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# Agglomeration of particles during coal combustion in multistage spouted fluidized tower

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**Abstract**−An experimental platform of spray agglomeration has been designed and built for removing small fly ash particles ($PM_{10}$) from coal combustion. Systematic experiments were conducted in a multistage spouted tower using kinds of agglomerant solutions. The particle concentration increases greatly from the first stage to the second stage of the tower. With the increase of flue gas flow rate the oscillation of impulse signal response curves increases and the internal circulation of the tower intensifies. The influencing factors such as the surfactant, PH value, flow rate of the agglomerant solutions and inlet flue gas temperature were analyzed. SEM was used to analyze the microstructure of the particles. Final results indicate that the special shape of a multistage spouted fluidized tower has significant influences on the effect of agglomeration. The findings from this work will be helpful to form the basis, and provide guidance for, further studies on the control of fine particles such as $PM_{2.5}$ or even smaller.

Key words: Coal Combustion, Deep De-dust, Submicron Particles, Spray Agglomeration, Multistage Spouted

## INTRODUCTION

Airborne fine particulate matter (PM) has recently become the subject of considerable environmental interest [1-4] due to its association with increased mortality, morbidity and decreased lung function, especially emitted from coal combustion sources in China [5-8]. Submicron particles ($PM_{2.5}$) are currently the main pollutants to the atmosphere in China. Although the efficiency of existing equipment (such as ESP, bag house) can reach as much as 99%, a mass of submicron particles are emitted into the atmosphere. Weifeng et al. [9-12] developed a novel submicron particle agglomeration technique to control the emission of submicron particles. The submicron particles in the flue gas are agglomerated by a physical and chemical process before the electrostatic precipitator (ESP). Then the agglomerated submicron particles can be captured by the dust collecting equipment effectively.

On the basis of previous researches, we proposed a novel style compounding spouted fluidized technique. Multistage spouted fluidized FGD technique is a new type of CFB-FGD technique. In the study of this technique we found that desulfurization ashes in the fluidized tower have notable effects on submicron particle agglomeration. Large amounts of submicron particles were found in either surface layering or agglomeration of particles. A multistage spouted fluidized tower can form stable internal circulating characteristics. The special shape of the multistage spouted fluidized tower has significant influences on the effect of agglomeration. Systematic experiments and theoretical studies have been done in this paper which can provide theoretical and technical supports for controlling small particles effectively in the tower. The methods of preparation for agglomerant solutions were also discussed with the aim of discovering some kind of cheap and effective agglomerant solution. The findings of this work will be very helpful in forming the basis, and provide guidance, for further studies on the control of small particles such as $PM_{2.5}$ or even smaller.

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## EXPERIMENTAL PLATFORM OF SPRAY AGGLOMERATION

### 1. Experimental System

The multistage spouted fluidized agglomeration system is composed of five subsystems: simulated flue gas producing system, solution preparing and spraying system, agglomeration tower, feedback system, dust removing and induced draft system. There are two stages to the multistage spouted tower. The cross sections of the both stages are square. The side length of the first stage is 200 mm, while that of the second stage is 350 mm. The cross section ratio is 1 : 3. A sketch of the system is shown in Fig. 1.

The simulated flue gas producing system contains an oil-fired air heater, burner, fuel tank and the feeder. The heat provided by

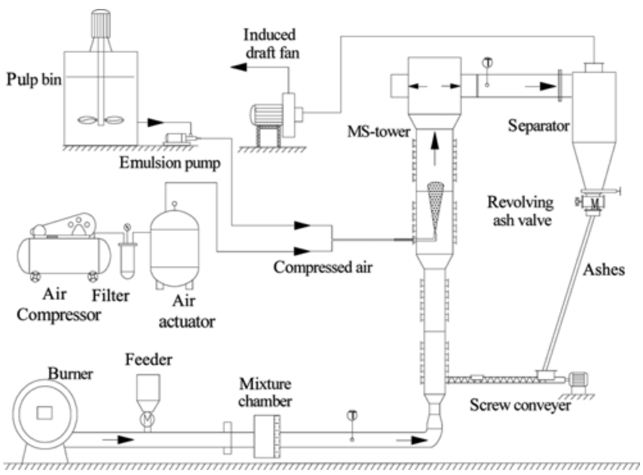


**Fig. 1. Hot condition test apparatus.**

the burner can heat air (1,000 Nm$^3$/h) up from 20 ºC to 200 ºC. The particle concentration in the system can be simulated by the dust introduced from the feeder. The flue gas distributor adopted in the system is a kind of typical concentric circular cone distributor of which the resistance is very small. There is a length of guide plates under the circular cones that are useful for stabilizing the two-phase flow. The solution preparing and spraying system contains a pulp bin, emulsion pump, atomizing system and two-fluid atomizing nozzle.

