Measuring the Short-Term Emission Rates of Particles in the "Personal Cloud" with Different Clothes and Activity Intensities in a Sealed Chamber

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ABSTRACT

A series of measurements were conducted to determine the short-term emission rates of particles in the "personal cloud" (i.e., particle emission from a clothed human body) in a sealed chamber. By recording the concentration of particles of different sizes during a period of time in the chamber, curves monitoring the evolution of particle concentration caused by emissions from a clothed human body were obtained. Based on the measured evolution of particle concentrations and deposition rates, the emission rates of particles from a clothed human body were estimated with a physical model. Generally speaking, the size-dependent emission rates of particles from a human body wearing a clean room smock were the lowest, while those from one wearing a cotton suit were the highest among the forms of clothing examined this work. Furthermore, the emission rates of particles from a clothed human body were positively correlated with the intensity of human activity. In addition, activities tended to have a more significant impact on the emission rates with regard to coarse rather than fine particles. The experimental data for the emission rates of particles from a clothed human body provided in this study may be used in further particle exposure assessments in certain indoor environments, such as clean rooms and aircraft cabins, as a valid input parameter.

Keywords: Indoor air quality; Aerosol particle; Resuspension; Deposition; Human activity.

INTRODUCTION

Epidemiologic evidence has shown a relationship between particle pollution exposure and adverse health effects (Dockery *et al.*, 1993; Chen *et al.*, 2012a). Particle pollution exposure is mainly related to particle concentration, which is largely influenced by the emission rate of particle sources. Since most people spend 85–90% of their time indoors (Klepeis *et al.*, 2001), people are exposed to indoor particle pollution for a considerable time. Although a large amount of outdoor particles can penetrate through building cracks into the indoor environments (Chen and Zhao, 2011), indoor particles emitted from indoor sources also significantly contribute to indoor exposure. Therefore, it is important to measure the emission rates of indoor particle sources for evaluating their contribution to indoor particle exposure.

A lot of studies have focused on characterizing the emission of such indoor particle sources as cigarette smoke (Spengler *et al.*, 1981; Wang *et al.*, 2012), cooking (Hussein *et al.*, 2005a; Huboyo *et al.*, 2011), cleaning activity (He *et al.*, 2004; Hussein *et al.*, 2006), candles or incense burning

(Afshari *et al.*, 2005), fireplaces (Fan and Zhang, 2001), use of sprays (Afshari *et al.*, 2005) and printers (He *et al.*, 2007; Morawska *et al.*, 2009a) etc. When the above indoor particle sources are absent, the human body with the clothes that cover it may be an important source of "personal cloud" (Wallace *et al.*, 1999). For instance, health care workers in clean rooms or passengers in aircraft cabins can constitute significant particle sources, since other sources are absent and outdoor particles are removed by high efficiency particle air filters installed in the ventilation system. An example for aircraft cabin was that the filed measurements by Dechow *et al.* (1997) showed that particles were mainly emitted by the passengers in the aircraft cabin. In a review of six studies on emission rates of particles from human body, Xu (1998) concluded that the emission rate of particles with diameter larger than 0.5 μm for a person sitting still was approximately 10^5 N/min. However, to our best knowledge, compared with the other indoor sources introduced above, there is as to now little information of size-dependent emission rates of particles from human body with different types of clothing and activity intensities. Lacking the knowledge of the emission of particles from clothed human body, it is difficult to improve indoor environments both in buildings and aerospace/nautical transportation, as a comprehensive understanding of the dominant relevant factors has not been reached.

The approach of this study was to measure the emission

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rates of particles in the "personal cloud" (i.e., particle emission from clothed human body in this study) in a sealed chamber. By recording size-dependent particle concentrations during a period of time in the chamber, the evolution of particle concentration of particles emitted by the clothed human body were obtained. Based on these measures of the evolution of particle concentration and deposition rates, we estimated the emission rates of particles from clothed human body with a physical model. Several conditions were taken into consideration, including different outfits and different activity intensities, in order to gain a better understanding of the characteristics of particle emission from the clothed human body.

