Separating paint mist from paint spraying waste gas: mechanism, model and application

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ABSTRACT

The paint spraying waste gas contains a large amount of paint mist, volatile organic compounds (VOCs) and other hazardous materials, which seriously affects human health and atmospheric environment. Paint mist cannot be separated from paint spraying waste gas effectively by the existing dry filtration methods because of the filter blocking. A new separation process and a novel coupling device with high separation efficiency have been developed. A numerical model was established to optimize the structure and operation parameters of the baffle interceptor by hydrodynamics method which verified by the coupling device experiment. From the simulating results, when plate spacing was 20 mm, folding angle was 90° and airflow velocity was up to 8 m/s, the separation efficiency of paint mist with the diameter of 15 μm was 84.7% and the pressure drop of the baffle interceptor was 220.2 Pa. Experiment was conducted under the above-optimized conditions, and the results showed that the pressure drop of the baffle interceptor was 303.33 Pa, and the paint mist separation efficiencies of the baffle interceptor and the interception-filtration coupling device were 78.34% and 96.38%, respectively.

Keywords: Filtration, Numerical simulation, Paint mist, Paint spraying waste gas, Separation

1. Introduction

Paint spraying technology is widely used in industrial production. As a very important manufacturing process, it is widely used in automobile, furniture, machinery, ship, and packaging industries. Paint spraying waste gas contains paint mist and volatile organic compounds (VOCs) [1, 2], which is toxic, harmful, flammable, and seriously endangers the atmospheric environment and human health [3-7]. Paint mist separation is the key step in the treatment of paint spraying waste gas, which affects treatment efficiency, equipment investment and operation cost. Therefore, the development of a simple, efficient and low-cost separation technology for paint mist is of great significance to the protection of air quality and human health.

Generally, a two-step method was adopted for paint spraying

waste gas treatment. Firstly, the paint mist was separated from the waste gas, and then the remaining VOCs were removed by adsorption, catalysis treatment or ionization treatment [8-15]. However, challenges remained for paint mist separation, because of its small particle size and strong viscosity [16].

Currently, wet separation and dry filtration are the main processes of paint mist treatment. The wet separation method [17-22] mainly includes water spraying, water film and absorption method. The paint mist is captured by water. As a result, a huge amount of wastewater is generated [23-26]. Also, the separated paint mist is easy to clog the equipment. Then, the high humidity of the treated waste gas does harms to its subsequent treatment process. To avoid the disadvantages from wet separation, a dry filtration is developed by using filter materials. For spray booths, appropriate ventilation and paint mist separation equipment are needed with

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Received August 13, 2020 Accepted October 12, 2020

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the separation efficiency from 95% to 99%. [27]. The dry separation technology is normally used in craft paper and synthetic nonwovens production industry since 1990s. Recently, it was used for paint mist separation. Mechanism of paint mist separation by using dry filtration was discussed by Anand. S. [28] Compared with wet purification technology, dry filtration method takes advantages of generating no wastewater, relatively simple equipment and low energy consumption. Furthermore, a $\text{Ca}(\text{OH})_2$ powder spraying technology was developed by Lee J R. et al., to alleviate the adhesion problem caused by paint mist particle [29]. It is considered to be a more economical and efficient method for separating paint mist. However, there are still many challenges remained. Most of the filter materials used in dry filtration cannot be reused. Because of the blockage of filter materials by paint mist, the dry filter device cannot operate continuously. It is necessary to replace the filter materials frequently, and the waste filter materials must also be treated as hazardous wastes. The cost increased significantly due to manual maintenance, replacement of filter materials and solid waste treatment.

In this study, the properties of paint mist were analyzed and the mechanism of filter blocking was studied. Based on previous research [30], an interception-filtration coupling technology was proposed. A numerical model was established in this study to optimize the structure and operation parameters of the baffle interceptor. The optimized parameters were verified by a practical operation which carried out by the interception-filtration coupling device. A numerical model was established, and an interception-filtration coupling device was developed based on the optimized parameters, which suggests the efficient and economical separation of paint mist from paint spraying waste gas.

2. Experimental

2.1. Materials

In this study, a quick-drying paint was prepared according to the ratio of topcoat : diluent : curing agent = 4:2:1, the main components of the paint are shown in Table S1. The paint was sprayed by a piece of spraying equipment to produce spraying waste gas which contains paint mist, and the produced paint mist was collected as experiment material.

