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Improving the removal of fine particles from desulfurized flue gas by adding humid air

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HIGHLIGHTS

- A novel process to reduce the emission of fine particles is presented.
- The supersaturation vapor environment can be formed in growth region.
- The fine particles would grow up to larger droplets by heterogeneous condensation.
- The larger droplets would be removed by a wire mesh mist demister efficiently.
- The removal performance is influenced by several parameters.

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ABSTRACT

Using the theory of heterogeneous nucleation, a novel process is proposed to enhance the removal performance of fine particles from desulfurized flue gas. The necessary supersaturated atmosphere is established by adding humid air into the growth region, located at the top of the desulfurization scrubber. The size of fine particles would be enlarged by heterogeneous condensation and then the condensation-grown droplets are intercepted by a wire mesh demister, set at the top of the growth region. The degree of supersaturation and the amount of condensable vapor caused by mixing the humid air and desulfurized flue gas were calculated numerically. Furthermore, the improvement of fine particle removal performance from desulfurized flue gas via heterogeneous condensation was studied experimentally, and the influences of several parameters, such as the amount of humid air added, the temperature and relative humidity of humid air and of the desulfurized flue gas, were analyzed. The results indicated that the removal performance of fine particles could be enhanced by this process. The improvement of fine particle removal performance was related to the supersaturated atmosphere formed in the growth region. Under typical working conditions, the supersaturation degree could reach 1.1–1.2, and the condensable vapor could reach 20 g·Nm^{-3} or more. In addition, it will be more appropriate to use this process when the desulfurized flue gas temperature is relatively high (55–60 °C). The number of fine particles emitted by the application of this novel process would be reduced by 30–40%.

1. Introduction

Emissions of fine particles have attracted increasing attention due to their adverse effects on human health and the environment [1–3]. Fine particles are widely considered to be one of the main pollutants emitted from coal-fired power plants [4,5]. Although almost all the coal-fired power plants are equipped with conventional precipitators, such as fiber bag precipitators and electrostatic precipitators, the removal performance of fine particles by these conventional precipitators is still not very effective compared with the high removal efficiency of coarse particles [6]. Moreover, the numerical concentration of fine particles after desulfurization even increases sometimes [7], which leads the emission of fine particles to further increase. It has been reported that desulfurized flue gas contains two different types of fine particles: the fine particles generated from coal combustion and the fine particles formed during the process of desulfurization [8]. The conventional precipitator mainly captures the fine particles, which are generated from coal combustion. However, the conventional precipitator is ineffective for removing the fine particles formed by the process of desulfurization. Hence, improving the

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removal performance of fine particles after desulfurization is of great significance. At present, since the particles in desulfurized flue gas are too small to be captured by conventional dust removal technology, it is believed that the most effective way to control the fine particles emission gas after desulfurization is the installation of wet electrostatic precipitators (WESP) [9]. However, the investment cost and the operating cost are very high.

It has been shown that the fine particle removal efficiency will be improved if the particles size can be enlarged by some means [10]. Recently, the heterogeneous nucleation of fine particles in a supersaturated atmosphere has been developed and proven to be an effective method for the enlargement of fine particles [11–13]. When fine particles are in a supersaturated atmosphere and the supersaturation degree was greater than the critical supersaturation degree of the fine particles, the heterogeneous nucleation and growth of fine particles will occur [14]. Fletcher [15] verified that the activation of particles starts from an embryo liquid lens and the formation of the embryo liquid lens depends on the Gibbs free energy change of the system. When the embryo liquid lens is formed on the surface of a particle and the radius of the formed embryo is greater than the critical radius, the fine particle is activated. Then the vapor will begin to condense on the surface of the activated fine particle spontaneously. As a consequence, the process of heterogeneous condensation leads the fine particles to grow into larger droplets, and the removal efficiency by conventional separators will also be significantly improved [16].