METHODS

Experimental Setup

Experiments in this study included two independent steps: (1) measuring particle deposition rates in the chamber, (2) measuring particles emission rates from a clothed human body in the chamber. The experimental configuration is illustrated schematically in Fig. 1. The dimensions of the stainless steel sealed chamber are $2 \times 2 \times 2$ m^3. We sealed the chamber by positioning a rubber strip along the entrance door's edges, thus ensuring an air exchange rate without mechanical ventilation lower than 0.01 ACH. Moreover, the pulmonary ventilation rate of a person is about 0.005 m^3/min (Riley *et al.*, 1978) or 0.3 m^3/hr. The volume of the chamber is 8 m^3. Therefore, it is sufficient to provide enough oxygen to participate for a one hour measurement. Before each experiment, the surfaces of the indoor chamber were cleaned up to avoid the influence of particle resuspension from the wall surfaces of the chamber. A mixing fan was installed in the chamber to ensure the well-mixed air condition. Our previous experimental study indicated that

this mixing fan was capable to create a relatively uniform environment in this chamber (Chen *et al.*, 2011).

Deposition is an important particle sink in indoor environments, which needs to be taken into consideration when measuring the emission rates of particles from clothed human body in a chamber. The summary of indoor particle deposition rates by Lai (2002) indicated that deposition rates measured under different experimental circumstances have a great disparity. Therefore, particle deposition rates in the chamber were measured in this study: indoor particle concentrations were continuously measured for about 8 hours to obtain the particle natural decay curves (shown in Fig. 2). The same measurements were repeated 3 times each. A FLUKE 983 optical particle counters (FLUKE Inc.) was used to measure particle concentrations. The Fluke 983 simultaneously measures and records six channels of particle sizes (0.3–0.5 μm, 0.5–1.0 μm, 1.0–2.0 μm, 2.0–5.0 μm, 5.0–10.0 μm and ≥ 10.0 μm). The counter has a coincidence loss of 5% when the particle concentration is 2,000,000 particles per cubic inch and a 100% counting efficiency for particles with a diameter larger than 0.45 μm (Fluke, 2005). The counters had been calibrated by the manufacturer and were also calibrated prior to each measurement using a Zero Counter Filter.

At the beginning of each experiment of emission rate measurement, the air in the indoor chamber was diluted by the ventilation system for half an hour to obtain a relatively low initial particle concentration in the chamber, which was recorded by the particle counter, as shown in Fig. 1. Then the participant was introduced into the chamber and indoor particle concentrations were continuously measured using the particle counter for 60 minutes to obtain the particle natural rise curve (example shown in Fig. 3). The entry process of the participant was performed as soon as possible to reduce the influence of the particle penetration when
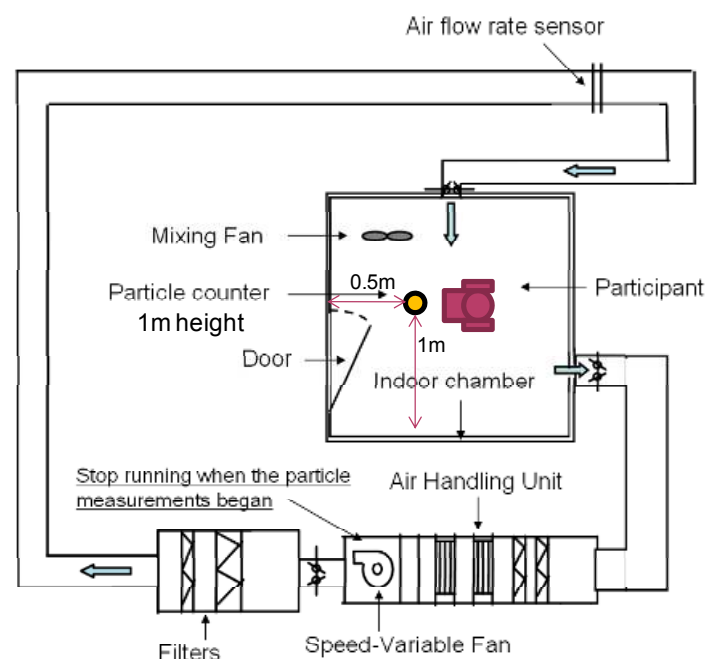

