Numerical Simulation on Distribution Characteristics of Particle Distribution Uniformity in a Radial Style Diesel Particulate Filter

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Abstract

In this paper three-dimensional mathematical model of gas-solid two-phase in a radial style diesel particulate filter (DPF) is established and flow computation software was used to simulating distribution characteristics of gas-solid two-phase and particle distribution uniformity. Several influence parameters such as flow velocity, divergence angle and particle diameter was investigated. Through the verification analysis, the simulation calculation results can reflect the laws of gas-solid two-phase flow inside this DPF. The results indicate that distribution uniformity of particle could be improved by reducing inlet velocity, divergence angle and particle diameter. The study is useful for structural parameters optimization designing and controlling particle regeneration of radial style diesel particulate filter.

1. Introduction

At present, the diameter of traditional axial diesel particulate filter is relatively so large that during the regeneration, it is easy to be cracked for uneven heating and high power microwave source is also required. In view of these problems, Gong Jinke, Wang Shuhui etc invented a radial style diesel particulate filter in which rotating filter block was used [1]. It could realize continuous regeneration with many advantages such as lower power microwave source and more evenly heating [2]. Particle distribution uniformity has important significance for the optimization design of DPF structure parameters and the further study of DPF regeneration characteristics.
In this paper, gas-solid two-phase flow simulation analysis is made in radial style diesel particulate filter using computational fluid dynamics software. Through calculation and analysis, we can get the characteristics of particle distribution uniformity in a Radial Style Diesel Particulate Filter with the changes of structure parameter.

2. Basic Mathematical Equations

2.1. Equation of continuity

equation of particle phase

\[
\frac{\partial (\delta \alpha_s \rho_s u_s)}{\partial x} + \frac{\partial (\delta \alpha_s \rho_s v_s)}{\partial y} + \frac{\partial (\delta \alpha_s \rho_s w_s)}{\partial z} = \sum \dot{m}_{ys}
\]  

(1)

equation of gas phase

\[
\frac{\partial [(1 - \alpha_s) \delta \rho_g u_g]}{\partial x} + \frac{\partial [(1 - \alpha_s) \delta \rho_g v_g]}{\partial y} + \frac{\partial [(1 - \alpha_s) \delta \rho_g w_g]}{\partial z} = \sum \dot{m}_{sg}
\]  

(2)

porous medium

\[
\frac{\partial (\delta \rho_f)}{\partial t} + \frac{\partial (\delta \rho_f u)}{\partial x} + \frac{\partial (\delta \rho_f v)}{\partial y} + \frac{\partial (\delta \rho_f w)}{\partial z} = 0
\]  

(3)

2.2. Momentum conservation equation

equation of particle phase

\[
\frac{\partial (\delta \alpha_s \rho_s v_s u_s)}{\partial x} + \frac{\partial (\delta \alpha_s \rho_s v_s v_s)}{\partial y} + \frac{\partial (\delta \alpha_s \rho_s v_s w_s)}{\partial z} =
\]

\[-\alpha_s \frac{\partial (\delta p)}{\partial t} + \nabla \cdot (\delta \tau_s) +
\]

\[
\sum \left( R_{gsi} + \delta \dot{m}_{gs} \right) + \alpha_s \rho_s (F_{si} + F_{lift,si} + F_{vm,si}) + \alpha_s \frac{\mu_s}{k} V_s
\]  

(4)
porous medium

\[ \frac{\partial}{\partial t} \left( \delta \rho_j u_j \right) + \frac{\partial}{\partial x_j} \left( \delta \rho_j u_j u_j \right) = \rho_f f + \frac{\partial}{\partial x_j} \left( \mu \frac{\partial \delta u_j}{\partial x_j} \right) \]  

(5)

\[ \frac{\partial (\delta p)}{\partial x_j} + \frac{\mu}{\kappa} u_j \]

equation of gas phase

\[ \frac{\partial (\delta(1-\alpha) \rho_g u_g u_g)}{\partial x} + \frac{\partial (\delta(1-\alpha) \rho_g u_g u_v)}{\partial y} + \frac{\partial (\delta(1-\alpha) \rho_u w_u)}{\partial z} \]

\[-(1-\alpha) \frac{\partial (\delta p)}{\partial t} + \nabla \cdot (\delta \tau_g) + \]

\[ \sum (R_{sp} \delta \rho_g u_g u_g) + \alpha_g \rho_g (F_{pg} + F_{pg,sp} + F_{pv,pg}) + (1-\alpha) \frac{\mu}{\kappa} V_g \]

In all the equations above, \( i = x, y, z \) is direction \( x, y, z \), \( \nu = u, v, w \) is velocity in direction \( x, y, z \), \( \mu, \rho \) the viscosity and density of fluids respectively, \( \kappa \) is permeability.