The components of the agglomerant solutions mainly include surfactant, solvent water, adsorbents, and PH value regulators. After comprehensive consideration on efficiency and economic factors, we chose four kinds of adsorbents to do the research: polyaluminium chloride (PAC), polyacrylamide (PAM), polyethylene glycol (PEG) and alginate. Solutions with different concentration were prepared by using distilled water and adsorbents. Then a certain amount of surfactant such as sodium dodecyl benzene sulfonate (SDBS) and PH value regulators was added and mixed adequately.

**2. Testing Methods**

There are monitoring holes along the tower. Fig. 2 shows the test-points of particle concentration and pressure measuring on the tower. $A_0$ and $B_0$ show the situations of the first stage of the tower; $C_0$ and $D_0$ show that of the second stage. Pressure transmitter, pitot tube and digital micro-manometer were used to record the pressure of the detection points.

Configuration software MCGS (monitor and control generated system) was used to realize the real-time monitoring. With advancing requirements of industrial control and rapid progress of software technology, the configuration software used in industrial control develops more and more quickly. MCGS is a configuration software that is based on each 32 bit operating flat roof of the Windows operating system, used to form the computer monitor and control generated system quickly. MCGS can collect and deal with the spot data, and offer the users the projects to solve the practical problems by multi-manner such as data gathering, alarming disposal, moving display and report forms output. MCGS also gives real-time and history data processing, flow control, animation display, trend curve as well as enterprise monitoring and control network.

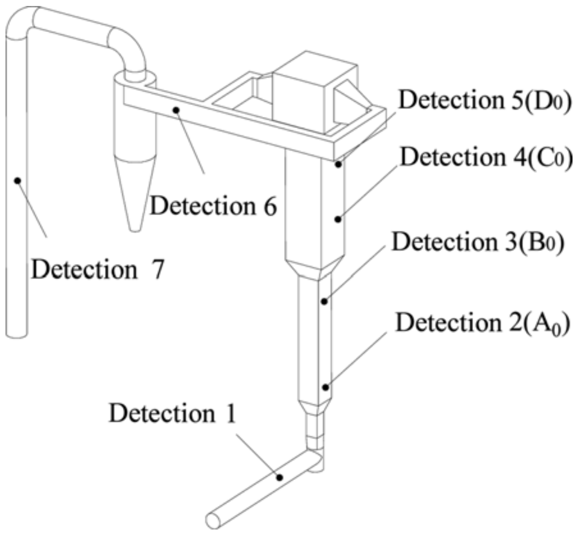


**Fig. 2. Positions of the detections.**

The particle concentration was obtained by using the method of constant speed sampling. To measure the concentration of gas-solid two-phase flow correctly and make the samples of particles be typical, the progress of sampling must be carried out under the condition of constant speed, which means the velocity of the gas in the probe is the same as that around the probe head. The sampling volume is calculated according to the gas velocity of the measuring point and diameter of the sample nozzle.

The agglomeration samples were analyzed by SEM to show the microstructure characteristics. The coal ashes we used in the experiments were obtained from Harbin Electric-Heat Co., Ltd. to simulate the particle concentration in the flue gas. The ashes were collected by the secondary ESP. The particle size distribution (PSD) of the original coal ashes is shown in Fig. 3. We can see the mass fraction of the particles which are smaller than 2.1 μm is 4.19%, while that of the particles between 2.1 μm and 3.3 μm is 7.53%. From the accumulated mass fraction we know that the particles larger than 10 μm account for 75.91%. The equivalent mean diameter of the power coal ashes is 9.36 μm. According to the empirical formulas, the minimum spouting velocity is about 0.01 m/s and the terminal velocity is about 0.004 m/s. Basic chemistry composition of the ash is shown in Table 1. The main operation parameters of the agglomeration experiment are shown in Table 2. We changed these parameters to study the influence factors of the agglomeration.

