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Experimental Research of Coal Dust Removal System at High Temperature

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For pulverized coal pyrolysis process, it is important to separate the coal dust from coal pyrolysis gas to obtain pure coal tar gas. However, it is difficult to remove the coal dust efficiently at high temperature. A two-stage coal dust removal system which consists of a cyclone separator and a dual-layer granular bed filter has been developed. Semicoke is selected to be the filter media of granular bed filter, because after the filtration process the mixture of semicoke and coal dust can be directly burned for power generation and the regeneration process of filter granules can be eliminated. A series of experiments were conducted to study the performance of this dust removal system and the impacts of temperature and tar gas on this system. The experiment results showed that semicoke performs better than silica sand as filter media and the dual-layer granular bed filter is more effective than single layer granular bed filter in this experimental condition. The best combination of the dual-layer granular bed filter is a 10-cm-thick upper layer filled with 0.83~1.25 mm filter granules and a 5-cm-thick lower layer filled with 0.38~0.83 mm filter granules. The results of this study indicated that the whole system is capable of removing coal dust from the mixture of coal tar gas and nitrogen gas even at 723 K, efficiency reaching up to 99.95 %.

1. Introduction

Hot gas filtration has been drawing more and more attention in many industrials (Heidenreich, 2013). Examples include coal gasification, biomass gasification and pyrolysis, waste incineration and other processes. For the pulverized coal pyrolysis process, it is also significant to separate the coal dust from coal pyrolysis gas to obtain pure coal tar, so a new dust removal system is needed.

It was pointed out that granular bed filter is a promising technology for hot gas clean-up (Xiao et al., 2013). However, high efficiency is often in conflict with low pressure drop and large dust capacity for the granular bed filter. Thus, moving granular bed filter (Chen et al., 2017) and dual-layer granular bed filter(Tian et al., 2016) were created to reduce pressure drop and ensure a large dust capacity on the premise of high efficiency. Because the structure of the moving granular bed filter is too complicated, in this article, a two-stage dust removal system was developed based on dual-layer granular bed filter, which consists of cyclone separator and fixed granular bed filter. The filter was packed with dual-layer filter granules, composed of a thick upper layer of large-sized granules and a thin lower layer of small-sized granules. As a main product of the coal pyrolysis process, semicoke can be used as the filter media without preheating. Another advantage is that after filtration process the mixture of semicoke and coal dust is available for combustion electricity production directly. Nevertheless, semicoke has been barely investigated experimentally as filter media of fixed bed filter (Xiao et al., 2013).

Several experiments of granular bed filter have been done at high temperature in different gas environments, such as in air (Döring et al., 2009), in biomass gasification gas (Stanghelle et al., 2007), in nitrogen gas (Kamiya et al., 2001), and in coal gas (Ko et al., 2006), but not in coal tar gas. This article aims to test the performances of the two-stage dust removal system, considering the impacts of temperature and coal tar gas on the dedusting efficiency.

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2. Experiment

2.1 Materials and apparatus

Semicoke, with three different particle sizes from 0.38 to 0.83 mm, 0.83 to 1.25 mm, 1.25 to 2.5 mm, was used as the filter granules in the fixed granular bed filter. The particle size distribution and median particle diameter of the coal dust were measured by a particulate size analysis system (LS-909). The dust particulates ranged in size from 2.677 to 231.913 μm (as shown in the Figure1). The median particle diameter of the dust was 48.004 μm. Nitrogen was selected as test gas to ensure the safety of tar gas at high temperatures.