2.2. Treatment Process and Equipment

The process flow of paint spraying waste gas treatment is shown in Fig. S1. Paint mist separation was achieved by the dry filter, and the remaining VOCs of waste gas was sent to the next step for further treatment.

The interception-filtration coupling device used in this study consists of a baffle interceptor and a dry filter. The dry filter is composed of polytetrafluoroethylene (PTFE) membrane filter element and a pulse back blowing system. Fig. S6 presents the schematic illustration of interception-filtration coupling device. The device was mainly composed of gas collection device, baffle interceptor, dry filter and fan. The structural dimensions of the baffle interceptor are as follows: the length of the straight section was 50 mm, the length of the bending section was 100 mm, the plate

spacing was 20 mm, and the folding angle was 90°. The airflow of spraying waste gas entering the gas collection device was 1140 Nm^3/h , and the airflow velocity at the inlet of baffle interceptor was 8 m/s. There were two detection points for paint mist concentration and pressure measurement which located before and after the baffle interceptor; Another detection port was provided for the paint mist concentration detection.

2.3. Methods

2.3.1 Analysis methods

The paint mist collected by the dry filter was analyzed by Scanning Electron Microscopy (SEM), Energy Dispersive Spectrometer (EDS), X-ray diffraction (XRD) and Fourier transform infrared (FT-IR). The surface morphology and elemental content of the flocs were characterized by SEM (Hitachi S-4800, Japan) equipped with EDS Analyzer. The XRD patterns were obtained using an X-ray diffractometer (Shimadzu 6100, Japan) with $\text{Cu K}\alpha$ radiation ($\lambda = 1.5418 \text{ \AA}$) in the 2θ range of 10–80° for crystalline structure investigation. The FT-IR spectra were obtained using a MAGNA-IR 560 spectrometer (Nicolet, USA) with the KBr tablet method at room temperature.

2.3.2 Numerical method

The flow field in the single channel of the baffle interceptor was simulated by ANSYS fluent 18.0. Separation efficiency and pressure drop are the key parameters for the evaluation of paint mist separation facility [31]. Therefore, the influence of the structure size and the process parameters on separation efficiency and pressure drop were studied.

In the calculation model, the particle size of paint mist was assumed uniform at the entrance of the single channel. The paint mist separation efficiency is calculated based on the equation below:

$$\eta = \frac{m}{n} \times 100\% \quad (1)$$

Where m is the number of paint mist particles captured in the single channel, n is the number of paint mist particles at the entrance of the single channel.

3. Results and Discussion

3.1. Cause Analysis of Filtration Failure

The dry filter was used to separate paint mist from paint spraying waste gas. After a short time running, the pressure-drop of the dry filter increased obviously and caused a failure of continuous running. The main reason is that the filter material of the filter element was blocked by paint mist. The paint mist on the surface of the filter element and detached from the filter element (as shown in Fig. 1 (a)) were collected and analyzed, respectively, for a deep understanding of the blocking mechanism.

As shown in Fig. 1 (b), the types of functional groups present in paint mist on the surface of filter element were determined by FT-IR analysis. The corresponding relations between wave-numbers and molecular bonds are shown in Table S2. The trans-

Fig. 1. The schematic illustration of the process for treating paint spraying waste gas (a); FT-IR analysis of the paint mist on the surface of filter element (b); XRD analysis of the paint mist separated from the filter element (c).

mittance at 2960, 2927, 1279, 1074, 1126, 838, 743, 1729, 1647 and 3469 cm^{-1} is more than 50%, which can be considered as the main functional group of the paint mist on the surface of the filter element. Therefore, the functional groups in Table S2 should be derived from benzene, ether, aliphatic group, cyclic, ketone, alcohol, olefin and alkane. Aliphatic and ethers groups may cause high viscosity.

The paint mist collected from the hopper was in a loose and dry state with low viscosity. Fig. 1 (c) shows the XRD analysis of the paint mist separated from the filter element. It can be seen that the main phase was rutile phase of TiO_2 , and it also contains a small amount of SiO_2 . This is proof that paint mist is rich in TiO_2 particles.

Fig. 2 shows the SEM-EDS analysis of the paint mist on the surface of the filter element. The particle size of most paint mist was between $1\text{--}30\text{ }\mu\text{m}$. The spheres with smaller sizes kept a relatively intact shape, while the spheres with larger sizes showed signs of collapse. It indicates that it is a hollow structure inside

the sphere which caused collapse when subjected to force. The compressibility of paint mist can result in the blockage of the channel of the filter material, and make the filter difficult to be cleaned up. The main component of large particles was organic matter containing of C and O.

