Performance evaluation of a three-stage composite wet scrubber for removing particulate matter

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Abstract. A three-stage composite wet scrubber was designed and developed to scrub fly ash particles through different modules from the effluent gas stream of an industrial production. The flue gas entering the scrubber is purified by the falling film scrubbing of Raschig ring packing, the spraying settlement of water mist, the mesh water film interception of grilles, and the electrostatic adsorption of filaments, thereby removing particulate matter and water mist. In the experiment, the particle removal efficiency at different packing heights, the inlet concentrations of fly ash and the inlet flow rates of flue gas were investigated. The experimental results show that, without any additives or pretreatment, the packing height is 30 cm, the particle removal efficiency of the new scrubber can reach more than 99.5%, and the outlet concentration is less than 8.75 mg/m³ when the inlet concentration of fly ash is less than 12.53g/m³ and the inlet flow rate is less than 12.13 m³/s. The three-stage composite wet scrubber was evaluated to add a novel scrubber in the list of wet scrubbers for industrial applications. This wet scrubber has a simple structure, easy operation, improved compactness, and high efficiency at low energy consumption.

1. Introduction

Wet scrubbbers are effective for removing particulate matter from fly ash in polluted gases. Wet scrubbbers are widely used in industrial dust removal due to their simple structure and ease of operation. Among all kinds of wet scrubbbers, spray scrubber has the advantages of simple structure, small pressure loss and not easy to be blocked by dust. However, the spray dust removal efficiency is low, and the gravity spray dust collector is mainly used for large-sized dust particles. The dust removal system with a combination of filler and spray technology shows a reliable dedusting effect. Li[1] analysed the effects of various factors on the removal of fine particles in a packed bed. The experimental study[2] on the pressure loss and interfacial resistance of two-phase flow in a porous bed filled with coarse particles indicated that interfacial resistance plays an important role in the total pressure loss of the bed containing coarse particles. This study confirmed the effectiveness of wet scrubbbers with packed bed.

Conventional wet scrubbbers often require high water and energy consumption to improve dust removal efficiency and have limited capability in removing fine particles. Researchers still aim to improve the dust removal efficiency of wet dust collectors. For instance, Ebert[3] studied wet scrubbbers that require different nozzle types and spray characteristics to achieve effective performance. Li[4] developed a column dust collector based on orifice plate and proposed that the impact of dust removal can be strengthened by making the gas-liquid mix uniform and stable.

In this research, a new type of three-stage composite wet scrubber was developed using different dust collection modules for filtering dust particles with different sizes. The dust removal system combines...
various dust removal mechanisms to improve the efficiency of dust removal. In the experiment, the particle removal efficiency at different packing heights, the inlet concentrations of fly ash and the inlet flow rates of flue gas were investigated.

2. Development of the three-stage composite wet scrubber

2.1. Experimental setup of the scrubber

A schematic of the three-stage composite wet scrubber developed in this study (figure 1). The scrubber is composed of a transparent plexiglass column with a height of 3 m and an inner diameter of 0.5 m and is divided into upper, middle and lower layers. At the bottom of the column, an air inlet pipe, which is connected with the centrifugal blower, with 1.5 m length and 0.13 m diameter is fitted. The supporting plate, as shown in figure 2(a), used for carrying the packing was installed on the lower layer of the scrubber to sustain the ceramic Raschig rings (parameters of a ceramic Raschig ring: 25 mm diameter, 210 m²/m³ specific surface area, and 73% porosity). The two metal axes connected with the coupling (two axes sleeved together) extend vertically downward from the central position of the tower top, the inner axle extends to the bottom end of the middle layer of the scrubber, and the outer axle extends to the bottom end of the upper layer. The three grilles are composed of wires with a fine grid of 1 mm diameter (figure 2(b)). They are arranged transversely at an angle of 45° with the inner axle, perpendicular to each other and staggered. The upper layer of the scrubber is filled with dense adsorption-filaments which have an electrostatic adsorption function, and the effect (figure 2(c)). Two motors are mounted on top of the tower to drive the inner and outer shafts to rotate, and the grilles and the absorbing filaments rotate with the axis. Four single-outlet atomising nozzles are installed on top of each layer of the scrubber for atomising water into fine droplets. Figure 2(d) presents the layout of the nozzles and atomisation effect.

