Numerical Simulation and Test of filter Resistance of vehicle Wood Fiber Air filter

Hong yu Liu¹a, Yan shu Ni²b

¹Chongqing College of Electronic Engineering, College of Intelligent Manufacturing and Automobile Chongqing, China
²Suihua college School of Electrical Engineering Suihua, China
²85729976@qq.com, b601350111@qq.com

Abstract— In order to increase the filter area of vehicle wood fiber air filter, improve the filtration efficiency of air filter, and reduce the filtration resistance of air filter, a kind of W-shaped wood fiber air filter is designed in this paper. Through the existing empirical formulas, it is found that the main factors affecting the filtration resistance are fiber filling ratio, Reynolds number Re and fiber arrangement. In this paper, the filter resistance of air filter is simulated based on Boltzmann method. Firstly, the change curve of filter resistance with filling rate and Reynolds number under parallel arrangement and staggered arrangement is studied, and compared with the existing theoretical formula. Then, by analyzing the fiber equivalent radius, filling rate and filter element thickness of filter resistance, the relationship curve between filter resistance and various influencing factors is obtained. Finally, the theoretical results are verified by using the self-developed filter performance test rig. The results show that the experimental results are in good agreement with the numerical simulation results. The filtration resistance does not change much at low Reynolds number, mainly decreases with the increase of the equivalent radius of the fiber, and increases with the increase of the filling ratio. With the increase of filter thickness, these results provide theoretical basis and suggestions for the structure optimization of air filter.

1. INTRODUCTION
Fiber air filter can effectively filter the tiny particles in the air. Some scholars have carried out a relatively comprehensive study on the process of single fiber particle trapping, especially for the filtration process of clean fiber. A series of theoretical and empirical formulas are obtained to calculate the filtration efficiency and filtration resistance of the filter element[1-4]. However, for the empirical formula of filtration resistance, the influence of air filter element structure parameters on filtration resistance is not taken into account, and the change of filtration resistance under the influence of each structure parameter is lacking. It is impossible to compare the effect of structural parameters on filtration resistance. In this paper, the filter resistance of W-shaped wood fiber air filter is numerically simulated and verified by experiments. The results are of great theoretical value and practical significance for the structure optimization of the air filter.

2. W-SHAPED WOOD FIBER AIR FILTER ELEMENT STRUCTURE
Most of the air filter elements are cylindrical or rectangular. In order to increase the filtration performance of the air filter, a wood fiber air filter with a W-shaped surface is developed in this paper. The outer surface of the filter element is combined with several W shapes, which increases the contact
area between the filter element and the particles in the air. The filter material is made of Korean pine with a density of 0.44g/cm³ and a moisture content of 13% or 16%. It has soft wood, straight texture, fine structure, strong corrosion resistance and easy processing. Wood fiber material[5] can be naturally degraded. The structure of W-shaped filter element is shown in Fig. 1. In order to prevent the wood fiber from flying into the cylinder during the engine operation and affect the normal operation of the engine, a layer of coarse filter cotton was pasted near the side of the engine, as shown in figure 2.

![Figure 1: Untreated air filter element](image1)

![Figure 2: Air filter after treatment](image2)

In order to meet the needs of the test, four engine air filter elements with different structure parameters have been developed in this paper. The structural parameters are shown in Table 1.

| Filter element number | Filling rate | Length (cm) | Width (cm) | Altitude (cm) |
|-----------------------|--------------|-------------|------------|---------------|
| 1                     | 0.03         | 19.7        | 18.6       | 3.3           |
| 2                     | 0.04         | 19.7        | 18.6       | 3.3           |
| 3                     | 0.05         | 19.7        | 18.6       | 3.3           |
| 4                     | 0.06         | 19.7        | 18.6       | 3.3           |

3. SIMULATION AND ANALYSIS OF FILTER RESISTANCE OF WOOD FIBER AIR FILTER CORE

Filtration resistance is one of the important indexes to measure the filtration performance of air filter core, and the main factors affecting it are air velocity, fiber filling ratio, fiber equivalent radius, filter core thickness and so on. Many scholars use drag force per unit length fiber to represent filtration resistance, and the relationship between them can be expressed as[6]:

$$\Delta P = \frac{F_d L}{A}$$

where $A$ is the cross-sectional area and the dimensionless drag force $F$ can be expressed as: $F = \frac{F_d}{\mu L}$