The SEM-EDS analysis of the paint mist separated from the filter element is shown in Fig. 3. From the results, a coarse particle surface was observed, and Ti intensity in all three points (points 1, 2 and 3) was relatively high, which is in the agreement with XRD result.

The SEM analysis of the paint mist on the surface of filter element and the paint mist separated from the filter element are shown in Fig. S2. The results show that the paint mist on the surface of filter element was spherical with high viscosity and compressibility, which is difficult to be separated from the surface of the filter element by back-blowing; the paint mist separated from the filter element was in a dry state with low viscosity, which is easy to fall off from the surface of the filter material by back-blowing.

Fig. 2. SEM-EDS analysis of the paint mist on the surface of filter element.

Fig. 3. SEM-EDS analysis of the paint mist separated from the filter element.

Based on these observations, if the high-viscosity paint mist can be intercepted and separated in the first place, the remaining low-viscosity paint mist can be effectively filtered as dry dust (the TiO_2 coated in the paint mist makes the paint mist easier to filter).

3.2. Design of Improved Separation Process and Device

3.2.1. Principle of the separation process

Based on the above research, a new separation process was put forward in this study, as shown in Fig. 4 (a). Firstly, most of the high-viscosity paint mist in spraying paint waste gas was intercepted and separated by the baffle interceptor. After that, the waste gas with low-viscosity paint mist was sent to the filter device with filter element for filtration and separation. The paint mist particles accumulated on the surface of filter material can be cleaned by

back-blowing to avoid filter element blockage, so the filter device can maintain long-term and stable operation.

3.2.2. Optimum design of the baffle interceptor

The baffle interceptor is the key equipment in this study. Baffles of the baffle interceptor were arranged in layers with the same plate spacing, and two adjacent baffles formed a baffle channel. If the design of the baffle interceptor is not reasonable, it will lead to low separation efficiency, large pressure-drop, high energy consumption, blockage, and finally cause operation failure. To get an overview of the performances, Computational Fluid Dynamics (CFD) was adopted to investigate the baffle interceptor. The internal flow field, separation efficiency and pressure drop of the baffle interceptor were simulated by CFD, and the optimized structure and process parameters of the baffle interceptor were explored.

Fig. 4. The schematic illustration of separating paint mist (a); The structural schematic (b) and geometry parameters (c) of the baffle interceptor.

3.2.2.1 Numerical simulation

a. Mathematical model

In this research, a baffle channel of the baffle interceptor was selected to establish the mathematical model. Considering the limitation of the characteristics of the baffle interceptor and calculation conditions, according to the actual situation within the allowable range, we made the below presumption during the process of modeling:

- (1) The flow field was simplified as a two-dimensional flow field in the numerical calculations, and the gas was regarded as dynamically incompressible.
- (2) Only the airflow acting on the paint mist particles was considered, and the influence of paint mist particles on airflow was neglected.
- (3) The paint mist was as assumed to be a sphere with constant particle size, the phenomenon of polymerization, fracture, collision was not considered.
- (4) The paint mist particles were assumed to be captured as soon as they crash into the wall of the route-way; The paint mist particles were considered escaped as soon as they leave the out-let of the baffle channel.
- (5) The influences of the rebound and re-entrainment above the wall of the particles were not considered.

The dispersed and continuous phases were paint mist and air respectively. The Realizable $k-\varepsilon$ model was used to simulate the gas field. In a two-dimension Euler system of coordinates, the flow field of gas was calculated by using the Semi-Implicit Method for Pressure-Linked Equation (SIMPLE) algorithm. Discrete phase particle trajectories were predicted by using the Discrete Phase Model (DPM) based on the Euler-Lagrange approach. The computations were carried out by solving the continuity and momentum equations, Navier-Stokes equation, $k-\varepsilon$ equation of continuous phase and the motion equation of particle [31, 32], which is described in Supplementary material. The model constants and parameters were set as default values and are well documented (ANSYS, Fluent)

[33]. The established model and its mesh generation by ANSYS ICEM are shown in Fig. S3 and Fig. S4.

b. calculation area and conditions

The structural schematic and geometry parameters of the baffle interceptor are shown in Fig. 4 (b) and Fig. 4 (c). The calculation conditions are shown below:

- (1) Medium condition: the continuous phase was the air with a density of 1.225 kg/m^3 and dynamic viscosity of $1.7894 \times 10^{-5} \text{ (N}\cdot\text{s)/m}^2$, the dispersed phase was paint mist with a density of 1.071 g/mL .
- (2) Inlet condition: waste gas entered the single channel of the baffle interceptor via the inlet vertically, and gas flow in the cross-section of the inlet was evenly distributed.
- (3) Outlet condition: the outlet manometer pressure was 0, and the operating pressure was $101,325 \text{ Pa}$.
- (4) Wall condition: wall surface roughness was 0, no-slip, adiabatic.
- (5) Working condition: dimensions and operating parameters of a single channel of the baffle interceptor are summarized in Table S3.

3.2.2.2 Calculation results and analysis

In Fig. 5 (a) and Fig. 5 (b), the paint mist separation efficiency increased with the decrease of plate spacing and folding angle, while increased with the increase of airflow velocity and particle size. The pressure drops increased along with the increase of the airflow velocity, but decreased with the increase of the angle; moreover, the plate spacing had no significant effect on the pressure drop, as shown in Fig. 5 (c) and Fig. 5(d).

Considering the factors of high separation efficiency, low pressure-drop and long-term operation, the parameters of the optimum conditions were found to be: 90° for the folding angle, 20 mm for the plate spacing, and 8 m/s for the airflow velocity. Under the above-optimized conditions, the separation efficiency of paint mist with diameter of $15 \mu\text{m}$ achieved 84.7% and the pressure

Fig. 5. Influence of geometry and operating parameters on separation efficiency and pressure drop: (a) plate spacing and airflow velocity; (b) folding angle and particle size; (c) plate spacing and airflow velocity; (d) folding angle.

Fig. 6. The trajectories of the paint mist (a, b, c) and velocity profile (d, e, f) in the channel of the baffle interceptor.

drop of the baffle interceptor was 220.2 Pa.

It can be seen from Fig. 6 (a), (b), (c) that most of the paint mist with a particle size of $1\mu\text{m}$ did not collide with the wall of the channel and the separation efficiency was extremely low; the larger the particles size, the more the number of paint mist particles collided with the wall of the channel, the higher the

separation efficiency. The change of particle size has little effect on the velocity field, as shown in Fig. 6 (d), (e), (f).

Fig. S5 indicates that the inlet pressure of the channel was evenly distributed, and the pressure difference between the two sides of the bend of the channel was high. A high-pressure zone was formed on one side of the bend of the channel, and a low-speed

Table 1. Test Results of Paint Mist Separation

Parameter	Position	Test 1	Test 2	Test 3	Average	Equipment performance		
The concentration of paint mist (mg/m^3)	Inlet (C_1)	139.16	106.03	103.56	116.25	The separation efficiency of paint mist (%)	Interceptor (η_a)	78.34
	The outlet of the interceptor (C_2)	21.36	25.87	28.30	25.18		Dry filter (η_b)	83.28
	The outlet of the dry filter (C_3)	5.08	3.71	3.84	4.21		System (η_c)	96.38
Pressure (Pa)	The inlet of the interceptor (P_1)	-30	-20	-30	-26.67	Pressure loss (Pa)	Interceptor (ΔP) $\Delta P = P_1 - P_2$	303.33
	The outlet of the interceptor (P_2)	-320	-320	-350	-330

Fig. 7. Particle size distribution of the paint mist before (a) and after (b) the inertial separator.

high-pressure zone was formed on the other side. Analysis in this paper shows that the essential reason for this phenomenon is that waste gas flows into the bend of the channel to one side under the action of inertia. It can be seen from Fig. S5 (a), (b), (c) that the pressure-drop decreased with the increase of folding angle, which is because the decrease of centrifugal force decreased the vortex. The pressure-drop increased with the increase of gas velocity, which is due to the increase of gas velocity leads to the increase of centrifugal force and the vortex produced, as shown in Fig. S5 (d), (e), (f).

3.3. Application Test

The test results of paint mist separation by the interception-filtration coupling device are summarized in Table 1. According to Table 1, the average separation efficiency of the baffle interceptor was 78.34%; the average separation efficiency of the dry filter and the interception-filtration coupling device was 83.28% and 96.38%, respectively. From the numerical simulation results, it can be inferred that most of the paint mist in paint spraying waste gas are particles with sizes greater than $10\ \mu\text{m}$, the remaining low concentration and low viscosity paint mist of waste gas can be effectively filtered and separated by the dry filter. Therefore, the coupling effect of interception and filtration was achieved in the system. The pressure-drop of the baffle interceptor (including a certain length of gas pipeline) was 303.33 Pa, which was consistent with the numerical simulation results. The equipment kept stable operation under the condition of low energy consumption.