2.2. Working principle of the scrubber

Fly ash enters the scrubber through a motor-driven screw feeder mounted on the air inlet pipe, and the adjustment range of the particulate feeding rate is 1.05~3.84 kg/h by changing the motor frequency. When the fly ash enters the air inlet pipe, it is thoroughly mixed with the airflow generated by the blower to form a dust-laden flue gas for the scrubbing experiment. The flue gas from the inlet pipe initially enters the lower layer of the scrubber and meets packing. At this time, the water used for scrubbing is pumped from the water storage tank through a pump and atomised at the top of the lower layer of the
tower by using the single-outlet atomising nozzle. The fine droplets produced by atomisation fall onto the packing surface to form a uniform water film. The characteristic of large specific surface area for the packing greatly increases the contact area of the dust-containing gas with the liquid, and enhances the adsorption effect of the water film on the fly ash particles. The flue gas is subjected to primary dust removal under the action of falling film adsorption; spray water mist scrubbing and gravity sedimentation to remove particulate matter with large particle size and fine dust particles. The residual fly ash particles enter the middle layer of the scrubber with the gas flow, and the sewage is discharged through the sewage pipe.

When the flue gas enters the middle of the scrubber, the rotating scraper grids enhance the airflow turbulence and increase the gas flow distance. The fine water droplets generated by atomisation fall on the grid and form a water film to intercept the particulate matter. This arrangement is advantageous to the full contact between droplets and dust particles for an improved scrubbing effect. Wastewater after scrubbing will flies to the inner wall of the tower under centrifugal force, and flows down into the sewage pipe. The function of the flap is to prevent water droplets from falling to the lower layer. Such fine particulate matter is removed through the mesh water film interception and spray settlement in the middle section of the scrubber. The gas entering the upper layer must to be defogged due to high humidity. Water mist and remaining particulate matter in the gas stream are electrostatically adsorbed by the rotating wetted filaments (the nozzle of the upper scrubber has stopped working). The water mist accumulates on the fiber surface to form a liquid, which also flies to the inner wall of the tower under the action of centrifugal force. Clean gas is discharged through the top exhaust pipe.

![Figure 2](image)

Figure. 2. Sub-equipment of the three-stage composite wet scrubber
(a) Supporting plate; (b) grilles; (c) adsorption filaments; (d) single-outlet atomising nozzles; (e) overflow tank.

2.3 Experimental Materials and Methods

The dust used in the experiment came from the fly ash produced after coal combustion in a thermal power plant, and it was used in the dust removal experiment after drying. The particle shapes were observed under an Olympus BX51 microscope. As shown in figure. 3, the particle shape was nearly spherical. The particle size distribution of fly ash was measured using a laser particle size analyser. Figure. 4 presents that 84% of the particle diameters were larger than 10 μm. In terms of quantity, the particles with a size of 19 μm occupied the largest proportion.

As the experiment used a single outlet atomising nozzle, the water flow rate was fixed at 9 L/min. In the experiment, the packing layer height ranged from 5 cm to 30 cm, the inlet flow rate of flue gas ranged from 3.60 m³/min to 13.95 m³/min, and the inlet concentration of gas particulate matter ranged from 2.71 g/m³ to 12.53 g/m³ were studied by changing the above-mentioned variables.

![Figure 3](image)

Figure 3. Shapes and sizes of dust particles
3. Experiment and results

The height of the packing layer, the particle concentration at the inlet and the flow rate at the flue gas inlet are three main parameters in the actual operation of the scrubber. They directly affect the performance of the scrubber. They must be considered to achieve the objectives of high efficiency and low energy consumption.