Because of the filtration resistance is close to constant when the Reynolds number is less than 1.0, the filtration resistance is only related to the fiber filling ratio. In the simulation, the Reynolds number is set to 0.2. For an expression of dimensionless drag, there are two empirical formulas, The Miyagi formula is[7]:

$$F = 4\pi \left[ -\ln \frac{d_f}{2h} - 1.33 + \frac{\pi^2}{3} \left( \frac{d_f}{2h} \right)^2 \right]^{-1} \quad (1)$$

The Kuwabara formula is[8]:

$$F = 4\pi \left[ -0.5 \ln \alpha - 0.75 - 0.25\alpha^2 + \alpha \right]^{-1} \quad (2)$$

the filling rate is: $\alpha = \frac{d_f^2}{4h^2}$

In these two expressions, filtration resistance is only related to fiber volume fraction. In 1997, Liu and Wang[9] proposed an equation for dimensionless drag force $F$:...
\[ F = W(Re, \alpha, Kn, \frac{l_v}{l_e}) \]  

Since the Kn is less than 0.007, the dimensionless drag force \( F \) is negligible, so it is not necessary to consider the influence of Kn. From formula (3), it can be seen that the factors affecting filtration resistance are not only the filling ratio, but also the arrangement ratio of fibers and Reynolds number \( Re \). In this paper, the relationship between the dimensionless drag force \( F \) and the filling rate of single fiber is studied.

### 3.1 Analysis of Filtration Resistance of Single Fiber Air Filter Element

As shown in figure 3, the hexagonal cylinder representing the fiber is placed in the center of the region (the diameter of the fiber is 20 \( \text{mm} \)), and the flow direction of the gas is perpendicular to the hexagonal prism. The fluid enters the flow field from the left side at the velocity of 0.1 \( \text{m/s} \). In the boundary treatment, the inlet adopts the velocity boundary, and the exit is considered to be fully developed. That is, \( \frac{\partial u}{\partial x} = \frac{\partial v}{\partial x} = 0 \). Periodic boundary conditions are used for upper and lower boundaries:

\[ f_i(0, t + \Delta t) = f_i'(h, t), \quad f_i(h, t + \Delta t) = f_i'(0, t) \quad (4) \]

The mesh resolution is 256 \( \times \) 256. When the flow field is stabilized, the particles enter from the left side, and the contact between the particles and the fibers is regarded as the arrested set during the moving process.

The simulation results show that the dimensionless drag force increases gradually with the increase of fiber filling ratio as shown in figure 4. The simulation results are similar to those of Kuwabara formula.

### 3.2 Multi-fiber Air Filter Element Filtration Resistance Analysis

In the calculation area, as shown in Fig.5, the six-prism columns representing the fibers are placed in the region according to the arrangement of the parallel and staggered rows, respectively. The spacing of the fibers in the drawing perpendicular to the flow direction is 20 \( \text{mm} \), the pitch of the fibers parallel to the flow direction is 27 \( \text{mm} \), and the boundary conditions of the flow field are the same as those of \( A \).
The simulation results are as follows:

(a) Filling rate is 0.03

(b) Filling ratio is 0.05

The relationship between the dimensionless drag force $F$ and Reynolds number at different fiber filling rates is shown in fig.6. It is shown that the drag force $F$ remains basically unchanged at low Reynolds number.

Figure. 5 Arrangement of fibers in flow field

Figure. 6 Re Influence on the dimensionless drag force $F$

Figure. 7 The relationship between the dimensionless drag force $F$ and the fiber fill rate
Fig. 7 shows the variation of drag force $F$ with fiber filling rate in various arrangements. The drag force $F$ obtained in this paper is consistent with the existing theoretical results. The results obtained under parallel arrangement are very similar to those obtained by Kuwabara formula, but the results under staggered arrangement are different from those under parallel arrangement, which indicates that fiber arrangement has an obvious influence on filtration resistance. The above simulation results prove the reliability of the numerical simulation of the flow field in this paper.