The particle size distribution of the paint mist before and after the inertial separator are shown in Fig 7 (a) and Fig 7 (b), respectively. The particle size before the baffle interceptor was ranged from

$0\ \mu\text{m}$ to $32\ \mu\text{m}$. The particles with the size smaller than $9.6\ \mu\text{m}$ and $3.2\ \mu\text{m}$ were accounted for 91.48% and 71.91%, respectively. All of the particles after the baffle interceptor were with the size smaller than $9.6\ \mu\text{m}$. Specifically, 93.05% of the particles ranged from 0 to $3.2\ \mu\text{m}$. It was shown that the baffle interceptor was super effective for the particles with the size over $10\ \mu\text{m}$.

Agglomeration of paint mist led to the increase of particle size thus the paint mist removal efficiency. Impact breakage of particle agglomerates is rarely observed due to its sticky property.

Pressure drop during the experiment with or without interceptor was detected respectively. The result is shown in Fig. S7. It is clear that the backflushing frequency and residual pressure drop increased over time without an interception. Moreover, after a long time running, backflushing cannot reduce pressure drop effectively and the system shut down after 150 min operation. With the interception process, the pressure drop of the filter, backflushing frequency and residual pressure drop keeps even during the whole operation time (6 h). It can be concluded that the clogging problem can be largely reduced by using an interceptor. Other technologies which have similar separation principal with the interceptor, such as cyclone, should be studied systematically in future research.

4. Conclusions

A new separation process was established based on the characteristics of paint mist and the blocking mechanism of the filter material. A novel coupling device consisting of a baffle interceptor and a dry filter for paint mist separation of paint spraying waste gas was proposed in this study. Both simulation and experiments were

carried out to optimize its performance in terms of separation efficiency, pressure drop and long-term operation. The conclusions are as follows:

- (1) The paint mist on the surface of filter element was spherical, with high viscosity and compressibility, which is difficult to be separated by filtration; the paint mist separated from the filter element was dry and has low viscosity, which is easy to fall off from the surface of the filter material by back-blowing.
- (2) The structural dimensions and optimized conditions of the baffle interceptor are as follows: The length of the straight section, bending section and the folding angle were 50 mm, 100 mm and 90°, respectively. The plate spacing was 20 mm with the airflow velocity of 8 m/s. Under the above-optimized conditions, the separation efficiency of paint mist with a diameter of 15 μm was 84.7% and the pressure drop of the baffle interceptor was 220.2 Pa. The separation efficiency increased with the increase of the particle size, airflow velocity and the decrease of the folding angle. While with the decrease of the folding angle and the increase of the airflow velocity, the pressure-drop increased. The optimum design for the baffle interceptor was determined to achieve high paint mist separation efficiency at an acceptable pressure-drop.
- (3) The average separation efficiency of the baffle interceptor was 78.34% and the average separation efficiency of the dry filter and the interception-filtration coupling device was 83.28% and 96.38%, respectively. The pressure-drop of the baffle interceptor was 303.33 Pa. The results of the numerical analysis were verified by the application test of the interception-filtration coupling device, which provides a new way for paint mist separation from paint spraying waste gas.

Acknowledgment

This work is jointly funded by the National Natural Science Foundations of China (No. 51974115) and Hunan Provincial Innovation Foundation for Postgraduate (CX. 2018B188), Key Research Program of Hunan, China (2018SK203), Science and Technology Program of Changsha, China (kq1703026).

Author Contributions

Y.Z. (Ph.D Student) conducted the experiment design, sample characterization, data Analysis, modeling and manuscript writing. X.H. (Ph.D) conducted the experiment design, sample characterization, manuscript draft writing. W.L. (Ph.D Student) conducted the calculation of flow field and modeling. T.X. (Ph.D Student) conducted the pilot scale experiment. X.D. (Ph.D) conducted the pilot scale experiment. D.X. (Professor) conducted the flow field calculation and modeling. Z.L. (Mr.) constructed the test platform and conducted the pilot scale experiment. H.W. (Professor) revised the manuscript and conducted flow field simulation. G.Y. (Professor)

revised the manuscript.

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