Removal characteristics of paint particles generated from paint spray booths

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Abstract

The objective of this study is to eliminate the tackiness of sticky paint particles occurring in paint booths using calcium hydroxide. It ultimately aims to identify the optimal filtration velocity to determine the optimal operation condition for particle collection in the filter. As the filtration velocity increased further in the range of 0.2–0.5 m/min, the pressure drop increased rapidly, while the cleaning efficiency, overall collection efficiency, and fractional collection efficiency tended to decrease. The filtration velocity for optimal filtration condition was identified to be 0.2 m/min.

Keywords Sticky paint particle · Calcium hydroxide · Filtration velocity · Overall collection efficiency · Fractional collection efficiency

Introduction

Air pollutant concentrations continue to increase owing to dramatic industrialization. Among various air pollutants, the inhalation of paint particle causes chronic respiratory diseases, lung cancer, dizziness, headache, and nausea in humans and exacerbates air pollution, thereby deteriorating the quality of life [1, 2].

In particular, the dust generated in the business site can cause unknown diseases in civilians [3]. The global automobile demand is expected to grow and the production of automobiles will increase in proportion to the growing demand. As a result, automobile painting will also increase. The automobile paints are sticky and air pollutants from the paint spray booths will increase in the future [4].

Sticky paint particles generated inside paint booths tend to give rise to problems such as difficulty in treatment, unregulated emission, and significant environmental pollution. Paint particles are emitted in a sticky state when paint is sprayed inside a paint booth [5, 6]. Previous studies have reported the use of wet scrubbers and disposable filters to remove paint particles. However, wet scrubbers require additional water treatment technology, and disposable filters need frequent replacement [7].

Existing methods such as the use of a filter to eliminate paint particles emitted in paint booths causes filter clogging as the paint is tacky. Sticky paint particles are particularly bad for filters, reducing their performance. Therefore, it is difficult to remove paint particles with a filter. Hence, a new technology is required for filtration to prevent sticky paint particles from being released into the atmosphere to reduce environmental pollution and improve our quality of life [8, 9].

In the present study, calcium hydroxide was used to eliminate sticky paint particles in the mixing chamber and to reduce tackiness before particles are collected on the

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surface of the filter element. Subsequently, the optimal condition was identified by varying the filtration velocity.

Materials and methods

Materials

The paint used in the present study is a coating paint widely used by auto painting companies. Following the technique used in many automobile paint shops, the automobile paint (Scandal Red, Jevisco) and the paint thinner (DR-421W, Noroo paint) were mixed in a one to one ratio and were used in this experiment. A number of publications have argued that calcium hydroxide contains many holes, which lead to its capacity for adsorption [10]. The physical properties of the calcium hydroxide used to eliminate the adhesiveness of the sticky paint particles are shown in Table 1. Calcium hydroxide images at 3000 $\times$ and 5000 $\times$ magnifications using Scanning Electron Microscope (SEM) are shown in Fig. 1. The size distribution of the calcium hydroxide is shown in Fig. 2 and the average particle size is 1.3 μm . Although the exact cohesion mechanism between calcium hydroxide and paint has not been identified, the present study illustrates the cohesion of calcium hydroxide and sticky paint particles in Fig. 3.

Filter

The material of the filter media used in this study is polyester membrane, with a filtration area of 4 m^2 . Since two of these were installed, the total filtration area is 8 m^2 . The filter physical properties are presented in Table 2. The SEM images of the filter's surface and cross section are shown in Fig. 4. The width of the filter was 550 μm . After losing stickiness from the cohesion of sticky paint particles and calcium hydroxide, the mixed particles were collected on a filter and played a part in discharging only clean air into the atmosphere. Figure 3 illustrates the production method and filter collection of the mixed particles.