3.3. Structural Factors Affecting Filtration Resistance

For the multi-fiber air filter, this section mainly analyzes the structural factors such as the equivalent radius of the fiber, the filling rate and the thickness of the filter element, which affect the filtration resistance.

The formula for calculating the filtration resistance is $\Delta P = \frac{4\mu v_0 H c F}{\pi D_f}$, the flow field resistance coefficient $f$ may be expressed as: $F = 8\pi(-\ln c + 2c - 0.5c^2 - 3/2)^{-1}$. $\mu$ is the dynamic viscosity of the airflow, kg/m·s, $v_0$ is the filtering speed, m/s, $F$ is the drag coefficient of the flow field, $D_f$ is fiber equivalent diameter, $\mu m$, $H$ is the thickness of filter element, mm, $c$ is the filter element filling rate. The filter resistance simulation results are as follows:

![Filter resistance simulation results](image)

In this paper, in the numerical simulation of filtration resistance, the gas flow rate is $0.4\text{m/s}, 0.8\text{m/s}, 1.2\text{m/s}, 1.6\text{m/s}, 2.0\text{m/s}, 2.4\text{m/s}$, Particle diameter set to $15\mu m$. In figure 8, (a), (c), (e) is a parallel arrangement, (b), (d), (f) is misaligned. In figure 8, the filling ratio of fiber selected by (a), (b)
is 0.04, that of fiber by (c), (d) is set to $35\mu m$, that of fiber by, (e), (f) is $30\mu m$, and that of fiber by (c), (d) is 0.04. The larger the fiber equivalent radius is, the lower the filtration resistance of the air filter core is, especially when the wood fiber equivalent radius changes from $20\mu m$ to $40\mu m$. When the equivalent radius of the fiber is more than $40\mu m$, the filtration resistance decreases slowly and increases with the increase of the velocity.

As can be seen from both (c) and (d) of Fig.8, the greater the filter element filling rate, the greater the filtration resistance, and the influence of the air flow velocity on the filtration resistance is also obvious, and the resistance is gradually increased with the increase of the filtration speed. From Fig.8 (e), (f), we can see that when the fiber equivalent radius, filling rate and particle diameter are fixed, the filter resistance increases with the increase of the thickness of the filter core, and the filtration resistance increases with the increase of the velocity. In addition, the filter resistance of the misaligned filter element is higher than that of the parallel arrangement. Although the misalignment increases the filter efficiency, it also increases the filtration resistance.

4. BENCH TEST AND VERIFICATION

In order to detect the filter resistance of wood fiber air filter, the test bed is designed according to the relevant requirements, and the construction diagram is shown in figure 9. A four stroke engine with a speed of 3000 r/min and a displacement of 1.5 L is selected in this paper.

4.1. Analysis of The Content and Results of The Test

Analysis of Filtration Resistance of Single Fiber Air Filter Element

The experimental conditions are as follows: room temperature 20℃, relative air humidity 50%±15% and standard atmospheric pressure 101.3 Kpa. According to the relevant test standards of dry air filter in China, the steps of filtration resistance test are as follows:

a) Wood fiber air filter elements to be tested for filtration resistance are placed above 30min in the above test environment.

b) Install the air filter assembly to be tested, and check its sealing to ensure that the air is not leaking, so as not to affect the test results.

c) Install the absolute air filter and check its sealing to ensure that the air does not leak, so as not to affect the test results.

d) Starting the air extractor, adjusting the air volume flow rate, pumping 10min above the rated air volume flow rate, in order to make the air filter element adapt to this test environment.

e) According to the relevant standard JB/T 9755.5-2013, 《performance Test method of Air filter for Internal Combustion engines》, the rated volume flow rate is 40%, 60%, 80%, 100% and 120%. After the test system is stable, Measure the pressure at both ends of the air filter.

f) According to the theoretical formula, the resistance of the air filter element is calculated.

g) Replace the air filter element with different parameters and repeat the above steps.