3.1. Effect of packing layer height on the particle removal performance of the three-stage composite wet scrubber

Figure 5 shows the effect of packing layer height on the fly ash removal efficiency and particulate matter outlet concentration of the packing section in the three-stage composite wet scrubber at different inlet concentration. $c_{p,out}$ was used to represent the concentration at the packing section outlet. The inlet flow rate of flue gas was maintained at 9.4 m$^3$/min. As the packing layer height increased, the efficiency filler section also increased gradually, whereas the concentration of particles at the outlet of the lower layer of the scrubber decreased gradually. When the packing layer height was increased to 25 cm, the increasing trend of particle removal efficiency and the decreasing trend of particle outlet concentration tended to be gentle. At this time, the fly ash removal efficiency and particulate outlet concentration of the packed section reached 96% and 100.7 mg/m$^3$ respectively with particulate matter inlet concentration of 2.70 g/m$^3$. The flue gas after primary scrubbing still maintained a large particulate matter removal potential. The role of the middle and upper layers of the scrubber was further prominent.

Figure 6 presents the efficiency of the overall fly-ash removal of the three-stage composite wet scrubber. A high efficiency of 99.6.7% and outlet concentration of 8.75 mg/m$^3$ were obtained for a packing layer height of 30 cm with a particulate matter inlet concentration of 2.70 g/m$^3$ and inlet flow rate of flue gas of 9.4 m$^3$/min. Figure 5 and figure. 6 show that the fly ash removal efficiency and outlet concentration have similar trends. The fly ash removal efficiency in figure 5 indicates that the packing in the lower layer of the scrubber filters most of the particulate matter in the flue gas. Thus, the packing section, as the first step of the washing and filtration of particulate matter, plays an important role in the dust removal of the entire system. The efficiency curve with a particulate matter inlet concentration of 6.45 g/m$^3$ is constantly above the curve with an inlet concentration of 2.70 g/m$^3$. Although the former has a high concentration of outlets, the particulate matter inlet concentration plays a critical role when calculating the dust removal efficiency, thus, the fly ash removal efficiency is also high.
Figure. 5. Effect of packing layer height on $\eta_p$% and $c_{p,\text{out}}$ of the packing section in the three-stage composite wet scrubber at different inlet concentrations of particulate matter at a flue gas flow rate of 9.4 m$^3$/min

Figure. 6. Effect of packing layer height on $\eta$% and $c_{\text{out}}$ of the three-stage composite wet scrubber at different inlet concentrations of particulate matter at a flue gas flow rate of 9.4 m$^3$/min

The most apparent difference between figure. 5 and figure. 6 is that in the range of particle removal efficiency and outlet concentration. As the packing height increased, the range of particle removal efficiency increased significantly from 93.0%-98.1% to 99.2%-99.8%. The outlet concentration changed greatly from 92.3-232.2 mg/m$^3$ to 8.8~28.4 mg/m$^3$. This finding indicates that the middle and upper layers of the scrubber can remove fine particulate matter that escapes from the packing layer, thereby playing a critical role in the deep dust removal of flue gas. Thus, the overall efficiency in the three-stage composite wet scrubber was improved. This result proves that the water film interception of grille meshes and the electrostatic adsorption of filaments have clear effects on the removal of fine particulate matter.

3.2. Effect of the particulate matter inlet concentration on the particle removal performance of the three-stage composite wet scrubber