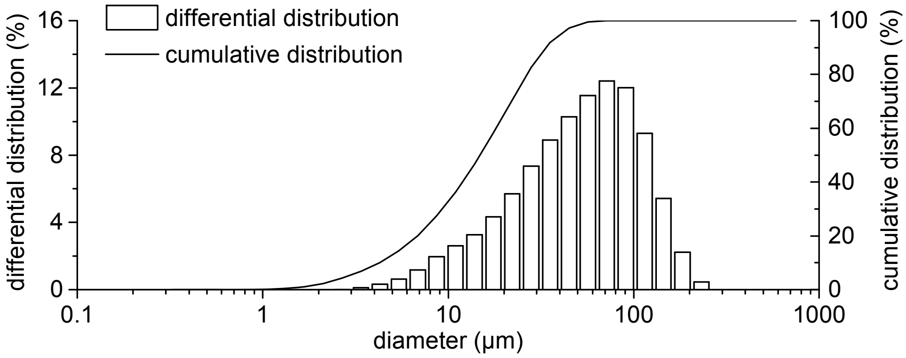

Figure 1: Particle size distribution of original coal dust

Figure 2 shows the flow chart and apparatus for the two-stage coal dust removal system, mainly containing four parts: nitrogen supply device, coal dust and tar gas supply device, dust removal device, tar condensing and tail gas recovery device. The nitrogen supply device includes an air compressor, a nitrogen bottle, two nitrogen buffer vessels and two gas boosters. Coal dust and tar gas supply device mainly includes screw feeder, tar syringe pump and gasifier. The above two devices supply a mixture of nitrogen and tar gas with coal dust for the whole system. Dust removal device, including cyclone separator and fixed granular bed filter, is a most important part of the system. Tar condensing and tail gas recovery device mainly includes settler, tar condenser and nitrogen recovery vessel.

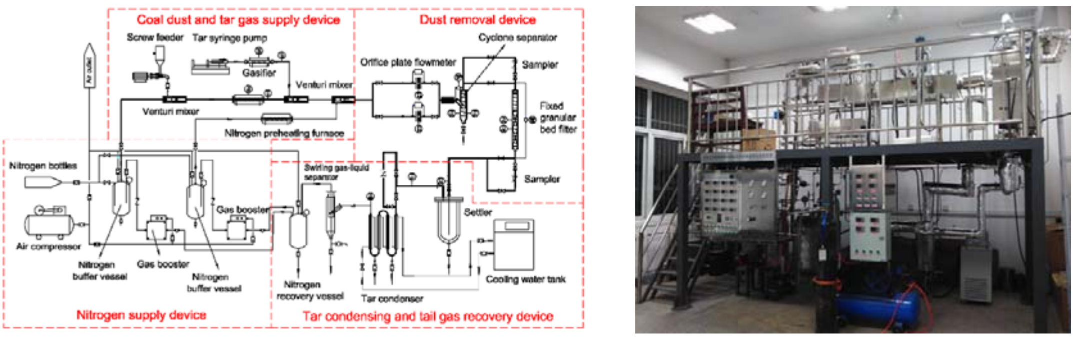

Figure 2: The flow chart and apparatus of two-stage coal dust removal system

2.2 Experimental procedure

Before the experimental testing, coal dust should be added into the hopper of screw feeder, and packed media should be filled in the fixed granular bed filter. Then nitrogen gas and tar gas were supplied. When system pressure was stable, screw feeder was opened and coal dust was mixed into nitrogen gas and tar gas. The mixture of nitrogen and tar gas with coal dust ran through cyclone separator and granular bed filter. Coal dust would be removed by cyclone separator and granular bed filter. Tar gas in the tar condenser was condensed into tar. Nitrogen flowed to nitrogen recovery vessel and was forced into nitrogen buffer vessel by gas booster, which was driven by air compressor.

We adopt weighting method to calculate dust removal efficiency of cyclone separator or fixed granular bed filter, according to the initial dust mass of the system together with the mass of dust collected by cyclone separator and granule bed filter in a certain time. The pressure difference transmitter is used to measure the pressure drop of granular bed filter.

3. Results and discussion

3.1 The separation performance of cyclone separator

When nitrogen flow rate was 1,500 NL/h, dust concentration was 75 g/m^3, the separation efficiency of cyclone separator reached up to 98.1 % at room temperature. Further analyzing and studying of removed dust diameter by cyclone separator was shown in Figure 3.

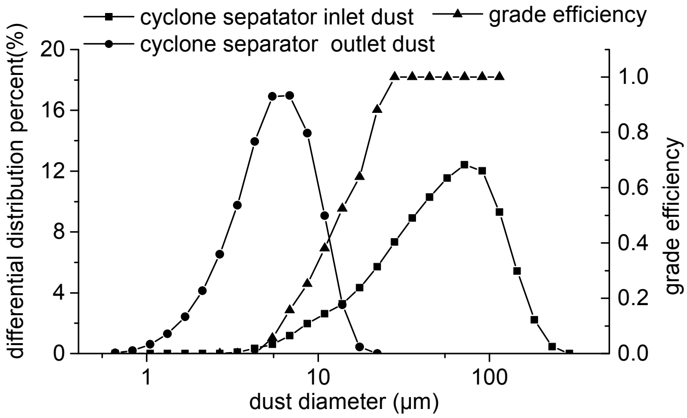

Figure 3: Particle size distribution of cyclone separator inlet and outlet dust and grade efficiency of cyclone separator

From the Figure 3, it is evident that the cyclone separator can remove the dust in the size of 28 μm or lager thoroughly, and the most of dust whose size is larger than 10 μm, but it has little effect on the dust in the size of 5 μm or smaller.