The resistance of the air filter element in Table1 was tested respectively. The results are shown in Table 2.
TABLE 2. STRUCTURAL PARAMETERS OF AIR FILTER ELEMENTS

| Rated flow Ratio (%) | Rate flow (m³/h) | No.1 filter Resistance (Pa) | No.2 filter Resistance (Pa) | No.3 filter Resistance (Pa) | No.4 filter Resistance (Pa) |
|----------------------|------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| 40                   | 42.3             | 30                          | 34                          | 38                          | 42                          |
| 60                   | 63.8             | 52                          | 61                          | 66                          | 73                          |
| 80                   | 84.7             | 77                          | 92                          | 104                         | 117                         |
| 100                  | 104              | 116                         | 135                         | 148                         | 156                         |
| 120                  | 125.6            | 164                         | 178                         | 193                         | 204                         |

The curves drawn from Table 2 are shown in figure 10:

Figure 10 shows that the greater the air velocity, the greater the filter resistance of the air filter, and the greater the filling ratio, the greater the filtration resistance, and the higher the air velocity, the more the increase of the filter resistance. In addition, according to the relevant national standards, the filtration resistance of the air filter element at rated air volume flow 1.8 m³/min should be less than or equal to 300 Pa. It can be seen that the filtration resistance obtained by the test accords with the standard.

4.2. Comparative Analysis of Theoretical and Experimental Results

According to Table II, figure 11 shows the comparison between the numerical simulation results and the experimental results of the air filter with different fiber filling rates.

Figure 11 comparison curve between filtration resistance test results and simulation results
From Fig. 11, it can be seen that the numerical simulation results of air filter resistance at different air velocities are basically consistent with the experimental results, and the error is within the allowable range of 10%.

5. CONCLUSION

a) Based on the filter theory of fiber filter, the filter resistance of wood fiber air filter is simulated by Boltzmann method, and the simulation results are verified by the self-developed air filter performance test rig.

b) The results show that the numerical simulation results obtained by the Boltzmann method are in good agreement with the theoretical formula, and the experimental results are in good agreement with the numerical simulation results, that is, the filtration resistance decreases with the increase of the fiber equivalent radius. With the increase of the filling ratio, the filter thickness increases.

c) When the air filter element structure is 19.7cm long, the width is 18.6cm and the height is 3.3cm, the results of the four groups of filter core filtration resistance all meet the requirements of the specification, among which, the filter resistance of No. 4 filter with the filling ratio of 0.06 is the smallest.

REFERENCES

[1] Kuwabara S. The forces experienced by randomly distributed parallel circular cylinders or spheres in a viscous flow at small Reynolds numbers [J]. Journal of the Physical Society of Japan, (1959), 14(4): 527-532

[2] Stechkina I, Fuehs N. Studies on Fibrous Aerosol Filters—I. Calculation of Diffusional Deposition of Aerosols in Fibrous Filters [J]. Annals of Occupational Hygiene, (1966), 9(2): 59-64

[3] Qian F, Zhang J, Huang Z. Effects of the operating conditions and geometry parameter on the filtration performance of the fibrous filter [J]. Chemical Engineering & Technology, (2009), 32(5): 789-797

[4] S.A.Hosseini, H. Vahedi Tafreshi. Modeling particle filtration in disordered 2-D domains: a comparison with cell models [J]. Separation and Purification Technology, (2010), 74(2): 160-169

[5] Du Danfeng. Research on Test and Filtration Theory of Engine Air Filter Element Formed with Micron Wood Fiber[D]. Harbin: Northeast Forestry University, (2010).

[6] Liu, Z. G., Wang, R K. Pressure Drop and Interception Efficiency of Multifiber Filters. Aerosol Science and Technology. (1997), 26 (4):313-325.

[7] Miyagi, T. Viscous flow at low Reynolds numbers past an infinite row of equal circular cylinders. Journal Of the Physical Society op Japan Vol, 1958, 13 (5): 493-496.

[8] Kuwabara S. The forces experienced by randomly distributed parallel circular cylinders or spheres in a viscous flow at small Reynolds numbers [J]. Journal of the Physical Society of Japan, 1959, 14: 527.

[9] Liu, Z. G., & Wang, P. K. Pressure drop and interception efficiency of multifiber filters. Aerosol Science and Technology, 1997,26(4), 313-325.

[10] Brown, R.C., 1989. Modern concepts of air filtration applied to dust respirators. Annual of occupational hygiene 33(4), 6:15-644.