Fig. 1. Experimental schematic for measuring the emission rates of particles from clothed human body in the sealed chamber.
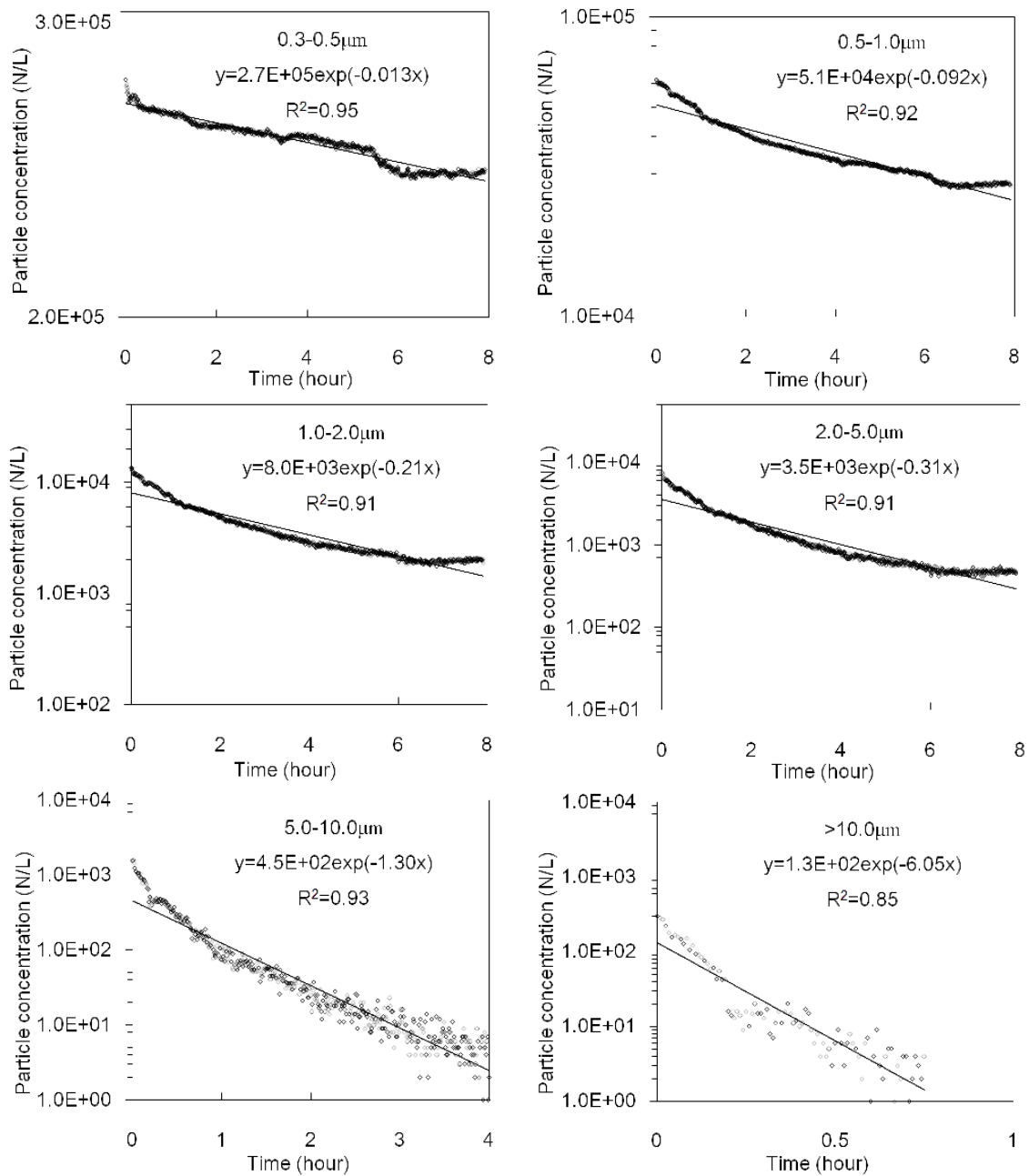
Fig. 2. Typical particle natural decay curves for obtaining deposition rates.

