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Heterogeneous condensation of water vapor on particles at high concentration

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ABSTRACT

Although heterogeneous condensation on fine particles is one of the most promising precondition technologies for particles abatement which has been proved by many works, little direct data were reported on the process of particles enlargement by vapor condensation. A direct measurement of enlarged particle size distribution in a lab scale growth tube by water vapor condensation is presented. Four parameters that affect the performance of the particle enlargement at high particle number by heterogeneous condensation were identified: supersaturation, particle size, residence time and particle wettability. The results show that particle enlargement exponentially increases with the increase of supersaturation. The particle size has a negative impact on particle growth ratio. The residence time is in favor of the particle enlargement which depends on the supersaturation level. Additionally, the residence time extension would weaken the vapor depletion on particle enlargement caused by particle number increase. Particle wettability may lead to different processes of particle enlargement. This work deeply revealed the process of vapor condensation on particles at high concentration by direct measurement.

1. Introduction

Interest in the study of the heterogeneous condensation of supersaturated vapor has increased in the last few years. This explosion of attention has been driven by the recognition of the central role that heterogeneous condensation plays in the atmospheric and environmental process of concern worldwide. In particular, the most promising particles abatement pretreatment by vapor condensation is strongly influenced by the heterogeneous condensation [1]. The traditional particle abatement devices are far less efficient in collecting submicron particles, especially for those in the range 0.1-1 μm [2], the removal efficiency decreases to 25% [3]. Improving the dimension of the particles is the main way to facilitate fine particles abatement. A couple of new technologies were proposed in the recent past for the enlargement of submicron particulates: wet electrostatic scrubbing [4] and heterogeneous condensation [5,6]. Among them, heterogeneous condensation of water vapor as a preconditioning technique for fine particles removal has been proved to be one of the most promising techniques to improve the performances of traditional devices [7].

Many works have been done on the heterogeneous condensation on submicron aerosols. The theory of nucleation on small insoluble particles was proposed by Fletcher [8]. He found the process of heterogeneous condensation is determined by the particle size and surface characteristics [9,10]. Porstendorfer et al. [11] 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. Chen et al. [12] investigated the heterogeneous condensation on SiO_2, Al_2O_3, TiO_2 and carbon black particles and led to a significant understanding of the nucleation process and a conclusion that critical supersaturation primarily depended on particle size and contact angle. Lammel et al. [13] studied the vapor condensation on carbon black particles and concluded that the soluble fraction of carbonaceous material could influence the nucleation ability of the carbon black particles. The nucleation process of individual glass particles was researched with an electrostatic levitation and the critical diameters were determined [14,15].

It could be found that these studies mentioned above were concentrated on the heterogeneous condensation at the low particle concentration ($<10^3$ cm^{-3}). Actually, the particle concentration in the flue gas discharged from the coal-fired boiler is much higher [16]. At the high particle concentration, above 10^4 cm^{-3}, the possibility of heterogeneous condensation on the particles might be decreased due to vapor depletion [17]. Numerical result showed that the absolute value of nucleation rate decreased with the increase of particle concentration [18], and the experimental results also showed that the vapor depletion

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impacted supersaturation and droplet size > 10% if the particles concentration was > 5 × 10^3 cm^{-3} [19]. Hence there are some differences in the enlargement performance between the high particle concentration and the low particle concentration.

Some research has been done with the particles at the high concentration. Measuring removal efficiency was the most usual way to estimate the enlargement performance of vapor condensation on submicron particles [20–22]. Heterogeneous condensation of residual particles, quartz particles, and paraffin oil droplets were experimentally investigated by employing removal efficiencies as a function [23]. Fan et al. [24] also experimentally studied the heterogeneous condensation on coal combustion particles through measuring the particles removal efficiency. Nevertheless, the process of the heterogeneous condensation on submicron particles at high concentration is hard to understand through measuring the removal efficiency.

