Study on Surface Structure of Filter Material of Cabin Air Filter Impacted by Droplets

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Abstract. As the filter material of cabin air filter is closely related to the filtration effect, this paper establishes a physical model of the droplet impact on different surface structures of filter material and numerically simulates dynamic characteristics of the droplet impact on different surface structures. The results show that the ability of filter material to capture droplets is directly proportional to the hydrophilic strength of filter material and the surface roughness (≤ droplet diameter).

1. Introduction
The cabin air filter helps improve the air quality inside vehicles, the primary role of which is to provide clean air for the passenger compartment. Cabin air filters are generally divided into single-effect cabin air filters and multi-effect cabin air filters, most of which use filter paper, non-woven fabrics, activated carbon, and others as filtering materials.

Mildew may occur in cabin air filters after long-time exposure to water, which will seriously degrade the air quality in passenger compartments. This paper establishes a physical model of droplet impact on different surface structures for the phenomenon of droplet contact with filter materials of cabin air filters and numerically simulated dynamic characteristics of droplet implications for different surface structures.

In terms of experimental researches, Cui Jie[1] did investigations on the edge characteristics of droplet impact on the flat plane, Bi Feifei[2] analyzed the influence of parameter variables on the dynamic characteristics of droplets during impact by using a high-speed camera to shoot the spreading features of some conventional liquid media on the solid surface, such as distilled water and ethanol, and Kim[3] studied on the retraction mechanism of droplets after impact on a flat plane.

With the development of electronic computer technology and the optimization of software algorithms, using numerical simulation to study droplet impact has become common. Due to the short time and many processes of droplet impact on the solid surface, spreading, retracting, oscillating, rebounding, and crushing occurs in milliseconds[4]. Considering that the phenomenon of droplets impacting solid surfaces exists in many engineering fields, this study selected water as a droplet medium and compared the simulation results as target droplets.

This paper mainly reflects innovation in the droplet impact objects. At present, most studies focus on the effects of droplet impact on flat plate structures. The reviews on non-plate structures, such as rectangular grooves, special-shaped grooves, isosceles triangular grooves, and right triangular grooves, are relatively few. Based on the CLSVOF (coupled level set and volume of fluid) method, it simplified the droplet impact on the cabin air filter surface as a physical model of droplet impact on different solid surfaces, and it expounded the influence of the outlet structure of the cabin air filter on the
dynamic characteristics of droplets. It is of considerable significance to explore droplets' problems impacting the surface of filter materials of cabin air filters for reducing mildew of cabin air filters and maintenance costs.

2. Modeling

2.1. Mathematical Model
This paper adopts the CLSVOF method for phase interface processing, which combines the conservation and accuracy of VOF and Level Set methods. In this method:

- **Continuity Equation:**
  \[ \nabla \cdot \mathbf{U} = 0 \]

- **Momentum Equation:**
  \[
  \frac{d}{dt} [\rho(\phi) \mathbf{U}] + \rho(\phi) \nabla (\mathbf{U} \cdot \mathbf{U}) = -\nabla P + \nabla \cdot \mu(\phi) \left[ \nabla \mathbf{U} + (\nabla \mathbf{U})^T \right] - \sigma \delta(\phi) \nabla \phi + \rho(\phi) \mathbf{g}
  \]

  \[\kappa = \frac{\nabla \phi}{|\nabla \phi|}\]

- **Energy Equation:**
  \[
  \frac{\partial}{\partial t} [\rho(\phi) C_p T] + \nabla \cdot [\rho(\phi) C_p U T] = \nabla \cdot (\lambda \cdot \Delta T)
  \]

In the formula, \( U \) - Vector (speed);
\( T \) - Temperature;
\( P \) - Pressure;
\( t \) - Time;
\( \lambda \) - Thermal Conductivity;
\( \rho \) - Density;
\( \mu \) - Viscosity;
\( C_p \) - Specific Heat Capacity;
\( \sigma \) - Coefficient of Surface Tension;
\( g \) - Gravity Acceleration;
\( \kappa \) - Interface Curvature
\( \phi \) - Symbolic Distance Function

Heaviside function can represent the density and viscosity at the interface:

\[
H(\phi) = \begin{cases} 0 & \phi < -w \\ \frac{1}{2} [1 + \frac{\phi}{w} - \frac{1}{\pi} \sin\left(\frac{\pi \phi}{w}\right)] & |\phi| \leq w \\ 1 & \phi > w \end{cases}
\]

In the formula, \( W = 1.5 \) m;
\( m \) - Minimum Grid Size

- **Viscosity:**
  \[ \mu(\phi) = \mu_0 (1 - H(\phi)) + \mu_1 H(\phi) \]

- **Density:**
  \[ \rho(\phi) = \rho_s (1 - H(\phi)) + \rho_1 H(\phi) \]

- **Surface Tension:**
  \[ F_s = \sigma \kappa \delta(\phi) \nabla \phi \]
\[ \delta(\phi) = \frac{\partial H(\phi)}{\partial \phi} = \begin{cases} 1+\cos\left(\frac{\phi}{w}\right) & |\phi| < w \\ \frac{2w}{H} & |\phi| \geq w \end{cases} \]

2.2. CFD Software

The version of FLUENT used in this article is FLUENT 16.0.