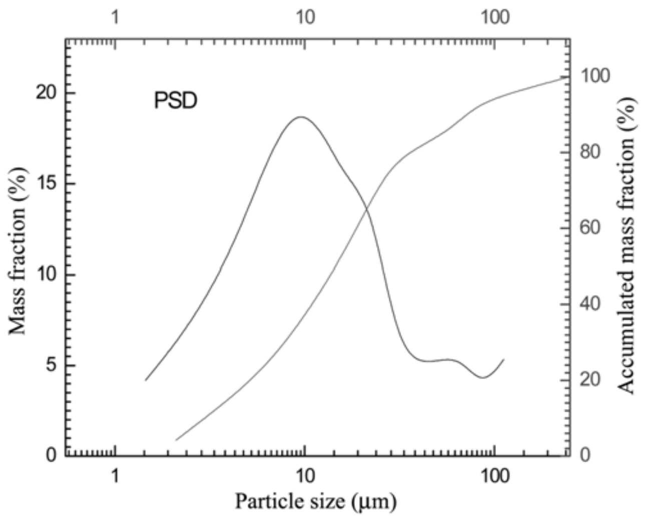


**Fig. 3. PSD of the original powder coal ashes.**

**Table 1. Basic chemistry composition of the powder coal ash**

| $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | $SO_3$ |
|---|---|---|---|---|---|
| 38-54% | 23-38% | 4-6% | 3-10% | 0.5-4% | 0.1-1.2% |

**Table 2. Operation parameters of agglomeration experiment**

| Parameter | Range |
|---|---|
| Flue gas flow rate/m$^3$/h | 500-650 |
| Temperature/ºC | 130-150 |
| Agglomerant solution flow rate/ml/min | 15-30 |
| Agglomerant solution concentration/% | 0.1-0.5 |

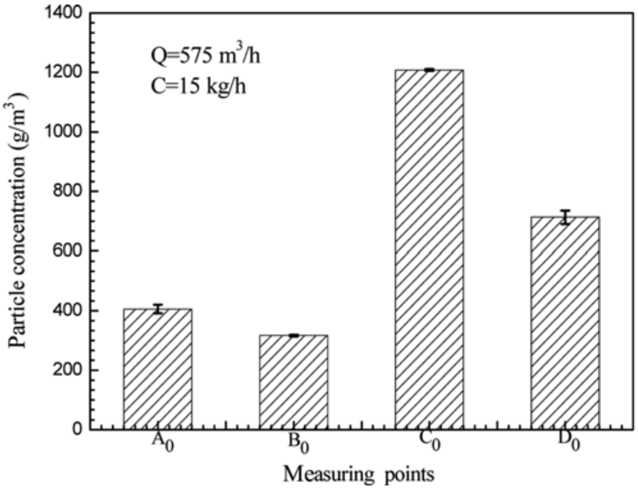


**Fig. 4. The particle concentrations of different levels of the tower.**

## RESULTS AND DISCUSSION

### 1. Particle Concentration Characteristics

The particle concentrations of different levels of the tower are presented in Fig. 4. In this experiment we kept the flue gas flow 575 $m^3$/h and particle feeding rate 15 kg/h. The ratio of flue gas velocity to minimum spouting velocity is about 130. We can see in Fig. 4 that particle concentration increases greatly from the 1st stage to the 2nd stage of the tower. It is 406 and 316 g/$m^3$ at detection $A_0$, $B_0$, while it changes to 1,208 and 713 g/$m^3$ at $C_0$, $D_0$. On the basis of previous researches, the internal circulating rate of the 2nd stage can reach 4, while 1-2 in the 1st stage. The ratio of the upper particle concentration to the lower stage is about 2. Once exterior circulating works, the ratio can reach as high as 20-30; it is related to the separation efficiency of the separator. Besides, we can see that the concentration at detection $C_0$ is the highest. It may be caused by internal circulation. The particles reflow along the wall of the 2nd stage tower to the bottom. Then they are carried upwards again by the flue gas. So the concentration becomes higher at $C_0$. Detection $D_0$ is close to the outlet of the tower and some of the particles flow out, so it is lower than $C_0$. Thus, the lower stage particle concentration is less than the upper stage. The special distribution of particles is propitious for agglomeration. The high particle concentration of the upper stage can provide more efficient reaction surfaces, which is useful for catching more small particles.