Figure. 7 shows the effect of the inlet concentration of fly ash on the particle removal efficiency and particulate matter outlet concentration of the three-stage composite wet scrubber at different inlet flow rates of flue gas. The packing layer height was maintained at 30 cm. With the increase of the particulate matter inlet concentration, the particle removal efficiency curve slowly increased and tended to be flat, and the particulate matter outlet concentration curve showed a steady upward trend. An increase in particulate matter contained in a unit volume of flue gas caused an increase in load on the scrubber. Therefore, additional fly ash escaped from the scrubber, and the particulate matter outlet concentration increased, which was consistent with the general particulate removal law. The increase in efficiency was marginal but remained above 99.6% for the range of operated variables. At the same particulate matter inlet concentration, the small inlet flow rate of flue gas caused the particulate matter to be filtered further fully, thus, the effect was considerable.
Figure 7. Effect of fly ash inlet concentration on $\eta$% and $c_{out}$ of the three-stage composite wet scrubber at different inlet flow rates of flue gas at a packing layer height of 30 cm

Figure 8. Effect of fly ash inlet concentration of on $\eta_{p}$% and $c_{p, out}$ of the packing section in the three-stage composite wet scrubber at different inlet flow rates of flue gas at a packing layer height of 30 cm

Figure 9. Effect of the inlet flow rate of flue gas on the overall particle removal efficiency of the three-stage composite wet scrubber.

3.3. Effect of the inlet flow rate of flue gas on the particle removal performance of the three-stage composite wet scrubber

Figure 9 presents the effect of the inlet flow rate of flue gas on the overall particle removal efficiency of the three-stage composite wet scrubber. The packing layer height was maintained at 30 cm. Figure 8 shows that when the inlet particle concentration was kept constant, an increase in the inlet flow rate of flue gas increased the outlet concentration, thus, the overall particulate matter removal efficiency was decreased. A similar trend was observed for the performance characteristics of the particulate matter inlet concentration at 3.29 g/m³ and 7.08 g/m³. At a low inlet flow rate of flue gas, considerable amount of inlet solid obtained additional residence time in the three-stage composite wet scrubber due to low gas flow rates, resulting in maximum efficiencies. The flue gas was more thoroughly washed and filtered in the scrubber to enhance particle removal.
4. Conclusions
A three-stage composite wet scrubber system, which combines the falling film scrubbing of packing, the spraying settlement of water mist, the mesh water film interception of grilles, and the electrostatic adsorption of filaments, was developed. The effects of packing layer height, flue gas flow rate and the inlet concentration of flue gas on the particle removal efficiency of the scrubber were investigated through experiments. The following conclusions were obtained: The particle removal efficiency of the three-stage composite wet scrubber increased with the increase packing height and fly ash inlet concentration, and decreased with the increase in the inlet flow rate of flue gas. The packing section removed more than 95% of the particulate matter as the first step in flue gas scrubbing. The outlet concentration of the scrubber was greatly reduced compared with the packing section. This finding indicated that the middle and upper layers of the scrubber can remove fine particulate matter that escapes from the packing layer, thereby playing a critical role in the deep dust removal of flue gas. Thus the overall efficiency in the three-stage composite wet scrubber was improved. When the particulate matter inlet concentration was fixed at 5.31 g/m³, a low flue gas flow enabled the gas to achieve long residence time in the scrubber and enhanced the dust removal effect. When the flue gas flow rate was 4.8 m³/min, the dust removal efficiency was 99.85%, the particulate matter outlet concentration was 7.5 mg/m³, and the dust removal performance was the best.

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References
[1] Li ZY, Kun D, Yan L, Zhang LL, Sun BC, Chu GW, Zou HK, Chen JF. (2017) Study on the removal of fine particles by using water in a rotating packed bed. The Canadian Journal of Chemical Engineering, 95(6):1063–1068.
[2] Li LX, Kong LB, Zou XM, Wang HS. (2016) Pressure losses and interfacial drag for two-phase flow in porous beds with coarse particles. Annals of Nuclear Energy, 101(2017): 481–488.
[3] Ebert F., Büttner H. (1996) Recent investigations with nozzle scrubbers. Powder Technology, 86(1): 31–36.
[4] Li XC, Xu XH, Zhang MR, Jiao YK. (2019) Column dust scrubber based on the orifice plate to intensify the gas-liquid mixing. Chemical Engineering & Technology, 42(11): 2302-2309.