STUDY OF THE WATER CLEANING PROCESS BY USING CFD-DEM METHOD: A CASE STUDY OF COARSE FILTER MATERIAL

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In this paper, the CFD-DEM coupling method was utilized to study the water cleaning and regeneration process of fibrous filter material. The effects of cleaning flow rate, time and adhesion force on the particle removal process were simulated. The results showed that the particle removal rate had a diminishing marginal effect with the increasing of cleaning flow rate. More than 80% of the particles were removed in the initial period, and then tended to stabilize. The higher the flow rate, the shorter the time needed to achieve stability. For G4 filter material, the function between the particle removal rate and the cleaning flow rate and time was given, and the best cleaning flow rate was 1.2 m/s while the cleaning time was 30 s. The surface energy of the fibers plays a dominant role in the cleaning process, and the reduction to 1/4 of the surface energy of the particles can effectively improve the cleaning and regeneration performance.

Keywords: Fibrous filter; water cleaning; regeneration; CFD-DEM; fine particles

1. Introduction

Atmospheric particulate matter (PM) pollution has become a serious global problem, especially PM\textsubscript{2.5} [1]. Fiber filtration is the most effective way to control indoor PM\textsubscript{2.5} [2]. However, the deposition of particles on the surfaces and micropores of the fibrous filter material would lead to partial blockage of the air flow and also increase the filtration resistance, which would increase energy consumption [3,4]. When the air filter reaches its service life, the frequent replacement will cause material waste and increase usage cost. Improper disposal of used filters may also bring new environmental pollution [5]. Traditional fibrous filter material had poor degradability and may release particulate contaminants.
during disposal in landfills or incineration [6], such as polyethylene (PE) and polypropylene (PP). The cleaning and regeneration of fibrous filter material have received extensive attention in recent years.

Water cleaning is a common convenient and low-cost method for material recycling, and it is widely used in all walks of life. Some scholars also have carried out relevant experimental researches [7-9], such as the research on the cleaning effect of conventional coarse and medium efficiency filter material [7], the research on the cleaning effect of reverse water [8], the research on the cleaning time [9], and the filter bed design and methods of washing [10]. However, there is a lack of specific research on relevant parameters, as well as repeated and clear research. In addition, the type of water used for cleaning is also one of the indicators that determine the filter cleaning standard. The water quality will affect the residue of microorganisms and the content of bacteria [11, 12]. Some scholars have prepared a variety of washable fibrous filters in recent years, but there is still a lack of in-depth research on the effects of microscopic forces, flow characteristics and interface properties during cleaning [13]. There is a new type of high-efficiency filter composed of the polytetrafluoroethylene (PTFE) and nylon fabrics at present, and the results showed that the removal efficiency has little change after five washing cycles, with high stability [14]. However, fiber filtration and cleaning are essentially a combined problem of fluid-solid two-phase flow in micron-sized pores with particle contact adhesion and detachment in theory. The particle-fluid interaction forces during water cleaning are complex, and the van der Waals force of micron-sized particles is very important [15]. Coupled computational fluid dynamics-discrete element method (CFD-DEM) is a multi-scale Eulerian-Lagrangian technique and has advantages for considering the influence of various forces on the particle motion state [16].

A 3-D model of the coarse filter material was designed to simulate the microscopic process of cleaning in this paper. The influences of cleaning flow rate, time and adhesion force on the particle removal process were discussed, and the change of particle kinetic behavior was revealed. This study provides new insight into the cleaning of fibrous filter material.

2. Methods

The flow of the fluid phase in the CFD model is determined by the volume-averaged Navier-Stokes and the continuity equation: [17]:

$$\frac{\partial}{\partial t}(\varrho \psi J u_f) + \nabla \cdot (\varrho \psi J u_f u_f) = -\varepsilon \nabla p + \nabla \cdot (\varrho J e_f) + \varrho J g - S$$  \hspace{1cm} (1)

$$\frac{\partial (\varrho J)}{\partial t} + \nabla \cdot (\varrho J u_f) = 0$$  \hspace{1cm} (2)

where: $\rho_f$, $\tau_f$, $u_f$ are the density, stress tensor, and the velocity of the fluid. g, p, and $\varepsilon$ are the gravitational acceleration, pressure and porosity. S are the momentum exchange between the fluid phase and the particulate phase.

The transition and rotational motion of each particle is expressed by Newton's second law in the DEM [18]:

$$m_i \frac{\partial \dot{x}_i}{\partial t} = F_c + F_{nc} + F_d + F_p$$  \hspace{1cm} (3)
\[ I \frac{\partial \omega}{\partial t} = M_T + M_R \]  

where: \( F_c \) is the contact force, \( F_{nc} \) is the non-contact force, \( F_d \) is the resistance of the fluid to the particle, \( F_p \) is the pressure gradient force, \( M_T \) is the torque due to tangential contact force, \( M_R \) is the torque due to rolling friction.