Table 1 Physical properties of the calcium hydroxide

Contents	Value
BET surface area (m^2/g)	37.3
Average diameter (μm)	9.82
Cumulative pore volume (cm^3/g)	0.181
Average pore diameter (nm)	10.07

Fig. 1 SEM images ($\times 3000$, $\times 5000$) of calcium hydroxide

Experimental procedure

Figure 5 shows the schematic diagram of the test unit for testing the performance of the experimental unit for the

Fig. 2 Particle size distribution of calcium hydroxide

Fig. 3 Mixed particles collected on the filter media after losing stickiness from the cohesion of sticky paint particles and calcium hydroxide

Table 2 Basic specification of experimental filter

Contents	Value
Filtration area	8 m ²
Pleat number	100
Filter media material	Polyester, membrane coating
Filter thickness	550 μm
Quality of the filter media	PTFE(Polytetrafluoroethylene)
Air permeability	7.5 cm ³ /cm ² /s
Cartridge dimension	494 mm × 1050 mm

removal of sticky paint particle using calcium hydroxide on a laboratory scale. The paint for coating was mixed with thinner at a dilutive ratio of 1:1 and then sprayed on a target coating object with a paint spray gun with compressed air at 3.0 kg/cm². The paint overspray that leaked out of the paint spray booth came into contact and agglomerated with the calcium hydroxide inside the mixing chamber (7). The pressure drop in the horizontal bag filter (11) and the activated carbon module (12) were measured with an electronic differential pressure transmitter (Rosemount, USA), with the measurement values being recorded in real time. The particle concentration of the particulate matter was measured with the aerosol spectrometer (GRIMM, model 1108). The structure and media of the filter, calcium hydroxide, and the agglomerated mixed particles of the sticky paint particles and calcium hydroxide were examined using the images of SEM (HITACHI, S-4700). Table 3 summarizes the experimental conditions.

Results and discussion

Pressure drop

The generation of drag following the accumulation of particle on the filter outer surface is referred to as pressure drop. It is expressed by Eq. (1) below [11].

$$D_p = \frac{L \times V \times t}{\rho_L} \quad (1)$$

In this Eq. (1), L represents the particle load (kg/m²); t , the filtration time (min); and ρ_L , the particle density (kg/m³) of the particle layer. Pressure drop of the filter itself is expressed as Eq. (2), and pressure drop of the particle layer as Eq. (3).

$$\Delta P_f = \frac{D_f \times \mu \times V_f}{60 \times K_f} \quad (2)$$

Fig. 4 SEM images of filter surface and cross section

Fig. 5 Schematic diagram of the laboratory scale test unit **Table 3** Summarizes of experimental conditions

Contents	Value
Flow velocity	0.2–0.5 m/min
Flow rate	1.6–4 Nm ³ /min
Number of filter elements	2
Type of the filter	Horizontal bag filter
Dimension of the filter	Depth: 494 mm Height: 1050 mm Thickness: 100 mm
Pulsing system unit	T-type pulse injector

$$\Delta P_p = \frac{D_p \times \mu \times V_p}{60 \times K_p} \quad (3)$$

In this Eqs. (2) and (3), ΔP_f , represent the pressure drop of the filter itself (Pa); ΔP_p , the pressure drop of particle layer accumulated on the filter surface (Pa); D_f , the thickness of filter (m); D_p , the thickness of the particle layer (m); μ , the viscosity of the gas (kg/m s); V_f , the filtration velocity (m/min); K_f , the filter permeability (m²); K_p , the particle layer permeability (m²); and 60 is the conversion factor (s/min).

The total pressure drop in the bag filter is defined as the sum of Eq. (2), which represents the pressure drop of the filter itself, and Eq. (3) represents the pressure drop of the particle layer. It is expressed as Eq. (4) [12].

$$\Delta P = \Delta P_f + \Delta P_p \quad (4)$$

Fig. 6 Filter pressure drop as function of filtration velocity

The formation of the particle in the filter can be detected, and the pressure drop of the initial particle removal can be measured using the given equation.

The filter cleaning interval was defined as the time interval between two cleaning operations. The filter cleaning interval also increased when the time for the pressure drop to reach the initial pressure drop becomes longer [13].

Figure 6 shows the changing trend of filter pressure drop in accordance with the filtration velocity. The increase in pressure drop was slow at a filtration velocity of 0.2 m/min compared to 0.5 m/min, and the filter cleaning interval was longer. At filtration velocities 0.2, 0.3, 0.4, and 0.5 m/min, the

average initial pressure drop was 127.72, 167.26, 196.56, and 295.18 Pa, respectively, and the average filter cleaning interval 427, 185, 115, and 40 min, respectively. As the filtration velocity increased, the tendency of the pressure drop grew faster, and the filter cleaning interval decreased.