3.2 The filtration performance of fixed granular bed filter

3.2.1 The contrast of filtration performance between using semicoke and silica sand as filter granules

Silica sand was selected to be packed media in granular bed in many previous studies (Liu and Wey, 2007). Using semicoke and silica sand as filter granules respectively, we compared the filtration performance of them. Table 1 shows that fixed bed using semicoke as filter granules has much higher efficiency and lower pressure drop than fixed bed using silica sand as filter granules.

Table 1: The contrast of filtration performance between using semicoke and silica sand as filter granules

Group	Particle size range (m)	Bed deph (cm)	Nitrogen flow (NL/h)	Pressure drop (Pa)	Filtration Efficiency (%)	Filter quality factor
Semicoke	0.38~0.83	15	1,500	1,000	98.76	4.39
Semicoke	0.83~1.25	15	1,500	690	96.01	4.76
Semicoke	1.25~2.5	15	1,500	580	90.32	4.03
Silica sand	0.38~0.83	15	1,500	1,120	98.06	3.52
Silica sand	0.83~1.25	15	1,500	700	95.80	4.53
Silica sand	1.25~2.5	15	1,500	610	88.62	3.56

In addition, the fixed bed filter using semicoke as filter granules also has other advantages. One is that semicoke is very common and cheap to those coal chemistry enterprise. Another one is that it saves regeneration process of filter granules to make the whole process easier. Because the mixture of semicoke and coal dust can be directly used in other chemical process later. We just need to pack new semicoke particles in fixed bed filter. If we need to guarantee continuous operation, we can put two fixed bed in parallel. When one is at work, the other can be packed filter granules waiting for the replacement.

3.2.2 The impact of bed depth on the filtration performance of fixed granular bed filter

Figure 4 shows the impact of bed depth on filtration efficiency and pressure drop of fixed granular bed filter. We can discover from the curves in Figure 4 that pressure drop curve increases gradually and filtration efficiency curve increases rapidly firstly and slowly later with bed depth increases. Further analyzing by using the concept of filter quality factor (Kuo et al., 2010) q_f by Eq(1) shows that 15 cm high bed depth has a largest filter quality factor 4.18. In this height, the filtration efficiency is 94.39 % and pressure drop is 690 Pa.

$$q_f = \frac{-\ln(1-E)}{\Delta p} \tag{1}$$

Where q_f is the filter quality factor, E is the dust removal efficiency, Δp is the pressure drop.

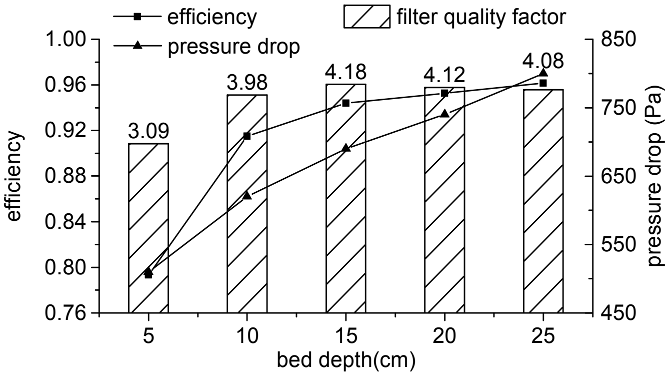

Figure 4: Filtration efficiency and pressure drop of fixed granular bed filter in various bed depth

3.2.3 The filtration characteristic of the dual-layer granular bed filter

Using semicoke as the filter granules, six groups of tests were carried out to measure the pressure drop and filtration efficiency of fixed granular bed filter. In the six experiments, #1, #2 and #3 were the single layer granular bed, and #4, #5 and #6 were dual-layer granular bed, while nitrogen flow rate was 1,500 NL/h and dust concentration was 75 g/m^3. The experimental results are shown in the Table 2.

Table 2: The filtration characteristic of the fixed bed filter with different filling schemes.