At present, FLUENT software, the most widely used and highly recognized computational fluid dynamics software, is developed by ANSYS Company. Due to its full application and high calculation accuracy, FLUENT is often used to simulate the flow field distribution in very complex geometric regions and widely used in engineering.

FLUENT has developed the most advanced Tgrid, which has outstanding flexibility and grid adaptability. Its notable feature is that it can generate advanced volume grids and allows users to use unstructured grids for calculation and solution. The FLUENT adopts Finite Element Analysis (FEA) to calculate and carry out iterative calculation according to the boundary conditions set by pre-processing and the selected calculation model and control equation. Users can add or customize corresponding fluid models according to their own needs.

Besides, the cloud map generated by FLUENT is intuitive and clear, and usually, people use it for line tracking, surface rendering, and other practical functions. From the output of FLUENT, we can output the flow field distribution at any cross-section, and the output format is flexible, which dramatically provides convenience for users[5].

2.3. CFD Software

In order to explore the droplet phenomenon more conveniently, distilled water is selected as the working medium in this paper. The three-dimensional physical model of droplet impact on different surface structures is shown in Figure 1.

![Figure 1. Physical Model of Droplet Impact on Groove Surface](image)

The length, width, and height of the calculation domain are taken as 10 mm, 10 mm, and 5 mm, respectively, and the surface structure at the bottom is taken as the wall boundary condition, and the rest is taken as the pressure inlet (atmospheric pressure). The droplet parameters are shown in Table 1.

| Parameters       | Value     |
|------------------|-----------|
| Diameter d/mm    | 2         |
| Temperature T/k  | 293.15    |
| Density ρ /kg • m^{-3} | 998.2 |
| Viscosity μ /Pa • s     | 0.001     |
| Surface tension σ /N • m^{-1} | 0.0728   |
At the initial time, the bottom of the droplet is tangent to the impact surface. The computational domain is divided by hexahedral structured grids, and the total number of computational grids is selected to be 4 million through grid independence verification.

2.3.1. Contact Angle.
The spreading degree of droplets after impacting on the surface is measured by contact angle (CA):

\[
\begin{align*}
CA < 90^\circ & \rightarrow \text{Hydrophilic Surface} \\
CA = 90^\circ & \rightarrow \text{Neutral Surface} \\
CA > 90^\circ & \rightarrow \text{Hydrophobic Surface}
\end{align*}
\]

Figure 2. Contact Angle (CA)

2.3.2. Wetting State
As shown in Figure 3, when CA = 90°, that is, the surface structure is neutral, the droplet can completely infiltrate into the groove; therefore, the groove side area and groove bottom area are larger, and the total contact area is also larger; When CA = 105°, the groove is semi-infiltrated. When CA = 120° and 135°, the droplet can no longer infiltrate into the trench.

Figure 3. Right triangle groove

3. Dynamic Characteristics of Droplet Impact on Different Surface Structures

3.1. Physical Models of Different Surface Structure Types
From Figure 4 to 7, they are physical models of different surface structures of impact on rectangular grooves, special-shaped grooves, isosceles triangular grooves, and right triangular grooves. In order to reduce variables, the depth of various types of grooves is set to be 0.1 mm.

Figure 4. Rectangular Groove  Figure 5. Special-shaped Groove
3.2. Influence of Droplet Impact on Dynamic Characteristics of Different Surface Structures

The velocity of the droplet impact on the surface is set at 0.4 m/s, and the range of contact angle is set at 90°~135°. As shown in Figure 8, taking the impact on the surface of the rectangular groove as an example, the droplet performs spreading movement firstly after impacting the surface of the rectangular groove. As the surface area of the droplet increases, the kinetic energy is converted into tension energy, potential energy, and viscous dissipation energy. When the spreading diameter of the droplet reaches the maximum, it enters the shrinkage stage, and when the spreading width reaches the minimum, it is recorded as a cycle. Due to the different surface structures, the conversion between kinetic energy and other energies of droplets will be different, and compared with the flat plate surface, the energy attenuation of droplet impact on the rectangular groove surface is faster.

In addition to four different surface structures, the addition of a flat plate structure is conducive to better comparative analysis.

