for Automotive Air Filter. The direct weighing method was used to calculate the prefiltration efficiency of the high inlet pipe. The pre-filtration efficiency test can be carried out separately or simultaneously with the original filter efficiency test of assembly. In the experiment of the pre-filter with ejector dust removal, a ejector line filter with sufficient filter efficiency and ash capacity should be used to collect the test dust filtered by the pre-filter. The prefilter with automatic dust removal valve should use a sealed container instead of the exhaust valve to collect the test dust filtered by the prefilter. For other types of prefilter, the dust collected from the prefilter should be collected by using a dust collector suitable to its structure.

The prefiltration efficiency of the high inlet pipe is as follows:

$$\eta = \left(\frac{C}{B}\right) \times 100\%$$  \hspace{1cm} (5)

where $\eta$ is prefiltration efficiency, %; $B$ is dust (droplet) quantity totally, g; $C$ are the amount of dust (droplet) at the filter or mass increment of prefilter dust (droplet) collector, g.

Simulation Analysis

Geometric Model

In this paper, the geometric model of high inlet pipe is established by using three-dimensional modeling software, and the geometric model of high inlet pipe is shown in Figure 1. In order to make the angle of different vortex fan contrasting, the high inlet pipe of three angle structure is compared. The difference is that the angle between the model I, II, III vortex fan and the airflow velocity (the sharp angle between the vortex fan tangent and the airflow velocity) is 45°, 65° and 85° respectively.

Physical Model

In this paper, the flow of air in the high inlet pipe is studied as the research object. Make the following assumptions:

(a) Even if the commercial vehicle is in the maximum load condition, the air speed of high inlet pipe will be less than Mach 0.1. The air is regarded as a uniform and single medium, which simplifies the unidirectional flow of the average fluid characteristic.

(b) The air inside high inlet pipe can be regarded as an incompressible gas with constant density.

(c) Time model: Use the steady-state analysis model in the time domain.

(d) Solver algorithm: SIMPLE.
The airflow velocity distribution at the entrance of the high inlet pipe is actually uneven, and when simulated, it is considered to be a uniform distribution of airflow flow rate.

**Boundary Setting and Calculation Domain**

The simplified geometric model is imported into the CFD pre-processing software to divide the grid. The simplified computational domain is shown in Figure 2. The calculation model is the internal flow field of the high inlet pipe. The geometric model is simulated by CFD software into the flow field in the high inlet pipe, and the following boundary conditions are defined:

<table>
<thead>
<tr>
<th>Table 1. Conditional parameter settings.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quality Flow inport (m$^2$·h$^{-1}$)</td>
</tr>
<tr>
<td>Flow field Outlet pressure (Pa)</td>
</tr>
<tr>
<td>Pipe surface</td>
</tr>
<tr>
<td>Ambient temperature (°C)</td>
</tr>
<tr>
<td>Air density (kg/m$^3$)</td>
</tr>
<tr>
<td>Number of grids</td>
</tr>
</tbody>
</table>

The mesh type is tetrahedron mesh, boundary Layer 3 layer; the total thickness of 2mm, when dividing the mesh in the vortex fan and near the bellow area for local encryption, the minimum size is 2mm. The meshes in other regions are divided into 5mm to improve convergence and speed of operation. The boundary settings and grid of the 3 models are the same.

**Velocity Field Analysis**

The angle of the vortex fan of the three models is divided into 45°, 65° and 85°, and the three have common characteristics. From the analysis of the pre-filtration effect of dust and droplet, the air enters the high inlet pipe in the way of Eddy current. The larger the speed gradient, the greater the speed difference between the wall and the center of the inlet. And the excessive speed pressure gradient can dump the dust and droplet in the air onto the wall of the vortex tube, thus separating the solid-droplet-gas. The analysis from above can be demonstrated by three model of velocity streaming diagram. And form those picture can see, with the angle the greater, The closer the velocity flow streaming line is to the wall of the vortex tube, the higher speed pressure gradient, the easier it is to separate the solid- droplet-gas three body. And from three model air inlet flow line diagram, the air intake volume is smaller instead. It must be considered. As shown in Figure 3.

![Figure 3. The three model air inlet flow line diagram.](image)

The qualitative analysis of high inlet pipe is known. From the Velocity field cloud diagram of three models, it can be seen that the position of the wall position to the center of the vortex fan, the airflow velocity of the air inlet of the three models has the speed pressure gradient. Form the model I can see that the flow rate of the wall is higher than that of the vortex fan center. Similarly, Model II and model III. The difference is that the velocity gradients of Model II and model III are larger than the velocity gradients of model I. By analyzing the velocity gradient of three models in the inlet, the velocity gradient of Model III is the largest, and the velocity of the wall is the largest, and the velocity gradient of model I is the smallest, and the speed of the wall surface is the smallest. This shows that as the
angle of the vortex fan becomes larger, the velocity gradient of the inlet becomes larger. The velocity flow field of the three models is shown in Figure 4 (45°, 65°, 85° three models is I. II. III).

![Velocity Gradient Diagram](image)

Figure 4. The three model velocity field gradient diagram.

**Test Analysis**

**Pre-filter Dust Analysis**

The dust test of the high inlet pipe is carried out by the national standard *QC/T 32-2017 test method for the performance of air filters for automobiles*. The dust materials for the experiment were SiO$_2$ and CaO, and the particle size of the experimental dust was shown in table 2.