Group	Particle size range(mm)	Bed depth(cm)	Pressure drop(Pa)	Filtration efficiency	Filter quality factor
#1	0.38~0.83	15	1,000	98.76 %	4.39
#2	0.83~1.25	15	690	96.01 %	4.76
#3	1.25~2.5	15	580	90.32 %	4.03
#4	0.83~1.25 + 0.38~0.83	10+5	700	98.06 %	5.63
#5	1.25~2.5 + 0.83~1.25	10+5	622	95.97 %	5.16
#6	1.25~2.5 + 0.38~0.83	10+5	644	96.45 %	5.18

From the first three groups of Table 2 we can see that pressure drop and filtration efficiency decrease with increasing particle size range. Each filter quality factor of last three groups is higher than that of first three groups. Therefore, for single layer filter, high efficiency is in contradiction with low pressure drop. But if we adopt dual-layer granules to fill with fixed granular bed filter, the upper layer granules can ensure low pressure drop and the lower layer granules can ensure high efficiency. So dual-layer bed is better.

3.3 The total efficiency of the two-stage dust removal system

A series of experiments were carried out with the two–stage dust removal system which consists of a cyclone separator and a dual-layer fixed bed filter. The dual-layer fixed bed filter was filled 0.83~1.25 mm granules in upper layer at 10 cm high and 0.38~0.83 mm granules in lower layer at 5 cm high. Nitrogen flow was 1,500 NL/m^3 and dust concentration was 75 g/m^3. The experimental results stated that the total efficiency of the two-stage dust removal system reached up to 99.98 %. The separation efficiency of cyclone separator was 98.22 %. The filtration efficiency of fixed dual-granular bed filter was 98.08 %.

Figure 5 shows that the cyclone separator can remove most of the dust whose size is larger than 10 μm and the fixed bed filter can remove most of the dust whose size is smaller than 10 μm. Therefore, putting cyclone separator and fixed bed filter in series is benefit to both of them. The cyclone separator can remove 98 percent of the dust to reduce the workload of fixed bed filter and prolong the operating period of fixed bed filter 50 times. The fixed bed filter can remove very tiny dust to improve the total efficiency of the whole system, which is beyond the ability of the cyclone separator.

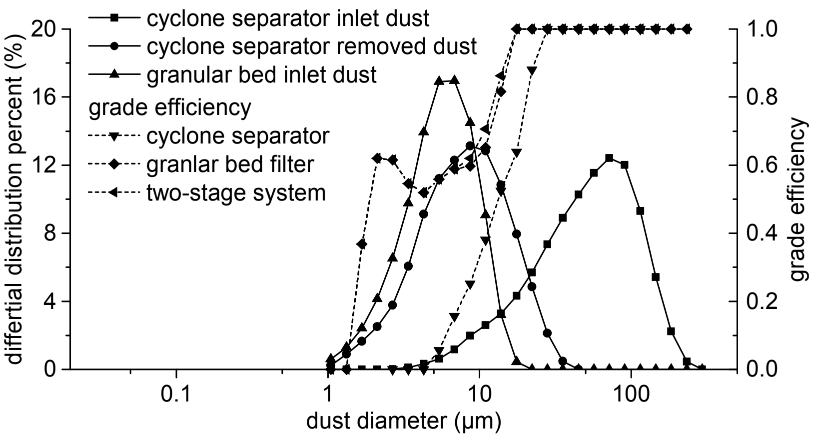

Figure 5: The particle size distribution of dust in different position and grade efficiency of cyclone separator and fixed bed filter and whole system

3.4 The impact of temperature on dust removal efficiency

3.4.1 The impact of temperature on removal efficiency without tar gas

Figure 6 shows that increasing temperature is bad for dust removal and its impact on the fixed bed filter is greater than the impact on the cyclone separator. As temperature increases from 393 K to 793 K, the separation efficiency of cyclone separator decreases from 98.1 % to 96.9 %, and the filtration efficiency of fixed bed filter decreases 94.3 % to 83.8 %, and the total efficiency of whole system decreases 99.89 % to 99.49 %. Therefore, to the whole system, the negative impact of the high temperature for dust removal is not very big.

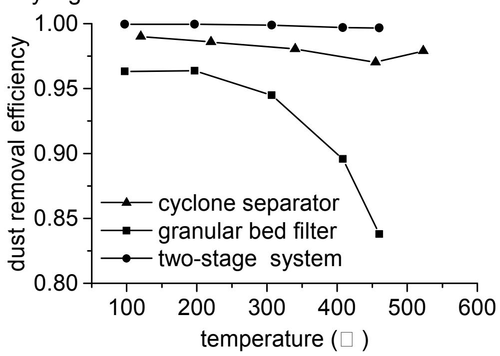

Figure 6: Dust removal efficiency of cyclone separator and fixed bed filter at different temperature.