The dynamic characteristics of droplet impact on different surface types are shown in Figure 9 - 12.
As can be seen from the figure above, when the contact angle is between 90° and 135°, the difference in transverse and longitudinal spreading factors of the isosceles triangle is the most obvious; that is, the surface groove structure of the isosceles triangle has the best orientation to droplets. When the contact angle increases, that is to say, the more hydrophobic the surface structure is, the less the transverse and longitudinal spreading factors of droplet decrease, which is also in line with common sense: the smoother the surface structure is, the more difficult it is for the droplets to be “captured”.

When CA = 90°, the surface type is neutral, and with the deepening of the impact process, the influence of different surface structures on the spreading factor becomes more and more apparent. When the intrinsic contact angle of the impact surface is 90°, the impact surface is neutral. As can be seen from Figure 9, over time, the influence of micro-scale grooves on the dynamic characteristics of droplets tends to be noticeable. The groove surface structure of the isosceles triangle has the most significant impact on the transverse and longitudinal spreading factors of droplets. It is worth noting that the flat plate’s spreading factor is between the transverse and longitudinal spreading factors of the other four types of surface groove structures.

When CA = 105°, the surface type is hydrophobic. Compared with Figure 8, the transverse and longitudinal spreading factors of droplets are reduced to different degrees. For hydrophobic surfaces, the transverse and longitudinal differences of groove structures on different types of surfaces are not distinct, and the oscillation periods are the same.

When CA = 120° and 135°, it can be seen from Figure 11 and 12 that the transverse and longitudinal spreading factors of droplets under different surface groove structures are smaller than those of droplets impact on the flat plate, that is to say, the hydrophobic surface plays a “blocking” role in the movement of droplets on the surface, and the droplets cannot be “adhered” to the hydrophobic surface.

3.3. Influence of Different Surface Groove Size on Dynamic Characteristics of Droplets
On the basis of the above physical model, taking the rectangular surface groove structure as the breakthrough point, the groove depth, width, and spacing are set to L, and L is taken from 0.05 mm to 0.8 mm. When taking the hydrophobic surface and CA = 105°, the impact velocity of the droplet is 0.4 m/s. After calculation, the dynamic characteristics of droplets impact on different rectangular groove sizes are as shown in Figure 13.
As can be seen from the figure, the size of the surface groove has a significant influence on the dynamic characteristics: When it is a small scale, there is less part of the droplet infiltrating into the groove; therefore, the groove structure has little influence on the dynamic characteristics, and the edge of droplet is smooth; When the size L of rectangular groove increases to 0.2 mm, the mass immersed in the groove rises to the point that the surface tension cannot be maintained, and the shape of the droplet starts to be affected by the groove, and the droplet can obviously form extension movement in the rectangular groove at 2 ms. At this time, the edge shape of the droplet appears twists and turns, and under the action of surface tension, it can still achieve the retraction process.

When the size L of the rectangular groove increases to 0.4 mm, the droplet can no longer present a complete droplet, and the motion state changes from surface spreading to extending motion in the groove. The research object in this paper carries out extension motion in the three grooves, and can only produce slight retraction motion after reaching the maximum extension diameter; however, it is far from reaching the original state. When L = 0.8 mm and t = 8 ms, the droplet becomes an extended motion in a single groove.

Therefore, in the range of groove size smaller than the droplet diameter, the larger the surface groove size, the more “adhering” the surface to the droplet.

4. Conclusion
In this paper, the cabin air filter meeting water is taken as the breakthrough point and combined with numerical simulation software, the results of water droplets impact on a rectangle, right triangle, isosceles triangle, and special-shaped groove are explored, and the results of droplet impact on the filter material surface of cabin air filter are compared.

The following conclusions are drawn from this study:
1. When the droplet impacts the surface of filter material, the oscillation period of the droplet in the transverse and longitudinal directions is not synchronized. At the later stage of the impact process, the anisotropy of droplet morphology becomes more evident. On the surface of filter material, the grain direction of filter material is parallel to the impact velocity direction of droplets, which can make the droplets “adhere” to the surface of filter material as little as possible, and is also beneficial to the maintenance of cabin air filter.

2. The dynamic characteristics of droplets are the coupling effect of contact angle and filter material surface roughness. With the increase of contact angle, the maximum transverse and longitudinal expansion factors decrease, and the anisotropy of droplet morphology tends to decrease. As the surface roughness of filter material increases, the wettability state tends to change. Besides, with the rise of the contact angle, the time required to reach the maximum diffusion coefficient.
becomes shorter. The surface roughness of the filter material should be as small as possible. When the diameter of the surface groove is lower than the droplet size, the “adhesion” effect is the worst, and the droplet filter material “captures” the least liquid.

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