<table>
<thead>
<tr>
<th>Particle size (μm)</th>
<th>SiO$_2$</th>
<th>CaO</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.5~3.5</td>
<td>0.6~1.0</td>
</tr>
<tr>
<td>2</td>
<td>10.5~12.5</td>
<td>2.2~3.7</td>
</tr>
<tr>
<td>3</td>
<td>18.5~22.0</td>
<td>4.2~6.0</td>
</tr>
<tr>
<td>4</td>
<td>25.5~29.5</td>
<td>6.2~8.2</td>
</tr>
<tr>
<td>5</td>
<td>31~36</td>
<td>8.0~10.5</td>
</tr>
<tr>
<td>6</td>
<td>41~46</td>
<td>12~14.5</td>
</tr>
<tr>
<td>7</td>
<td>50~54</td>
<td>17~22</td>
</tr>
<tr>
<td>10</td>
<td>70~74</td>
<td>32~36</td>
</tr>
<tr>
<td>40</td>
<td>88~91</td>
<td>57~61</td>
</tr>
<tr>
<td>80</td>
<td>99.5~100</td>
<td>87~98</td>
</tr>
<tr>
<td>120</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

The inlet system of the commercial vehicle is installed on the bench experimental platform, the high pipe is hoisted on the bracket, and the high inlet pipe and air filter are connected to the activity, which is easy to replace. The test results of the experimental device and model I (45°) are selected manually in the ash system, as shown in Figure 5, and the ratio of the front and rear weights of the portioning device in the figure is the pre-filtration efficiency of Model I (45°).

From the experimental data in the figure, it can be seen that the efficiency of the pre-filter dust of the three vortex fan angle model is 80.5%, 87.6%, and the 86.5%. The models of the angle of three vortex fans of 45°, 65° and 85° were experimented respectively, and the experimental conditions were the same. The experimental results of the pre-filtration efficiency are shown in Figure 6. As can be seen from the graph, the 65° efficiency of the angle model of the vortex fan is the highest, and with the increase of the angle of the vortex fan, the pre-filtration efficiency of the three models is reduced by some, which may be due to the rebound of dust caused by the increase of resistance, resulting in twice air pollution.
Pre-filter Droplet Analysis

In the experiment of pre-filter droplet, the conditions of commercial vehicles under driving condition are considered. The precondition of the separation efficiency of the high inlet pipe to the droplet and air is \( v_s = 4.5 \text{m/s} \) the velocity of the droplet falling, and the driving speed of the car is \( v = 22.2 \text{m/s} \). Rainwater is treated as a droplet of different particles, in which the diameter distribution of droplets is shown in table 3.

<table>
<thead>
<tr>
<th>Particle range (mm)</th>
<th>Number of particles (m)</th>
<th>Number of particles (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2~1</td>
<td>84076</td>
<td>67</td>
</tr>
<tr>
<td>1~2</td>
<td>36306</td>
<td>29</td>
</tr>
<tr>
<td>2~3</td>
<td>3702</td>
<td>3</td>
</tr>
<tr>
<td>&gt;3</td>
<td>675</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>124759</td>
<td>100</td>
</tr>
</tbody>
</table>

The experimental device of the pre-filter droplet is the same as the experimental device for pre-filtration dust. The droplet enters the intake system using a manual method. The water collecting device is installed in three locations of the intake system respectively, and the experiment is shown in Figure 7.

The models of the angle of three vortex fans of 45°, 65° and 85° respectively were fixed on the experimental bench for pre-filter droplet experiment, and the experimental conditions of the three were the same. The experimental results of the pre-filtration efficiency are shown in Figure 8.
Figure 9. The contrast of pre-filtration dust and droplet efficiency.

From the experimental data in the figure, it can be seen that the efficiency of the pre-filter droplet of the three vortex fan angle model is 79.5%, 85.6%, and the 88.9%. 85° angle model is the most efficient. With the increase of the angle of the vortex fan, the efficiency of the pre-filter fog has gradually increased.

Considering the polylines of the two, the reason why the pre-filter droplet and dust efficiency curve is different, may be due to the solid, liquid two kinds of media have different properties. Taking into account the efficiency of pre-filtered dust and liquid fog, the two polylines combined into a picture, as shown in Figure 9. From picture can see, the optimal vortex fan angle is 75°.

Summary

Numerical simulation of three high inlet pipe models in commercial vehicles using CFD software. And the speed cloud map of the angle of different vortex fan is obtained. It is proved that the velocity gradient can separate the duet, droplet and the gas by the pre-filter because the angle of the vortex fan leads to different velocity gradients. Through the test and efficiency calculation of three models, it is concluded that the angle of the angle between the vortex fan and the airflow leads to the pre-filtration efficiency of the high inlet pipe, and with the increase of the angle, the efficiency of the pre-filter dust increases and decreases instead. The efficiency of the pre-filter droplet increases slowly with the angle, which verifies the accuracy of the simulation. The angle of the vortex fan is increased appropriately, and the efficiency of the pre-filter droplet is improved under the requirement of satisfying the efficiency of the pre-filtration dust. The model with 75° angle is the best choice. Comprehensively, pre-filtration efficiency of up to 87%.

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References