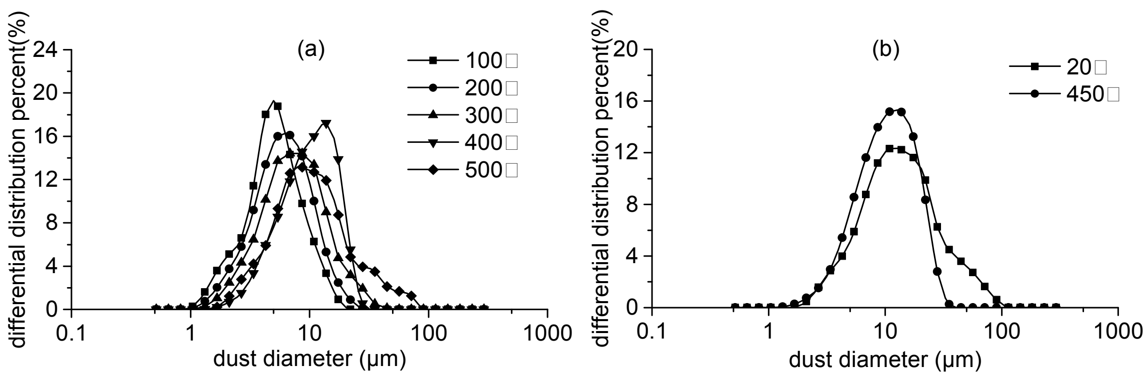

Figure 7: Particle size distribution at different temperature: (a) dust at the outlet of the cyclone separator, (b) dust removed by the fixed bed filter.

Figure 7(a) shows that the particle size distribution curve of cyclone separator not removed dust moves to the right as the temperature rise. Because high temperatures strengthen the diffusion of small particles, the centrifugal force of cyclone separator is not easy to separate these small particle dust.
Figure 7(b) shows that the particle size distribution curve of fixed bed filter removed dust moves to the left as the temperature rise. For one thing, increasing the temperature strongly increases attrition of particles, which could release small particles (Xiao et al., 2013). For another thing, high temperatures strengthen the diffusion of small particles. It is helpful to filter granules to capture these small particles. But as a whole, the influence of high temperature on the fixed bed filter do more harm than good from experimental results in Figure 6.
3.4.2 The impact of temperature on removal efficiency with tar gas
From Table 3 we can see that the dust removal efficiency of the cyclone separator and the fixed granular bed filter at 723 K with tar gas are higher than that at 293 K respectively. The total efficiency reach up to 99.95 %. It states that the existence of tar gas is benefit to the dust removal process in this experimental condition.

Table 3: The dust removal efficiency of different temperature and coal tar flow

Temperature (K)	Filter media	Nitrogen flow (NL/h)	Coal tar flow (mL/h)	Cyclone separator efficiency	Granular bed filter efficiency	Total efficiency
293	0.83~1.25 mm (15 cm)	1,500	0	98.10 %	94.30 %	99.89 %
723	0.83~1.25 mm (15 cm)	1,500	0	96.90 %	83.80 %	99.49 %
723	0.83~1.25 mm (15 cm)	1,500	100	98.48 %	96.39 %	99.95 %

4. Conclusions

A new two-stage dust removal system has been developed. Research on the dust removal performance of the new system at room temperature and high temperature has been done by this device. According to the experiment results, the conclusions drawn from this study is summarized as follows:
1. Semicoke is a better choice to be used for filter granules than silica sand because of its high efficiency, low cost and no regeneration.
2. Dual-layer bed is better than single layer bed. The best filling scheme of the fixed bed filter is filling 0.83~1.25 mm granules in upper layer at 10 cm high and 0.38~0.83 mm granules in lower layer at 5 cm high. The filtration efficiency of the fixed bed filter reaches up to 98.06 % and its pressure drop is only 700 Pa under this scheme.
3. Combining cyclone separator with fixed bed filter in series not only improve the grade efficiency of the whole system but also prolong the operating period of fixed bed filter 50 times.
4. The existence of tar gas is benefit to the whole dust removal process in this experimental condition.

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