The aim of this work is to investigate the process of heterogeneous condensation on submicron particles at the high particle concentration (the order of magnitude is 10^6 cm^{-3}). A lab scale equipment based on the growth tube was employed to examine the effects of supersaturation, particles size, gas residence time and particle wettability on heterogeneous condensation process. In particular, the process was not explored by the usual way, but was rather done by a direct measuring way. So the effect parameters of enlargement process could be better revealed by comparing the particle size distribution (PSD) at the inlet and the outlet of the growth tube.

2. Experimental section

2.1. Particles

To estimate the size effect on the heterogeneous condensation of particles, the fine SiO_2 particles and coarse ones were adopted. 94.8% of the fine SiO_2 particles are concentrated in the range from 0.05 to 0.2 μm, while 93.0% of the coarse ones are concentrated in the range from 1 to 3 μm, and corresponding mean sizes are 0.133 and 2.100 μm, respectively. At the same time the fine particles of SiO_2 were employed to study the effect of supersaturation and residence time. Specially, for understanding the effect of contact angle, the fine particles of $CaSO_4$, SiO_2, and Fe_2O_3 were used due to their different surface wettability with water. The percentages of the $CaSO_4$ and Fe_2O_3 ranging from 0.05 to 0.2 μm are 90.4% and 95.6%, respectively.

2.2. 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 SiO_2, $CaSO_4$, and Fe_2O_3. 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.

2.3. Experimental setup

As illustrated in Fig. 1, the experimental apparatus includes three parts as follows, 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 [25]. 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 then 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.

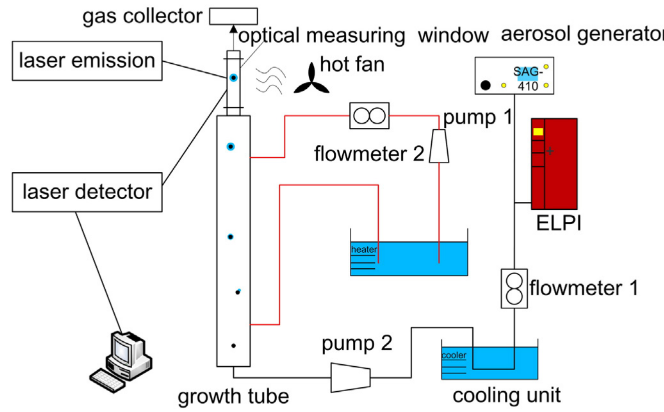

Fig. 1. Experimental apparatus.

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 PSD in the range between 0.05 μm and 1500 μm. In particular, the instrument was customized to extend its measuring range from 1–1500 μm to 0.05–1500 μm, and the software was customized to match the customized instrument, too. 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. This method have two advantages: 1. The PSD can be detected at the outlet of the growth tube once the particles finish growth; 2. the hot wind introduction prevents the droplet evaporating and condensing on the optical window so that the light detection of the droplets containing particle can be reached. Additionally, an electrical low pressure impactor (ELPI, Dekati, Finland) was used for particle concentration.

3. Result and discussion

3.1. Supersaturation effect

The process of particle enlargement by the heterogeneous condensation can be divided generally into two steps [26]. First, the particles have to be activated, which is called nucleation or activation. Secondly, the nuclei grow to droplets by condensation of vapor. In the heterogeneous condensation, the supersaturation not only affects the nucleation process [27], but also does the particles growth [28]. The supersaturation profiles throughout the growth tube are described by employing a heat and mass transfer modeling [29]. It can be seen in Fig. 2. that the supersaturation in the growth tube increases with the water temperature increase and the location of maximum supersaturation moves towards inlet of the growth tube with the water temperature increasing (when the water temperature is 303 K, 313 K, and 323 K, the maximum supersaturation is 1.032, 1.143 and 1.324, and the corresponding location is 33.44 cm, 28.00 cm and 24.24 cm away from inlet of the growth tube, respectively).