### 2. Internal Circulating Characteristics of the Tower

Results indicate that both internal circulation and the concentration of particles are enhanced by the tower's multistage spouted structure. Studies [13,14] show that an intensified internal circulation of the particles will result in a drastic increase in oscillation of impulse signal response curves. In the experiments the inlet particle concentration was kept 0.013 kg/$m^3$ while the temperature was maintained 140 °C. Fig. 5 shows the influence of flue gas flow rate on internal circulating characteristics. We can see that with the increase of flue gas flow rate the oscillation of impulse signal response curves increases. We infer that with the increase of the flue gas flow rate, the flue gas velocity in the middle of the tower increases faster than that of the sidewall. This intensifies the transverse distribution of

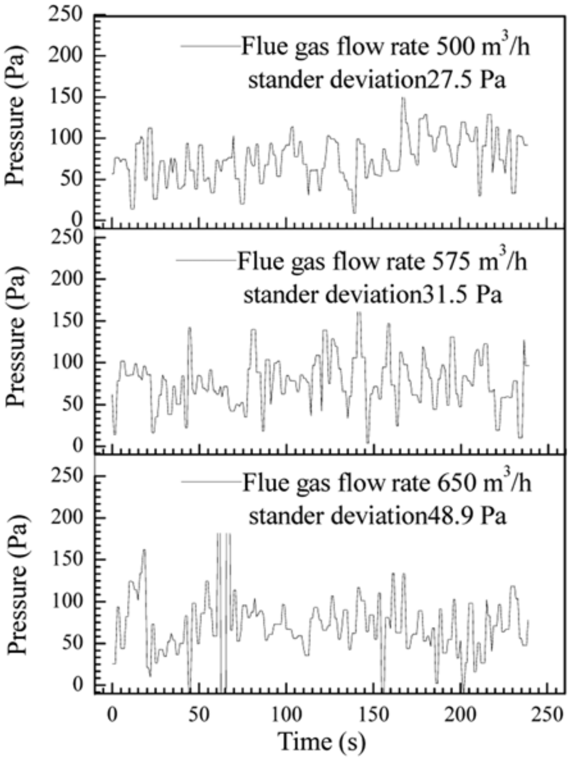


**Fig. 5. The influence of flue gas quantity on internal circulating characteristics.**

the airflow. Furthermore, the faster the gas flows, the more particles it carries upwards. All these reasons intensify the internal circulation of the tower.

There are flow guide devices in the second stage of the tower. The particles which reach the top of the tower can reflow along the devices to the bottom of the second stage. Again, they are carried by the flow from the 1st stage of the tower and form the internal