opening the door. Furthermore, the particle concentrations were monitored to ensure that the initial concentration did not change a lot. It should be noted that for particles with larger diameters, the influence of deposition is stronger than that of emission. Thus the curves for particles with larger diameters could decay rather than rise. For particles with the diameter larger than 10 μm, due to the extremely low concentrations and correspondingly low precision, the curve is not as smooth as that for particles with smaller sizes. The emission rates of particles from a human body with three kinds of clothes (clean room smock, polyester sportswear and cotton suit, as shown in Fig. 4) were measured. The average temperature and relative humidity in the chamber ranged from 23.5 to 26.3°C and 56.0 to 69.9%,

respectively. Due to the emission by the human subject, the indoor temperature and humidity increased during each experiment. However, the increases of temperature and humidity were all less than 0.9°C and 8.3%, respectively. Before each experiment, the clothes to be tested were exposed to outdoor environment for about 12 hours following the same procedure in order to obtain a similar initial status of particle loads. The tested clothes were put on the same chair located in the same place during the same period of a day (over night). Furthermore, to ensure the particle concentrations in the outdoor environment were similar when the tested clothes were exposed, the particle concentrations were simultaneously measured and the data show that the differences of outdoor particle concentrations between the
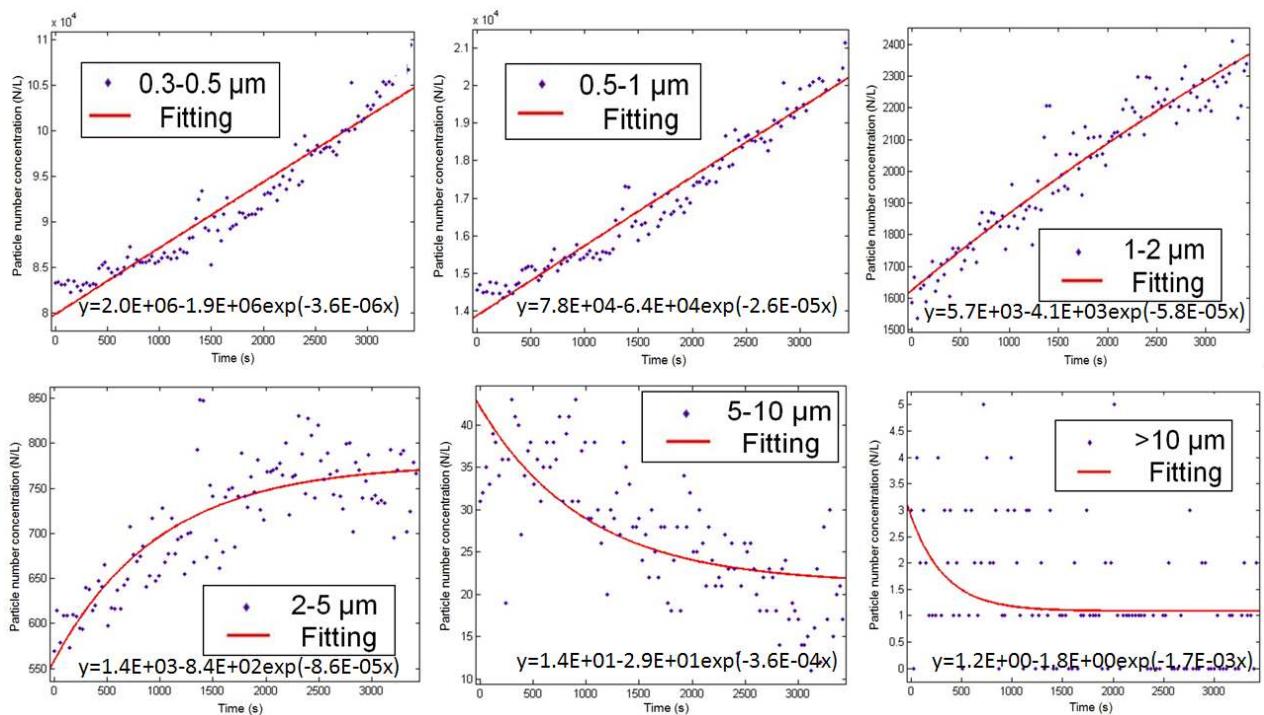
Fig. 3. Typical evolution (or decay for coarse particles) of particle concentration for obtaining emission rates (Clean room smock, Sitting still).

Fig. 4. Tested clothes: (a) Clean room Smock, (b) Polyester sportswear, (c) Cotton suit.

experiments were smaller than 10%. Compared with the duration of the emission test (1 hour), we expected that exposing the test clothes to outdoor environment for 12 hour is long enough to suppress the influence of initial particle loads, which was consistent with the measured results. However, the exact particle loads were not measured. The human subject employed in this study is a 21 year old male with an average height and weight (1.75 m and 70 kg), which may represent the typical characteristics of young males. Additionally, the emission rates of particles from a clothed human body performing three different kinds of activities (sitting still, strong and slight activity) were measured. For the strong and slight activity cases, the participant performed a series of prescribed activities in the chamber during the experiment, as shown in Table 1. The difference between the strong and slight activity levels was their amplitude. The variable parameters are summarized in Table 1.