The result showed that the filter pressure drop had a tendency for a quick increase along with an increase in the filtration velocity. On the filter surface, particle accumulate and build a particle layer with the amount of particle captured by the mechanism of inertial impaction and direct interception. Filtration velocity is an important factor in particle collection equipment with filters, and is also a factor to be considered in respect to energy required for the operation of unit.

Cleaning efficiency

Pressure drop increases as the thickness of the particle layer formed on the surface of the filter increases through the course of the operation time. To operate for prolonged periods, the particle layer formed on the filter surface should be regularly cleaned. This task is referred to as the filter cleaning efficiency [14]. Figure 7 shows the dust stuck on the bag filter and the dust falling from the bag filter by a pulsing operation. The dust falling from the bag filter was stored in a hopper.

While removing the accumulated particle layer on the filter, the efficiency of filter pressure drop recovery is referred to as its cleaning efficiency. It is expressed as Eq. (5) below [15, 16].

$$\eta_{\text{cleaning}} = \frac{\Delta P_{\text{max}} - \Delta P_{\text{R}}}{\Delta P_{\text{max}} - \Delta P_{\text{I}}} \times 100 (\%). \quad (5)$$

In Eq. (5), η_{cleaning} represents the cleaning efficiency (%); ΔP_{max} , the pressure drop (Pa) when the removal condition is reached; ΔP_{R} , the remaining pressure drop (Pa) remaining in

the filter after removal; and ΔP_{I} , the initial pressure drop (Pa) of the filter. In this study, the removal operation employed the pulse-jet type method. The cleaning efficiency of the filter following changes of filtration velocity can be determined through Eq. (5).

At filtration velocities of 0.2, 0.3, 0.4, and 0.5 m/min, the average cleaning efficiency was 99.68, 96.68, 93.12, and 89.4%, respectively. Figure 8 shows the cleaning efficiency according to the removal frequency. As the filtration velocity increased, the cleaning efficiency decreased. The average cleaning efficiency experienced a 10% difference on average up to the third removal between filtration velocities at 0.2 m/min and 0.5 m/min.

The particle layer accumulated on the filter surface was characterized by easier removal when the filtration velocity was lower rather than higher. In the removal operation, which cleans the particle layer accumulated on the filter surface, the remaining pressure drop was maintained at a high level when the filtration velocity was high rather than when it was slow. This is because a greater amount of particles dislodged from the filter surface tends to be re-entrained when the filtration velocity is high compared to when it is low.

This study found that the cleaning efficiency was correlated with the residual pressure drop. Cleaning efficiencies of 99.68 and 89.4% were followed by residual pressure drops of 127 and 323, respectively. An inversely proportional relation was found the higher the cleaning efficiency, the lower the residual pressure drop.

Collection efficiency

Overall collection efficiency indicates the collection efficiency of total number of particles being collected by filter element related to the inlet particle number concentration. It is expressed as Eq. (6) [17].

$$\eta_t = \frac{C_{\text{in}} - C_{\text{Out}}}{C_{\text{in}}} \times 100\%. \quad (6)$$

Fig. 7 Dust collection on the bag filter (a) and dust cleaning by shaking off from bag filter (b)

Fig. 8 Cleaning efficiency trend according to filtration velocity

In this Eq. (6), η_t represents the overall collection efficiency (%); C_{in} , the inlet number concentration ($\#/cm^3$); and C_{out} , the outlet number concentration ($\#/cm^3$).

The collection efficiency of particles according to the diameter size is referred to as fractional collection efficiency. It is expressed as Eq. (7) [18].

$$\eta_{fx} = \left(1 - \frac{C_{ox}}{C_{ix}}\right) \times 100\%. \quad (7)$$

In this Eq. (7), η_{fx} represent the fractional collection efficiency (%) for a certain paint particle size; C_{ix} , the paint particle number concentration ($\#/cm^3$) of the given particle size at the inlet; and C_{ox} , the paint particle number concentration ($\#/cm^3$) of the given particle size at the outlet.