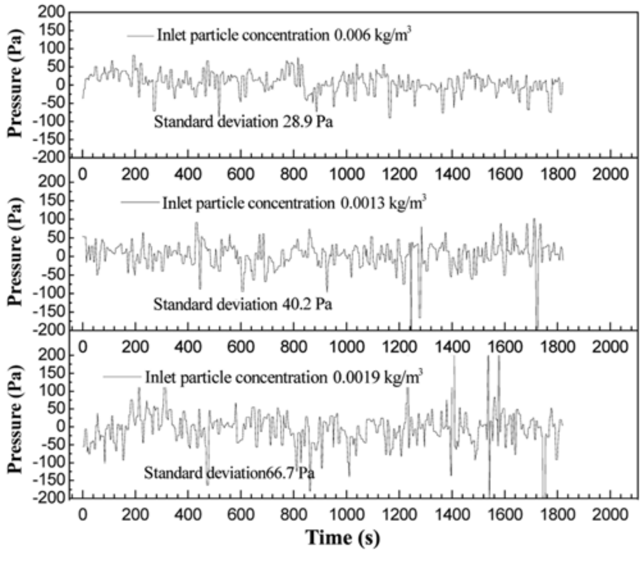


**Fig. 6. The influence of inlet dust concentration on internal circulating characteristics.**

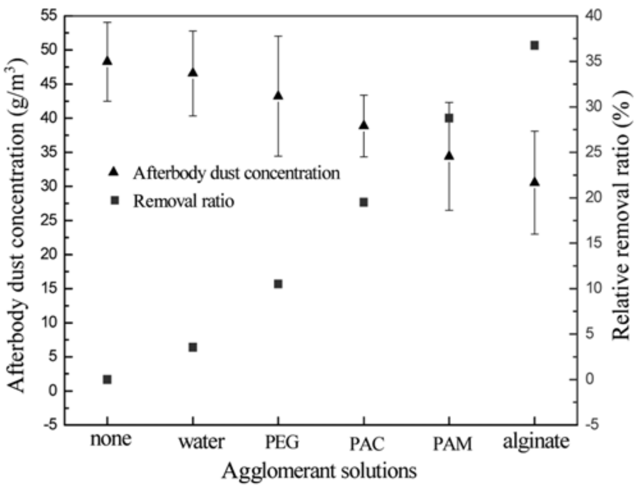


Fig. 7. The influence of different agglomerant solutions.

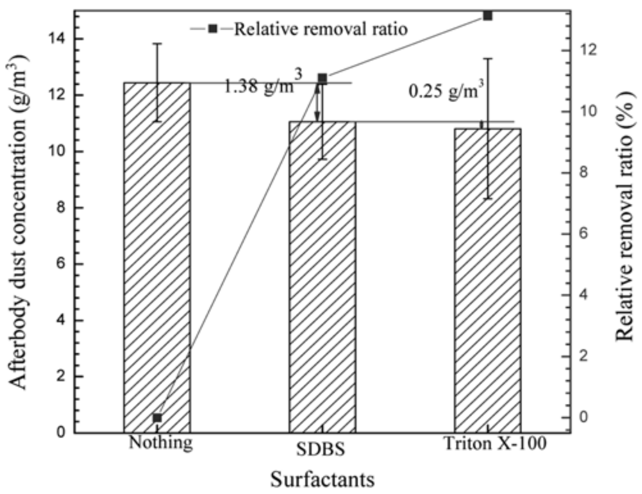


Fig. 8. The influence of the surfactants.

circulation. In the experiments the flue gas flow rate was kept 575 $m^3/h$ while the inlet flue gas temperature was maintained 140 ºC. Fig. 6 shows the influence of the inlet particle concentration on internal circulating characteristics. With the increase of the inlet particle concentration the oscillation of impulse signal response curves increases. In addition, the standard deviation of the datum also increases, which indicates that the fluctuation intensifies. We conclude that with the increase of the inlet dust concentration, the internal circulation intensifies.

**3. The Influence of Different Agglomerant Solutions on Agglomeration**

In this experiment the inlet flue gas temperature was 140 ºC and the flue gas flow rate was 575 $m^3/h$. The mass concentration and flow rate of all the agglomerant solutions were 0.1% and 25 ml/min. The afterbody dust concentrations after spraying different solutions were observed. From Fig. 7 we can see that the original afterbody dust concentration is 48.3 $g/m^3$; after water is sprayed in the tower, the concentration declines slightly. The relative removal ratio is only 3.5%. The largest decrease of the concentration happens after spraying alginate. The concentration declines to 30.5 $g/m^3$ and the relative removal ratio can reach 36.8%. PEG belongs to the kind of high polymer with low molecular weight, and the agglomerant effect is bad. The relative removal ratio is just 10.5% and it's even lower than inorganic high polymer PAC. The relative removal ratio after spraying PAM can reach 28.8%, which is just lower than that of spraying alginate.

We can see among all the agglomerant solutions that alginate has the best effect. But the price is too high to afford large scale application. Among all the polymer flocculants, PAM has been widely applied because the raw materials are cheap and easy to obtain. Besides, it has strong flocculating ability. After comprehensive consideration of efficiency and performance price ratio, PAM was chosen to study the influencing factors of the agglomeration.