Table 1. Variable parameters in this study.

Variable Parameter	Range or values in this study
Diameter	0.3–0.5; 0.5–1; 1–2; 2–5; 5–10; > 10 μm
Cloth type	Clean room smock; Polyester sportswear; Cotton suit
Activity intensity	Sitting still; Strong activity (All the intensity of the movements were strong:); 0–10 min, Walking 10–20 min, Sitting with upper body movements 20–30 min, Walking with arms movements 30–40 min, Walking 40–50 min, Sitting with upper body movements 50–60 min, Walking with arms movements Slight activity (All the intensity of the movements were slight); 0–10 min, Walking 10–20 min, Sitting with upper body movements 20–30 min, Walking with arms movements 30–40 min, Walking 40–50 min, Sitting with upper body movements 50–60 min, Walking with arms movements

Particle Deposition Rates

Particle deposition has been studied experimentally in controlled chambers or real buildings (Offermann *et al.*, 1985; Xu *et al.*, 1994; Byrne *et al.*, 1995; Fogh *et al.*, 1997; Normura *et al.*, 1997; Lai *et al.*, 2002; Thatcher *et al.*, 2002; Chao *et al.*, 2003; Wallace *et al.*, 2004; Bouilly *et al.*, 2005; He *et al.*, 2005; Hussein *et al.*, 2005b; Lai and Nazaroff, 2005; Chen *et al.*, 2006; Hussein *et al.*, 2006; Hamdani *et al.*, 2008; Hussein *et al.*, 2009; Chen *et al.*, 2012b). Due to the perfect air tightness of the chamber, the outdoor particle penetration and indoor particle removal by air exchange can be neglected. Therefore, the particle mass balance equation of the chamber can be described by

$$\frac{dC_{in}}{dt} = -KC_{in} \tag{1}$$

where C_{in} is the particle concentration in the chamber (N/L), t is time (s), K is the particle deposition rate (s^{-1}). Thus,

$$C_{in} = C_{int}e^{-Kt} \tag{2}$$

where C_{int} is the initial indoor particle concentration in the chamber (N/L). By fitting the natural decay curves, the size-dependent particle deposition rates can be obtained.

Particle Emission Rates

In this study, particle emission rates from the clothed human body were assumed as constants during the experiments (which was consistent with our measurement results as shown later). Thus, the particle mass-balance equation of the chamber can be described by (Hussein and Kulmala, 2008; Chen and Zhao, 2011):

$$\frac{dC_{in}}{dt} = \frac{\dot{S}}{V} - KC_{in} \tag{3}$$

where $\dot{S}$ is the emission rate of particles from the clothed human body in the chamber (N/s) and V is the volume of the chamber (L). Thus,

$$C_{in} = \frac{\dot{S}}{VK} + (C_{int} - \frac{\dot{S}}{VK})e^{-Kt} \tag{4}$$

where C_{int} is the initial background particle concentration in the chamber. Given the particle deposition rate, the emission rate can be obtained by fitting the curve of particle concentration versus time.

It should be noted that the particle emission rates measured with this method include both the particles emitted from the surfaces of the clothed human body and exhaled ones.

