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Effects of chemical composition and carbon residue on removal of coal-fired particles by vapor condensation

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ABSTRACT

Vapor condensation on coal-fired fine particles is one of the most promising preconditioning technique for fine particles removal. The physical and chemical properties of particles is one of the major factors governing this process. In order to investigate the effects of chemical composition and carbon residue of coal-fired fine particles on this process, in this work, the connection of particle's surface wettability with the chemical compositions and carbon residue was established. The results showed that coal-fired particle's surface wettability was affected by the major compositions of the particle as follows: Al_2O_3, SiO_2, SO_3, CaO and Fe_2O_3, and the carbon residue had a negative effect on particle's surface wettability which was proportional to the carbon residue fraction. The experiments of particle enlargement under supersaturated vapor environment showed that the performance of particle enlargement was related to the chemical compositions and carbon residue. We could conclude that chemical compositions, carbon residue affect condensation of water vapor on coal-fired fine particles in such a way that the chemical compositions and carbon residue determined the wettability of the particle surface, thus different enlargement performance was presented.

1. Introduction

Very fine inhalable particles can remain suspended in the atmosphere for a long time, travel long distances from the emitting sources and, once inhaled, they can reach the deepest regions of the lungs and even enter in the circulatory system [1]. Therefore, the smaller the particle size, the higher its toxicity [2]. At present, fine particles emitted from coal combustion are generally considered to be a significant threat to atmosphere environment and human health [3, 4]. Nevertheless, the traditional particle abatement devices are mainly designed and optimized to treat particles with sizes above or around 1 μm, and they are far less effective towards the submicron dimensions [5], previous study has shown that the removal efficiency of submicron particles can decrease to 25% [6]. However, it is believed that higher removal efficiency can be obtained if the sizes of the fine particles can be enlarged by a pretreatment method, such as electric agglomeration [7, 8], acoustic agglomeration [9, 10], chemical agglomeration [11] and vapor condensation [12]. In this methods, vapor condensation on fine particles has been studied and it has been demonstrated to be a promising method more than 30 years. During this process, heterogeneous nucleation of water vapor will be occurred on the surface of fine particles, which lead a size growth of particles and subsequently the droplets contain particles can be captured by the traditional particle treatment devices.

Heidenreich et al. [13] have applied vapor condensation as a preconditioning technique for the separation of submicron particles from gases, both theoretical and experimental results showed that with a mass of condensable water vapor of ca. 5.5 g/m^3, submicron particles can be enlarged with high growth rates to droplets with mean diameters of ca. 3 μm. Yoshida have researched the application of particle enlargement by vapor condensation to industrial dust collection at low particle number concentration, the results suggested that exhaust gas of high temperature and high humidity was especially profitable to apply this technique [14]. Because the high temperature and high humidity of flue gas emitted from coal plants, many works [15–18] have been done to study the vapor condensation on coal-fired particles, and the results have been proved the removal efficiency could be improved by 40–50% [19, 20]. As a preconditioning technique, it is easily to understand that the removal efficiency is tightly connect with the performance of particle enlargement by vapor condensation.

In order to understand the knowledge of the heterogeneous nucleation of water vapor on submicrometer particles, many experimental works have been done. Chen et al. [21–23] have investigated the removal efficiency of vapor condensation on submicrometer particles of SiC, SiO_2, TiO_2, Al_2O_3, carbon black, and naphthalene in a flow cloud

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chamber, the results showed that the higher wettability of particle's surface, the higher removal efficiency could be obtained. Porstendorfer et al. [24] investigated the heterogeneous condensation of vapor on Ag and NaCl particles and observed the significant dependence of the heterogeneous condensation on particle size and surface properties. Helsper et al. [25, 26] have investigated the effect of surface properties of ultrafine particles and have also observed a strong dependence on particle size and chemical compositions. Moreover, it was observed that remarkably high supersaturation of water vapor were required for condensation on particles consisting of carbon. Unlike these research focusing on removal efficiency, our previous work have studied the effect of operating parameters on characteristics of vapor condensation on coal-fired particles [27, 28], the effects of supersaturation level, residence time, particle concentration and wetting agent addition on particle enlargement have been studied. We also found that the particles that emitted from the different coal power plants showed a different growth performance. This results also demonstrated that the vapor condense on a particle of various compositions, the physical and chemical interactions between the vapor and the particle surface would strongly influence the condensation process.