**4. The Influence of the Surfactants on Agglomeration**

In the research, experimental parameters of flue gas flow rate (575 $m^3/h$), temperature (140 ºC), PAM flow rate, concentration (25 ml/min, 0.1%) and the mass concentration of surfactants (0.5%) were kept constant. We compared the afterbody dust concentration after spraying PAM with adding SDBS, adding Triton X-100 and adding no surfactants. We can see the results in Fig. 8. Compared with the situation of adding no surfactants, the concentration declines 1.38 $g/m^3$ with SDBS and 1.63 $g/m^3$ with Triton X-100. The relative removal ratio can reach 11.1% and 13.1%. It proves that the surfactants can lower the surface tension and improve the ability of wetting particles. We can also see that the effect of adding Triton X-100 is better than adding SDBS, because Triton X-100 has better wetting ability [15].

**5. The Influence of PH Value Regulators on Agglomeration**

With the decrease of PH value, the surface charge of the particles changes and the thickness of double electrical layer reduce. This makes polymer chains more flexible and extendable, which is propitious for absorbing particles. We input 0.5% phosphoric acid to adjust the PH value. Experimental parameters of flue gas flow rate (575 $m^3/h$), temperature (140 ºC), PAM flow rate, concentration (25 ml/min, 0.1%) and the mass concentration of surfactants (0.5%) were kept constant. The changes of the afterbody dust con-

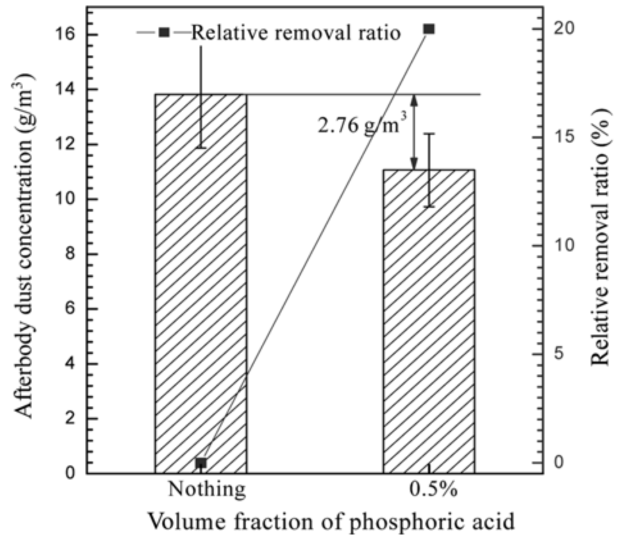


Fig. 9. The influence of PH value regulators.

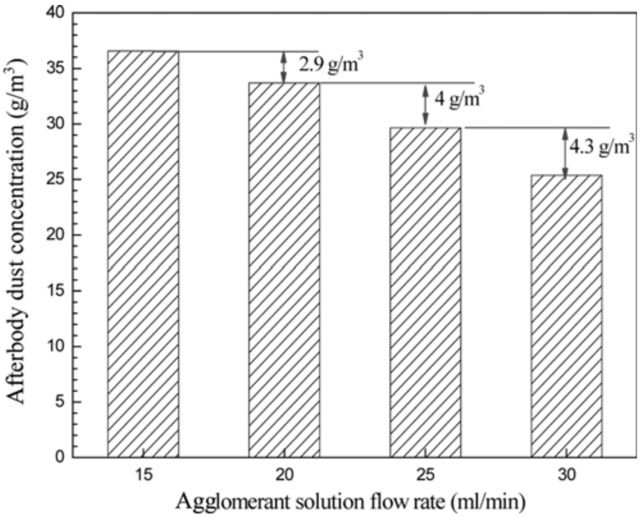


**Fig. 10. The influence of the agglomerant solution flow rate on agglomeration.**

centration were used to compare the effect of adding regulators. The results are shown in Fig. 9. We can see that the concentration declines from 13.8 g/m$^3$ to 11.1 g/m$^3$ and the relative removal ratio reaches 20%. We can infer that PH value of the agglomerant solutions has a big influence on the effect of agglomeration. The efficiency of agglomeration increases with the decline of the PH value.