2.3 Turbulence equations in Standard \( k \) \( \epsilon \) model

\( k \) equation

\[ \frac{\partial (\rho_m u_k)}{\partial x} + \frac{\partial (\rho_m v_k)}{\partial y} + \frac{\partial (\rho_m w_k)}{\partial z} = \]

\[ \frac{\partial}{\partial x} \left( \frac{\mu_{t,m}}{\sigma_k} \frac{\partial k}{\partial x} \right) + \frac{\partial}{\partial y} \left( \frac{\mu_{t,m}}{\sigma_k} \frac{\partial k}{\partial y} \right) + \frac{\partial}{\partial z} \left( \frac{\mu_{t,m}}{\sigma_k} \frac{\partial k}{\partial z} \right) \]

\[ + G_{k,m} - \rho_m \epsilon \]

In this equation, \( k \) is Turbulent Kinetic Energy, Turbulent Dissipation Rate, \( \rho_m \) is mixture density of Gas and particle phase, \( \mu_{t,m} \) is Turbulent viscosity.

\( \epsilon \) equation

\[ \frac{\partial (\rho_m u_k \epsilon)}{\partial x} + \frac{\partial (\rho_m v_k \epsilon)}{\partial y} + \frac{\partial (\rho_m w_k \epsilon)}{\partial z} = \]

\[ \frac{\partial}{\partial x} \left( \frac{\mu_{t,m}}{\sigma_k} \frac{\partial \epsilon}{\partial x} \right) + \frac{\partial}{\partial y} \left( \frac{\mu_{t,m}}{\sigma_k} \frac{\partial \epsilon}{\partial y} \right) + \]

\[ \frac{\partial}{\partial z} \left( \frac{\mu_{t,m}}{\sigma_k} \frac{\partial \epsilon}{\partial z} \right) + \frac{\epsilon}{k} (C_{1\epsilon} G_{k,m} - C_{2\epsilon} \rho_m \epsilon) \]

In equation (8), \( \sigma_k \) is the number of Prandtl corresponding to turbulent dissipation rate, \( C_{1\epsilon}, C_{2\epsilon}, \sigma_k \) are constants of the model, According to the values recommended by Launder and later experimental verification, \( C_{1\epsilon} = 1.44, C_{2\epsilon} = 1.92, \sigma_k = 1.3 \).
3. Geometric Model and Boundary Conditions

3.1. Geometric modeling grid

Using Gambit software, the mesh of this Diesel Particulate Filter is generated. The grid is hexahedron-Wedge Hybrid and the mesh size is set as small as possible which is conducive to get the stability numerical solution. The model grid is shown in Figure 1 (section a and b are x = 35mm, x = 130mm).

Figure 1. Grid of a radial style diesel particulate filter

3.2. Calculation of boundary condition setting

The flow rate in the DPF is not high, so the gas can be considered as incompressible. The velocity and pressure is used as boundary condition of entrance and exit. Pressure outlet boundary condition is set to 0Pa, considering only the entrance and exit pressure relative value, ignoring the filter body resistance to airflow and all surface conditions are set to the no-slip boundary condition. Gas phase material density and dynamic viscosity at 300 degrees C: \( \rho = 0.3827 \text{kg/m}^3 \), \( \mu = 2.946 \text{Pa·s} \). The volume fraction of particle phase is 0.05 [3]. Using the turbulence intensity and hydraulic diameter as Turbulent input conditions, turbulence intensity can be get according to equation (9) calculation:

\[
I = 0.16 \, \text{Re}^{-1/8} \quad (9)
\]

\[
\text{Re} = \frac{UD_H}{\nu} \quad (10)
\]

In these equations, \( I \) - turbulence intensity, \( D_H \) - entrance pipe diameter, m; \( \nu \) - kinematic viscosity, m²/s⁻¹.

4. Results of Numerical Calculation and Analysis

4.1. Influencing factor of particulate concentration distribution

- The effect of exhaust velocity
In this case, parameter is seted as Table 1. Through calculation, the particulate concentration distributions of different exhaust velocity in the expansion tube section (x=35mm) and the filtering body section (x=130mm) are shown as figure 2 and figure 3.

It indicate that: In the two section, the particle concentration showed a parabola distribution. The exhaust velocity does not change the structure of particle concentration field.

In calculation section x=35mm, under these three exhaust velocity (20 m/s, 40 m/s, 80 m/s) particle concentration minimum values were 0.04997, 0.01757, 0.01716. The minimum velocity, the smaller particle concentration minimum values. As the exhaust velocity decreases, the expansion tube within the region of the vortex strength is weakened, the role of particles separation around the eddy center area is also corresponding weakened, so the minimum value become larger.

<table>
<thead>
<tr>
<th>Fixed value</th>
<th>Dilation angle</th>
<th>Filtering body length</th>
</tr>
</thead>
<tbody>
<tr>
<td>90º</td>
<td></td>
<td>240 mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Change value (exhaust velocity)</th>
<th>20 m/s</th>
<th>40 m/s</th>
<th>80 m/s</th>
</tr>
</thead>
</table>

Figure 2. Curve: granule concentration of different velocity in x=35mm

Figure 3. Curve: granule concentration of different velocity in x=130mm
In the filter section (x=130mm), particle concentration maximum value and the minimum value difference showed a trend of decrease. When the exhaust flow rate is 20m/s, particle concentration curve almost parallel to X axis and the particle concentration distribution uniformity is best.