Some preliminary results of vapor condensation on different kinds of particles were reported by our team, the process of vapor condensation on typical coal ash compositions including quartz, ferric oxide, calcium sulphate and mullite also have been studied [29]. However, scant data of direct particle size distribution after growth have reported the effects of chemical compositions on the process of vapor condensation on coal-fired particles. In this work, the chemical compositions, carbon residue and contact angles of coal-fired particles was firstly tested. Then the connection of wettability with chemical compositions and carbon residue of coal-fired particles was originally established. Moreover, we have deduced a mathematic relationship between the major chemical compositions of coal-fired particles and its contact angle. Finally, the performance of vapor condensation on coal-fired particles will be experimentally presented.

2. Experimental details

2.1. Measurement of contact angle

A contact angle goniometer (Model JC2000D2, China) with high resolution camera (Model Guppy pro, Germany) was applied to measure the contact angles of different kinds of coal-fired particles. The particles cylindrical thin slices were prepared by placing a powder sample in a compression die and applying a force of 5000 N by means of a hydraulic press. This force was maintained for 30 min. Then the thin slice was put on the measurement table and 1.5 μL water was dripped on its surface, this process would be captured by the high resolution camera and finally the picture of the water contacting moment could be analyzed by computer to obtain particle's contact angle.

2.2. Experimental setup

As illustrated in Fig. 1, the experimental apparatus includes three parts as follow, aerosol generation part, the particles growth part and the measurement part.

The aerosol generation part consists of an aerosol generator (Model SAG-410, Germany) and an air compressor which supplies pure air as carrier gas.

The particles growth part consists of a growth tube, a cooling unit and a hot water thermostat. The growth tube was made of glass with an internal diameter of 1.5 cm and a length of 40 cm, the same one as reported by Tammaro's work [30, 31]. The hot water inlet to the growth tube was designed as tangential to assure a perfect adhesion of water with the tube walls. In the experiment, the liquid temperature was kept at the desired value, T_h, by means of a thermostatic bath. The cooling unit cooled the aerosol gas into dew point, and then the cooled and saturated gas was sent into the growth tube and encountered the hot water supplied by the thermostatic bath. The water vapor was transferred from the tube wall into the cooled gas which generated a supersaturation environment for the mass diffusivity is bigger than the heat diffusivity of water vapor. And the supersaturations were controlled by hot water temperature control.

The measurement part consists of a laser droplet measuring instrument (Model OMEC-DP-02, China), an optical measurement window, and a hot wind fan. The laser instrument allows the measurement of particle size distribution in the range between 0.05 μm and 1500 μm. The optical measurement window, which was made of optical glass, is closed to the outlet of growth tube avoiding the evaporation of droplets containing particles. The hot wind fan provides a hot airflow around the optical window to avoid droplet evaporating and condensing on the window. During the experiments, the temperature of growth tube outlet gas was measured and then the temperature of hot airflow was set at this value. Additionally, an electrical low pressure impactor (ELPI, Dekati, Finland) was used for particle concentration.

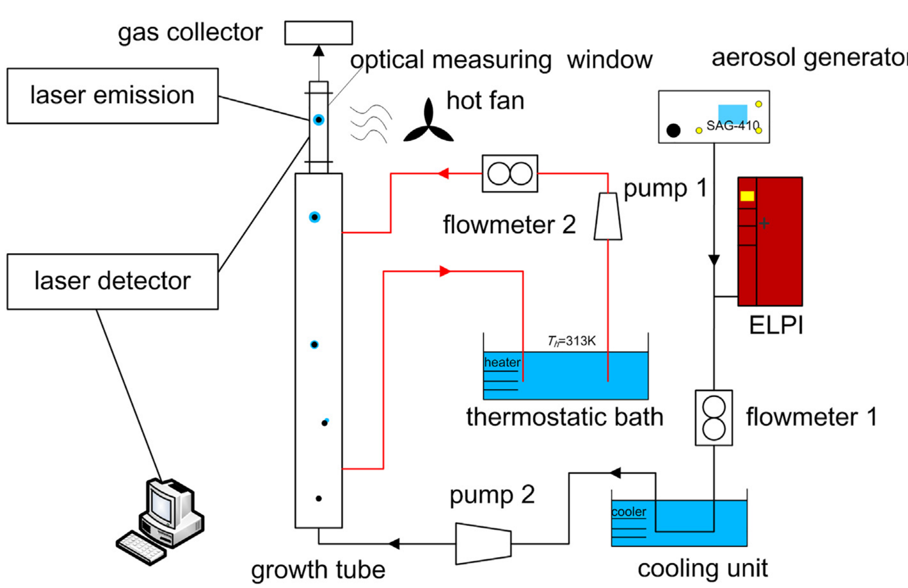

Fig. 1. Experimental apparatus.