The total number of particle emitted into the atmosphere was determined through Eq. (6), and the collection efficiency according to the size of the particle ranging from small particles to large particles was determined through Eq. (7). Briefly, the collection efficiency of the filter was determined, and the interpretation of the experiment with regard to the changes in filtration velocity was made possible.

Figure 9 shows the fractional collection efficiency per particle size ranging between 0.25 and 32 μm according to the filtration velocity. In all the conditions of filtration velocities at 0.2, 0.3, 0.4, and 0.5 m/min, the collection efficiency of the particle size 1 μm was maintained at 99.44, 98.4, 96.27, and 95.29%, respectively; at the particle size 2 μm , 99.87, 99.73, 98.6, and 98.24%, respectively; and at the particle size 10 μm , 99.88, 99.05, 99.3, and 98.81%, respectively. Fractional collection efficiency is characterized by its dropping efficiency when filtration velocity is high. In case of large particles, the collection efficiency increases, and it decreases when the particle size is small.

As shown in Fig. 10, the average of overall collection efficiencies at filtration velocities of 0.2, 0.3, 0.4, and 0.5 m/min

was 99.11, 97.28, 93.29, and 89.77%, respectively. When filtration velocity increased, the overall collection efficiency tended to decrease.

The decreasing tendency of collection efficiencies when filtration velocities are higher is due to the three factors that contribute to the penetration of particles: straight through, seepage, and pinhole plugs [19]. Due to these factors, particles infiltrating the interior of the collection filter increase and in turn decrease the collection efficiencies.

Filtration velocity has a decisive influence on the infiltration rate of particle in the filter. Therefore, an unlimited increase in the filtration velocity is not effective. Conversely, particles within the equipment may undergo sedimentation when the filtration velocity is unlimitedly low. It is important to identify the filtration velocity that yields maximum efficiency.

Agglomeration between sticky paint particle and the calcium hydroxide

A mixing chamber performs the role of agglomeration sticky paint particles and the calcium hydroxide. As a result, the mixed particles that have lost adhesiveness accumulate in the filter, extending the lifespan of the filter. Figure 11 is a real image after sticky paint particle and the calcium hydroxide agglomerating together through contact with each other.

Figure 12 shows images of the agglomerated sticky paint particle and calcium hydroxide at magnifications using a SEM. The observation of the images showed that the average size of the sticky paint particles was 5 μm [20]. The areas expected to be the calcium hydroxide and un-agglomerated sticky paint particles were 4.857 μm and 4.933 μm , respectively. The remaining areas, observed by naked eye, were determined to be an agglomeration of the calcium hydroxide and sticky paint particles.

Fig. 9 Fractional collection efficiency trend according to filtration velocity

Fig. 10 Overall collection efficiency trend according to filtration velocity

Fig. 11 Real image after sticky paint particle and the calcium hydroxide agglomerating

Conclusions

In this study, we used a hybrid air purifier to remove sticky paint particle generated from paint spray booth. The adhesiveness of the paint was eliminated using a mixing chamber where agglomeration of the paint particle with calcium hydroxide takes place. A filtration velocity of 0.2 m/min showed a lower increase of pressure drop compared to 0.5 m/min. At filtration velocities of 0.2, 0.3, 0.4, and 0.5 m/min, the average initial pressure drop was 127.72, 167.26, 196.56, and 295.18 Pa, respectively; the average removal time 427, 185, 115, and 40 min; and the average cleaning efficiency 99.68, 96.68, 93.12, and 89.4%, respectively. The filtration velocity of 0.2 m/min yielded the best results. Filtration rates below 0.2 m/min were considered as terminal velocity at which mixed particles formed from the cohesion of sticky paint particles and calcium hydroxide sank to the bottom before being collected on a filter.

In conclusion, our study results serve as valuable data for determining the optimum conditions for the efficient operation of integral air purifiers in removing sticky paint particle generated from painting facilities.

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Fig. 12 Photographs of agglomerated calcium hydroxide and sticky paint particles by SEM and un-agglomerated sticky paint particle picture

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