Comprehensive analysis shows that: with the entrance exhaust velocity decreases, in the expansion tube area and a filtering body segment, particle concentration distribution uniformity becomes better, that is, particulate trap particle has better concentration distribution uniformity.

• The effect of particle diameter

In this case, parameter is set as Table 2. Through calculation, the particulate concentration distributions of different exhaust velocity in the expansion tube section (x=35mm) and the filtering body section (x=130mm) are shown as figure 4 and figure 5.

<table>
<thead>
<tr>
<th>TABLE II. DIFFERENT PARTICLE DIAMETER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed value</td>
</tr>
<tr>
<td>Dilation angle Filter body length exhaust velocity</td>
</tr>
<tr>
<td>90° 240 mm 40 m/s</td>
</tr>
<tr>
<td>Change value (particle diameter)</td>
</tr>
<tr>
<td>1μm 0.5μm 0.1μm</td>
</tr>
</tbody>
</table>

It indicate that: In the two section, the particle concentration showed a parabola distribution. The exhaust velocity does not change the structure of particle concentration field. As the particle diameter decreases, particulate concentration distribution in the expansion tube regional curves more quietly.

In figure 4: In the filter section, when the particle diameter is 0.1μm, there is small fluctuations of Particle concentration curve (remained in the 0.05). This is because inertia is small, the small diameter particle has good flow property.

Analysing and comparing Figures 4 and 5, it is easy to find that in the expansion tube area, near the centerline axis, particle concentration reaches its maximum value, but in the filter section shaft near the center, the particle concentration is minimal. This is because backflow effect in the cross section of x = 35mm is more obvious and particles are aggregated in the vicinity of the axis under the action of the air flow. In a word, with good flow property, concentration distribution curves of small diameter particles are smoother.

• The effect of dilation angle

In this case, parameter is set as Table 3. Through calculation, the particulate concentration distributions of different exhaust velocity in the expansion tube section (x=35mm) and the filtering body section (x=130mm) are shown as figure 6 and figure 7.

In figure 6, it is indicated that, in the region of expansion tube, particle concentration distribution is axial symmetry and slope of particle concentration curves increses with the expansion of dilation angle. When the dilation angle increases to 120°, curve inclination change from acute angle to obtuse angle suddenly and distribution uniformity becomes bad. This is because as the expansion angle increases, in the expansion tube, eddy current generated gradually and increases slowly.

In figure 7, in the filter section (x=130mm), when dilation angle is the 60° and 90°, the particle concentration did not change much and the slope of the particle concentration distribution curve is nearly 0, though When dilation angle was increased to 120°, concentration curve begins to appear fluctuation. This is because compared with other expansion angle, in the filter body section of the particulate trap of 120°, the vortex and circumfluence phenomenon is very apparent, particles affected by the air-flow relatively large.

In general, the expansion angle has great influence on particle concentration distribution, DPF with small expansion angle on the whole particle distribution is uniform than the big one.
Figure 4. Curve: granule concentration of different particle diameter in x=35mm

Figure 5. Curve: granule concentration of different particle diameter in x=130mm

TABLE III. DIFFERENT DILATION ANGLE

<table>
<thead>
<tr>
<th>Fixed value</th>
<th>exhaust velocity</th>
<th>particle diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>40 m/s</td>
<td>1μm</td>
</tr>
<tr>
<td>Change value (dilation angle)</td>
<td>60°</td>
<td>90°</td>
</tr>
</tbody>
</table>
5. Experimental Verification

Considering great influence which the distribution characteristics of velocity has on the distribution characteristics of particle distribution uniformity in a Radial Style Diesel Particulate Filter and the difficulties to measure the particle velocity separately, in this paper only gas flow velocity were measured and comparative analysis was made with the result of numerical simulation to verify if the gas-solid two-phase flow model is correct.

5.1. Experiment method

Isothermal, stable test devices are established on stable test table to measure the distribution characteristics of velocity. The structure parameters of DPF which is used in the experiment is in the following: Dilation angle is 90° and Filtering body length is 240mm. Schematic diagram of experimental setup is shown in figure 8.
5.2. Experiment results and model validation

When the exhaust velocity is 20 m/s, the velocity values of gas in $x = 35$ mm, $x = 65$ mm and $x = 120$ mm, $x = 190$ mm, $x = 250$ mm these five section were measured and compared with numerical simulation values and the results of comparison is shown in Figure 9 and Figure 10.

6. Conclusion

- The gas solid two phase flow model established in this paper is correct. In the error range allows, it is in line with the actual situation, the analysis results have a certain reference.
The distribution of particles in the Y axis plus or minus two direction is basically symmetrical. The smaller entrance exhaust velocity, the smaller effect particle by eddy current, so the particle distribution uniformity is better.

In a radial style Diesel Particulate Filter, particle diameter is smaller, the effect of reflux is smaller, so the particle distribution was more uniform.

Expansion angle is bigger, more prone to eddy current. Reducing the expansion angle is beneficial to improving the particle distribution uniformity.

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References