**6. The Influence of the Agglomerant Solution Flow Rate on Agglomeration**

In the experiments we kept the flue gas flow rate (575 m$^3$/h), flue gas temperature (140 °C), PAM concentration (0.1%) to be constant. The afterbody dust concentration was observed after adjusting the flow rate of PAM from 15 ml/min to 30 ml/min. The final results are shown in Fig. 10. We can see that with the increase of the flow rate, the afterbody dust concentration declines and the amplitude reduction increases. It is inferred that with the increase of the agglomerant solution, the evaporation time rises and moisture circumstances are propitious to adhere particles. Furthermore, with the increase of the flow rate, the numbers of the atomized droplets increase and the probability of the collisions between the particles increases. So the agglomeration efficiency increases with the rising of the agglomerant solution flow rate.

**7. The Influence of the Inlet Flue Gas Temperature on Agglomeration**

In the experiments we kept the flue gas flow rate (575 m$^3$/h), the concentration and flow rate of PAM (25 ml/min, 0.1%) to be constant. The afterbody dust concentrations were observed after adjusting the temperature of inlet flue gas to 130 °C, 140 °C and 150 °C. The final results are shown in Fig. 11. We can see that with the increase of the flue gas temperature, the afterbody dust concentration decreases and the amplitude reduction declines from 5.3 g/m$^3$ to 3.8 g/m$^3$. The relative removal ratio reaches 32.1% and 55.3%. It is inferred that the activity of the agglomerant solution increases with the increase of the temperature. On the other hand, the high temperature makes polymer chains more flexible and extendable, which is propitious for absorbing particles. But evaporation time decreases and existing time of moisture circumstances shortens with the in-

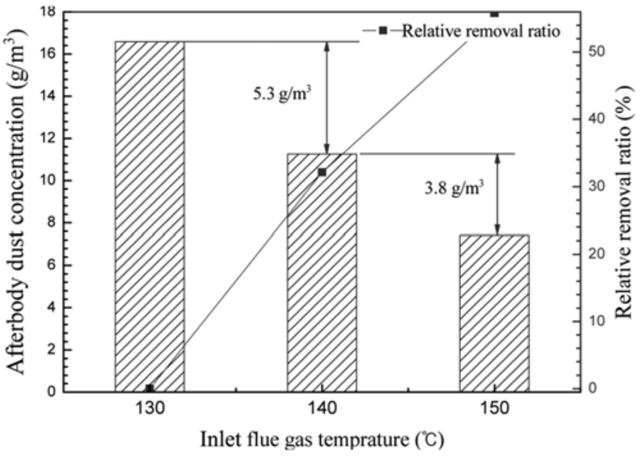


**Fig. 11. The influence of the inlet flue gas temperature on agglomeration.**

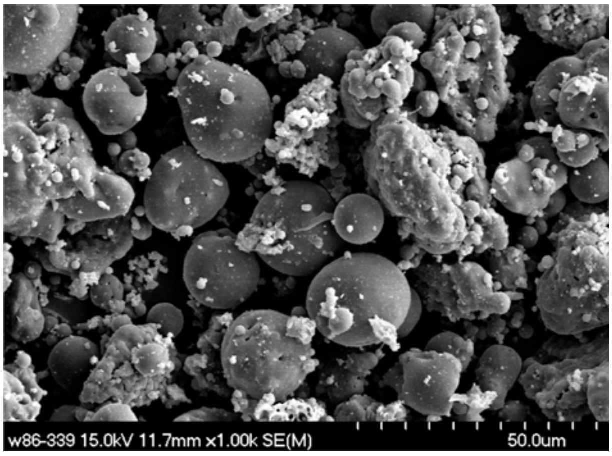


**Fig. 12. Microstructure of the original fly ash.**

crease of the temperature, which goes against adhering particles. So we can see after increasing the temperature that not only the dust concentration decreases but also the amplitude reduction becomes smaller.