The models of Hertz-Mindlin [19] and Johnson-Kendall-Roberts Contact Model (JKR) [20] are both used throughout this paper. In order to remove the deposited particles, sufficient removal force should be applied to overcome the adhesion between particles and fibers. The hydrodynamic force is the primary removal force that detached the deposited particles from the surfaces [21]. The Gidaspow model was used, which is the combination of the equations of Ergun and Wen Yu [22].

Commercial software Ansys FLUENT 19.0 and EDEM 2018 were used to conduct a coupled simulation in the Euler-Lagrange framework. To start the CFD-DEM coupling, the flow field is first calculated to converge in CFD. Then the flow information is transferred to the DEM and the interaction forces between the fluid and the particles are calculated to obtain information such as the velocity and position of the particles. Finally, the flow field is updated taking into account the effect of the particles and the simulation proceeds to the next time step.

3. Establishment of numerical model

3.1. 3-D filter and computational domain

A typical laminar filter structure was used to simplify the model in this paper [23,24]. It was based on the following assumptions: the filter material was laminar, all fibers were oriented horizontally and had the same fiber diameter, and the fibers were randomly interlaced. Washable fiber material generally had high mechanical strength and good chemical stability [25]. The structure was assumed to be constant in the simulation. The 3-D model was simplified to eight layers with a layer spacing of 15 μm and model thickness of 225 μm. The fiber diameter, porosity and fiber density were set according to G4 filter material and compared experimentally by dimensionless parameters. Table 1 shows the structural parameters of G4 filter material [26, 27].

<table>
<thead>
<tr>
<th>Grade</th>
<th>Fiber diameter(μm)</th>
<th>Porosity(%)</th>
<th>Thickness(mm)</th>
<th>Basis weight(g/m²)</th>
<th>Density(kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G4</td>
<td>15</td>
<td>95.12</td>
<td>2</td>
<td>108.76</td>
<td>1380</td>
</tr>
</tbody>
</table>

The 3-D filter model and the computational domain were shown in Fig. 1. Water flowed along the z-axis in the positive direction for cleaning, opposite to the direction of air filtration. Non-slip boundary condition was taken to the fiber surfaces. The water flow inlet boundary was imposed velocity inlet, and the outlet boundary condition was imposed pressure outlet.
The standard k-ε model was chosen to calculate the two-phase flowed field within the fibrous filter material [28]. The relevant parameters settings were shown in Tab. 2.

Table 2. Parameters applied to the simulation

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Particle</th>
<th>Fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>2000</td>
<td>1380</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>0.25</td>
<td>0.21</td>
</tr>
<tr>
<td>Shear modulus (Pa)</td>
<td>2.2×10⁸</td>
<td>3×10¹⁰</td>
</tr>
<tr>
<td>Coefficient of restitution</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Coefficient of static friction</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Coefficient of rolling friction</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Surface energy (J/m²)</td>
<td>0.1~0.5</td>
<td>0.05~0.5</td>
</tr>
</tbody>
</table>

3.2. Mesh

The arrangement of fibers in the computational domain was complicated and irregular. So an unstructured tetrahedral grid was performed. The particle motion and the flow field near the fibers were more complex and require mesh encryption. Mesh independence should be verified to exclude the influence of the mesh number on the simulation results. The initial filtration resistance of the 3-D filter was simulated at a wind speed of 1.0 m/s. The variation of the filtration resistance of the increasing of the number of grids was showed in Fig. 2. The initial filtration resistance starts to level off when the number of grids is about 3.47 million. The continued increased of grids have no significant effect on the calculation results, and the grid size near the fibers is 8 μm in this number of grids.
3.3. Experimental systems and model verification

The schematic diagram of the experimental test setup was shown in Fig. 3. The experimental set-up was built according to China's national standard (GB/T 14295-2019) [29]. The distribution of measuring points was compiled according to China's national standard (GB50019-2015) [29]. An HD2114P.0 Portable Micromanometer was used to measure filter resistance. The measuring accuracy is ± (2% reading + 0.1 m/s), and the pressure range is ± 0.4% F.S. An HD37AB1347 Indoor Air Quality Monitor was used to measure the velocity. The measuring accuracy range is ± 3%. A GRIMM1.109 Portable Aerosol Spectrometer was used to measure concentrated particles before and after the air filters were applied. The upper limit of counting concentration was 2,000,000 P/L. The particles ranging from 0.25 to 32 μm in diameter could be separated into 31 channels. The repeatability was 5%. The particle size distribution of the experimental dust was shown in Fig. 4. The particle sizes were shown with an average value of about 2.5 μm.