At present, the wet flue gas desulfurization (WFGD) system has been applied to reduce the emissions of SO_2 in coal-fired power plants. In a desulfurization scrubber, the relatively cold desulfurization slurry contacts with the relatively hot flue gas. Simultaneously, the mass and heat transfer take place, leading the desulfurized flue gas to approach the saturated state at 50–60 °C. Hence, it is easier to establish a supersaturated atmosphere in desulfurized flue gas. Yan [17,18] and Bao [19,20] reported that the supersaturation can be established by means of adding steam to desulfurized flue gas. However, a plenty of steam will be required when the desulfurized flue gas is at a high temperature, which leads to increase operating costs. Heidenreich [21] studied the growth rates and the enlargement of the fine particles in a supersaturated atmosphere caused by mixing warm and cold air flows. The results indicate that for a mass of condensable vapor of 5.5 $g{\cdot}m^{-3}$, the fine particles with the size in the range of 0.1–1 μm can grow up to larger droplets with an average size of 2–3 μm in only 0.1 s by heterogeneous condensation.

In this paper, a novel technique based on heterogeneous nucleation to reduce the emissions of fine particles after desulfurization process is proposed. The necessary supersaturation is established by adding relatively cold humid air into relatively hot desulfurized flue gas. Because the principle of heterogeneous condensation and the method of establishing a supersaturation are simple, the investment and operating costs for this process can be decreased significantly. In this paper, the degree of supersaturation and the amount of condensable vapor caused by mixing the humid air and desulfurized flue gas were calculated numerically. In addition, the influences of several parameters, such as the amount of humid air added, the temperature and relative humidity of humid air and of desulfurized flue gas, were investigated experimentally.

2. Experimental system and numerical calculation

2.1. Experimental system

The facility used in the experiment is shown in Fig. 1, including an automatic coal-fired boiler (CZML-0.12, China), an electrostatic precipitator (ESP), a WFGD system, a particle growth region, a humid air generation system and a measurement system. Approximately 350 $Nm^3\ h^{-1}$ of flue gas was generated by the boiler. The buffer vessel was set between the boiler and the ESP to maintain the stability of particle size distribution and concentration. After the flue gas passed through the ESP, coarse particles were separated. After leaving the ESP, the flue gas flowed into the desulfurization scrubber to contact countercurrently with the desulfurization slurry. At the top of the SO_2 absorption zone, there was a chevron mist eliminator to intercept the entrained droplets. The particle growth region is set at the top of the scrubber, which is marked in the area bounded by the dotted line. In the particle growth region, the larger condensational droplets would be formed by heterogeneous condensation, and then the grown droplets were intercepted by the wire mesh demister at the top of the particle growth region. The humid air was generated by a humidifier tower, where the temperature, the relative humidity, and the gas flow could be adjusted to appropriate values. To approximate the actual status, the limestone-gypsum wet flue gas desulfurization method was used in the experiment, and the recycle ratio and the liquid-to-gas (L/G) ratio were set as 1 and 15 $L{\cdot}Nm^{-3}$, respectively.

In addition, the removal efficiency of wire mesh demister for grown droplets was about 20%, and the grade removal efficiency is illustrated in Fig. 2

2.2. Measurement instrument

The particle concentration and size distribution was determined by the electrical low pressure impactor (ELPI, Finland). It can perform a real-time measurement with high stability, and the measuring range of particle size is from 0.023 μm to 9.314 μm. The basic operation principle of the ELPI is to combine inertial classification from the low pressure impactor with real-time electrical detection. The fine particle is first sampled through a unipolar, diode-type corona charger and then passed through a cascade low pressure impactor. The current carried by charged particles impacting on the collection plate can be measured in real time. Finally, the measured current distribution is converted to particle size distribution using an experimentally determined charger efficiency. In order to avoid the interference of droplets, the sample gas was heated to 150 °C to evaporate the droplets. Also, the heat tracing mode was used to avoid the condensation of vapor in the sampling pipe. The temperature-humidity transmitter (HMT337, Finland) was used to measure the temperatures and humidities of the desulfurized flue gas and the humid air.

2.3. Numerical calculation

Because the direct measurement of amount of condensable vapor and the supersaturation degree were difficult to attain experimentally, numerical calculations were carried out. The supersaturated gas phase is a metastable phase in which the vapor exceeds that of the stable thermodynamic equilibrium; thus, the degree of supersaturated gas phase can be described as follows [22]:

$$S = \frac{P(T,x)}{P_s(T,x)} \tag{1}$$

where $P(T,x)$ is the actual vapor pressure, and $P_s(T,x)$ is the saturated vapor pressure.

The amount of condensable vapor can be calculated by the following formula [21]:

$$A = a_s - a \tag{2}$$

where A is the amount of condensable vapor, a_s is the moisture content at supersaturation degree S, and a is the moisture content at saturation degree.