**8. Microstructure Characteristics of Aggregates**

The Hitachi S-4700 SEM was used to analyze the microstructure of the particles. We can see the microstructure of the original coal ashes from Fig. 12. There are numerous regular sphere particles and cokes with irregular shape. It is obvious that large particles occupy the majority and the spaces between them are large. Fig. 13 shows that small particles increase obviously and the spaces become more compact between large-scale particles. Besides, we can see the polymer chains of PAM. Large numbers of particles are adsorbed and adhered on the chains. Through contrasting the two pictures, it is obvious that spraying agglomerant solutions can adhere large amounts of small particles, which is advantageous for agglomeration and deep de-dust. The particle size distribution (PSD) of the power coal ashes after agglomeration operation is shown in Fig. 14. We can see the mass fraction of the particles which are smaller than 2.1 μm is 1.95%, while that of the particles between 2.1 μm and 3.3 μm is 4.78%. From the accumulated mass fraction we know

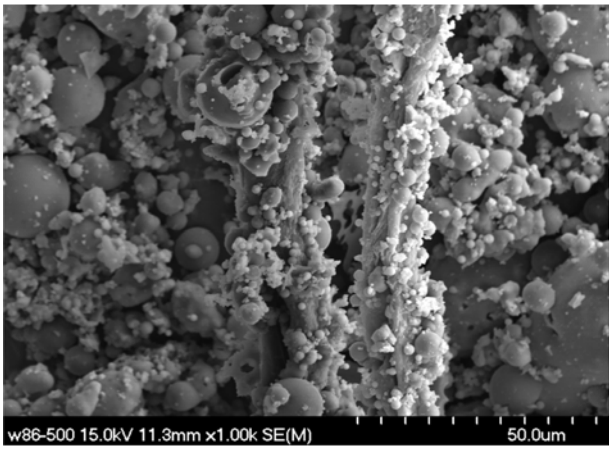


**Fig. 13. Microstructure of the fly ash after spraying PAM.**

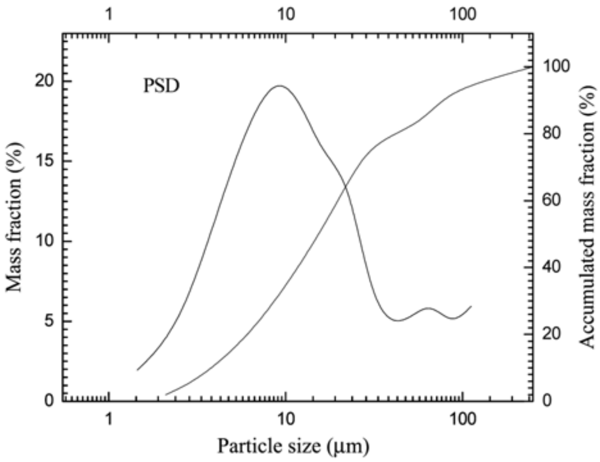


**Fig. 14. PSD of the powder coal ashes after spraying PAM.**

that the particles which are larger than 10 μm account for 79.25%. Compared with the PSD of the original ashes in Fig. 3, there is an obvious trend that particles in the large scale range increase and decline considerably in the small scale range. We can see spraying agglomerant solutions has notable effect on particle agglomeration.

## CONCLUSIONS

1. The particle concentration increases greatly from 461 g/m$^3$ in the first stage to 961 g/m$^3$ in the second stage of the tower. The special distribution of the particle concentration is propitious for forming stable internal circulation and promotes the agglomeration. With the increase of flue gas flow rate the oscillation of impulse signal response curves increases and the internal circulation of the tower intensifies.

2. Among all the agglomerant solutions, alginate has the best effect, but from comprehensive consideration of efficiency and performance price ratio, PAM is the best choice. The surfactants can lower the surface tension and improve the ability of wetting particles. Triton X-100 also has better wetting ability than SDBS. The efficiency of agglomeration increases with the decreasing PH value of the solutions. In addition, with the increase of the flow rate the afterbody dust concentration declines and the amplitude reduction increases. We can also see after raising the temperature that not only the dust concentration decreases but also the amplitude reduction is reduced.

3. SEM was used to analyze the microstructure of the particles. After spraying agglomerant solutions, small particles increase obviously and the spaces are more compact between large-scale particles. Large amounts of particles are adsorbed and adhered on the chains of PAM. Compared with the PSD of the particles, there is an obvious trend that the numbers of particles in the large-scale range increase and decrease a great deal in the small scale range after agglomeration. We can see that the special shape of the multistage spouted fluidized tower has significant influence on the effects of agglomeration, and spraying agglomerant solutions has a notable effect on particle agglomeration.

## ACKNOWLEDGMENTS

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