Fig. 3. Diagram of filter performance test bench

1-current collector; 2-upstream static pressure probe; 3-tested filter; 4-downstream static pressure probe; 5-expanding tube; 6-soft connection; 7-downstream sampling head; 8-upstream sampling head; 9-wind speed hole; 10-axial fan
Five pieces of the same material of G4 filter by using the dust were loaded to the same resistance at the filtration velocity of 1.0 m/s. The cleaning time was 10 s, 20 s, 30 s, 40 s and 50 s at the water flow rate of 1.2 m/s, respectively. The removal rate was calculated by weighing the fibrous filter material before and after cleaning, with repeated five times.

The dimensionless resistance was used to compare and verify. The airflow through the fibrous filter material is laminar, and the resistance was followed as Darcy’s law [30]:

$$\frac{\Delta p}{H} = f(\alpha) \frac{\mu V}{d_f^2}$$

where: $f(\alpha)$ is the dimensionless resistance, and $\mu$ is the dynamic viscosity of the air, and $d_f$ is the fiber diameter, and $H$ is filter thickness.

The comparison of the dimensionless resistance between CFD-DEM simulation and G4 experimental results was shown in Fig. 5(a). The slope value of the linear fit is $f(\alpha)$, and the relative deviation is 3.23%. The cleaning time of the simulation and experiment was normalized. The comparison of the particle removal rate between simulation and experiments with the trend of cleaning time under 1.2 m/s was shown in Fig. 5(b). The removal rate in the simulation was statistically calculated for the number of deposited particles before and after cleaning. The variation trends of the simulated and experimental results were in line, with an average deviation of 3.55%. In a word, the established 3-D filter and the CFD-DEM coupling method are accurate and credible.
4. Results and discussion

4.1. Effect of the cleaning flow rate

The particles are subjected to a consequent change in flow traction at different cleaning flow rates, which will affect the detachment and movement of the particles from the fiber. The change of the final removal rate of particles with the cleaning flow rate after cleaning time of the normalization time $T=1$ was shown in Fig. 6.

**Fig. 6. Effect of cleaning flow rate of final particle removal rate**

The removal rate is calculated by weighing the fibrous filter material before and after cleaning, with repeated five times. The removal rate increased from 54.78% to 92.56% when the cleaning flow rate increased from 0.2 m/s to 1.0 m/s, with an increase of 37.78%. While the removal rate increased from 95.61% when the cleaning flow rate increased from 1.0 m/s to 2.0 m/s, with an increase of only 3.05%. The final removal rate of particles increases with the increased of cleaning flow rate, but there was a marginal decreasing effect [28].

The distribution of velocity and resistance in the fibrous filter material at the cleaning flow rate was 0.8 m/s, 1.0 m/s, and 1.2 m/s at the normalization time $T=1$ in Fig. 7.
The presence of the fibers reduced the flow cross-sectional area when the water flowed through the fibers, and the average flow rate of the pores increased by to 40% compared with the inlet flow rate. The back of the fibers produced low flow rate area, which was also a low resistance area around the fibers. The front row of fibers shaded the back row of fibers so that the resistance decreases layer by layer. The cleaning flow rate increased from 1.0 m/s to 1.2 m/s, and the average flow rate in the low flow rate region was only increased by 0.02 m/s. The change in flow traction was small and the residual particles were also hardly moved, which explained the small increase in the final removal rate after the cleaning flow rate of 1.0 m/s.

4.2. Effect of the cleaning time

The resuspension rate of particles of the surface was increased with the time of the exposure to the fluid [31]. It would reach a constant state only after a period of time. The evolution of the particle removal rate with the normalization time for five different cleaning flow rates was shown in Fig. 8(a). The removal rate increased rapidly to 90.63% under the normalization time from 0 to 0.6 at the cleaning flow rate of 1.2 m/s. The removal rate increased slowly under the normalization time from 0.6 to 0.9, only 2.49%. Figure 8(a) also showed that the particle removal rate are above 80% under the rapid cleaning to stabilization. Comparison of cleaning flow rate 1.2 m/s, 1.6 m/s and 2.0 m/s, respectively, and T=0.6, 0.4 and 0.2 began to stabilize. The cleaning time had an effect on the regeneration of filter
material cleaning effect in a certain range, and then the removal rate tended to stabilize. The higher the cleaning flow rate, the shorter the time to reach stability. The cleaning flow rate was 0.4 m/s and 0.8 m/s, the removal rate for G4 was still not 90% for a longer time. The cleaning flow rate was 1.2 m/s, 1.6 m/s and 2.0 m/s, and the removal rate reached about 90%, when T=0.6, 0.44, 0.16, respectively. From the engineering considerations, it was not recommended too high flow rate for the requirement of efficient cleaning, which may damage the structure and reduce the life of the filter. The cleaning time corresponding to T=0.6 at 1.2 m/s was 30s, and the fast cleaning to 90.63% removal rate can meet the requirement of reuse. It was suggested that the cleaning parameter for G4 is 1.2 m/s and the flow rate cleaning was 30s. After converting the cleaning time, the fitted surface was shown in Fig 8 (b). The $R^2$ was 0.975, which had good coincidence. The relationship between the removal rate and the cleaning flow rate and time for G4 filter material was obtained as follows:

$$E(v,t) = 1.1 - 0.29 e^{-0.48v} - 0.81 e^{-0.11t}, (v<2.1, \ t>0)$$  \hspace{1cm} (6)$$

![Graph showing the relationship between cleaning flow rate and time for G4 filter material.](image)

**Fig. 8. Effect of non-dimensional time on particle removal rate**

Figure 9 shows that the changes of particle dynamics at a position on the windward side, when T=0.6, 0.7, 0.8, 0.9, respectively. The position of the particles on the fiber was changed, but most of them were not detached, and the velocity gradually stabilizes, only a few particles were resuspension. This may be the particles were continuously disturbed by the fluid in the low-speed turbulent environment, the potential energy gradually accumulated, and they will be resuspended when they break through the “potential energy well” of surface adhesion [32]. The energy balanced model [33] can explain this phenomenon to some extent.
4.3. Effect of the adhesion force

Figure 10(a) shows that the fiber surface energy $\gamma_f$ increased from 0.1 J/m$^2$ to 0.5 J/m$^2$ at the particle surface energy of 0.1 J/m$^2$, and the removal rate decreased from 91.89% to 80.96% at the cleaning flow rate of 0.8 m/s. This was because the increase of the surface energy of the fibers, which increased the adhesion between the particles and the fibers, and the particles was more difficult to remove from the fibers. Figure 10(b) shows that the $\gamma_p$ increased from 0.1 J/m$^2$ to 0.5 J/m$^2$ at the $\gamma_f$ of 0.2 J/m$^2$, and the removal rate decreased from 89.67% to 82.72%, which showed the same pattern as Fig. 10(a). But the difference was that with the increased in particle surface energy, which was not only increased the adhesion between particles and fibers, but also enhanced the agglomeration of particles. The absolute value of the slope of removal rate of fiber surface energy was 0.28 after linear fitting, which was larger than the absolute value of the slope of removal rate with particle surface energy 0.166. The fiber surface energy played a dominant role in the cleaning process, and reducing the surface energy of fibers can effectively enhance the cleaning and regeneration performance.

Fig. 10. Effect of surface energy
Figure 11 shows that the variation of particle removal rate with surface energy ratio \((\gamma_f/\gamma_p)\) at the cleaning flow rate of 0.8 m/s under the particle surface energy of 0.2 J/m\(^2\) and 0.3 J/m\(^2\), respectively. The removal rate increased significantly from 90.39% to 98.02% after the ratio was reduced to 0.25 for a particle surface energy of 0.2 J/m\(^2\). The removal rate increased significantly from 89.67% to 96.36% after reducing the ratio to 0.25 for a particle surface energy of 0.3 J/m\(^2\). The change of \(\gamma_f/\gamma_p\) at 1/4 is due to the fact that when the surface energy of the particle is constant, which will reduce the surface energy of the fiber reduces the adhesion between the particle and the fiber. Particles deposited in the low-velocity region were resuspended under the lower fluid drag, and detached from the fibers.

The results shows a certain cleaning flow rate, the particle removal rate could be improved when the surface energy of the fiber is reduced to 1/4 of the particle surface energy.

![Graph showing particle removal rate vs. \(\gamma_f/\gamma_p\)](image)

**Fig. 11. Effect of ratio of surface energy \(\gamma_f/\gamma_p\)**

5. Conclusion

The CFD-DEM coupling method was applied to study the water cleaning process of fibrous filter material in this paper. The conclusions of this study can be summarized as following. The removal rate of particles is increased with the increasing of cleaning flow rate, but there was a marginal decreasing effect. For G4 filter material, the best cleaning flow rate was 1.2 m/s, while the cleaning time was 30s. More than 80% of the particles were removed in the initial period in the water cleaning process, and then tended to stabilize. The higher the flow rate, the shorter the time required to reach stability. The surface energy of the fibers plays a dominant role in the process of cleaning. The particle removal rate could be significantly improved when the surface energy of the fiber is reduced to 1/4 of the particle surface energy at a certain cleaning flow rate.

The CFD-DEM method can be used to predict the optimization of cleaning operation parameters and provide guidance about the design of new washable filters.

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