RESULTS

Particle Deposition Rates

Fig. 6 shows size-dependent particle deposition rates in the sealed chamber compared with data from existing literature, which was incorporated when measuring the emission rates of particles from the clothed human body in the chamber. As shown in Fig. 2, particle natural decay curves were used to obtain the deposition rates. Each experiment was conducted three times in order to get information on the uncertainty of the method (summarized by the error bars given in Fig. 6). Fig. 6 also shows that experimental data obtained in this study were consistent with that of existing studies (Offermann *et al.*, 1985; Xu *et al.*, 1994; Byrne *et al.*, 1995; Fogh *et al.*, 1997; Normura *et al.*, 1997; Lai *et al.*, 2002; Thatcher *et al.*, 2002; Chen *et al.*, 2012b). It can be seen that the deposition rates in this study were in the lower part of the published data, which was consistent with the fact that the speed of the mixing fan in this study was relatively low.
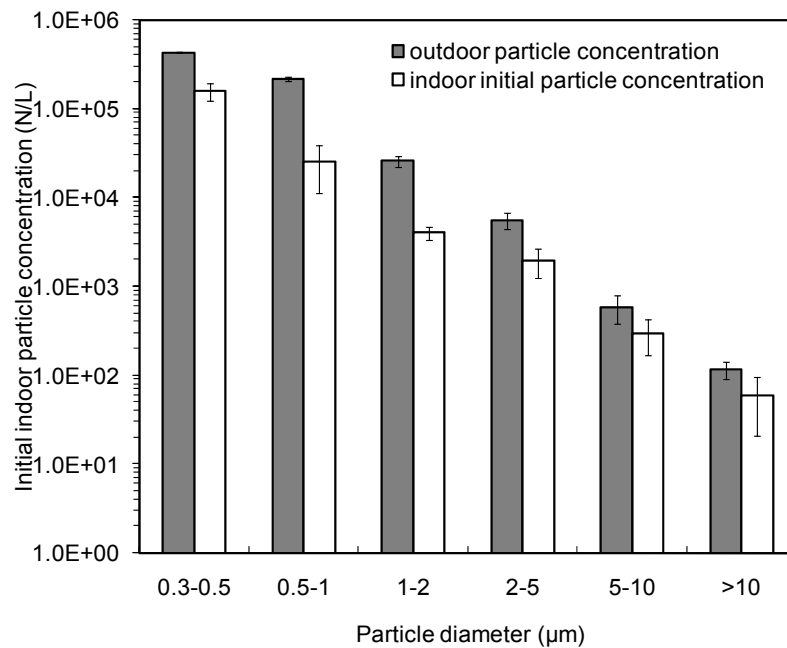
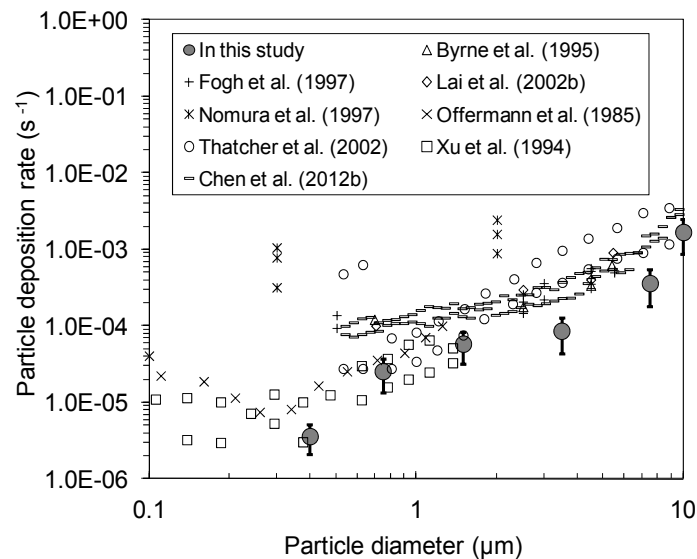**Fig. 5.** Outdoor and indoor initial particle concentrations in this study (logarithmic vertical axis).

Fig. 6. Size-dependent particle deposition rates in the sealed chamber, compared with data published in the literature.

Emission Rates with Various Clothes

As shown in Fig. 3, the particle evolution of particle concentration was used to obtain the emission rates. According to Fig. 7, which shows the comparison of size-dependent emission rates of particles from the human body with various clothes with a participant sitting still, the particle emission rates from the human body wearing a clean room smock were lower than both that with polyester sportswear and cotton suit within the studied particle diameter range (larger than 0.3 μm). For particles with a diameter smaller than 5 μm, the emission rates of particles from the human body wearing polyester sportswear were higher than those from the human body with a cotton suit on. However, the emission rates for cotton suit were higher than that for polyester sportswear for particles with a diameter larger than 5 μm. However, the relatively large measurement errors for coarse particles may indicate that the differences are not significant. Since the concentrations of fine particles were much higher than that of coarse particles, generally speaking, the emission rates of particles from the human body wearing a polyester sportswear were the highest among the selected clothing.

Emission Rates with Various Activity Intensities

Fig. 8 shows a comparison of size-dependent emission rates of particles from the human body wearing polyester sportswear, with a participant performing various activities. Generally speaking, for particles with a diameter smaller than
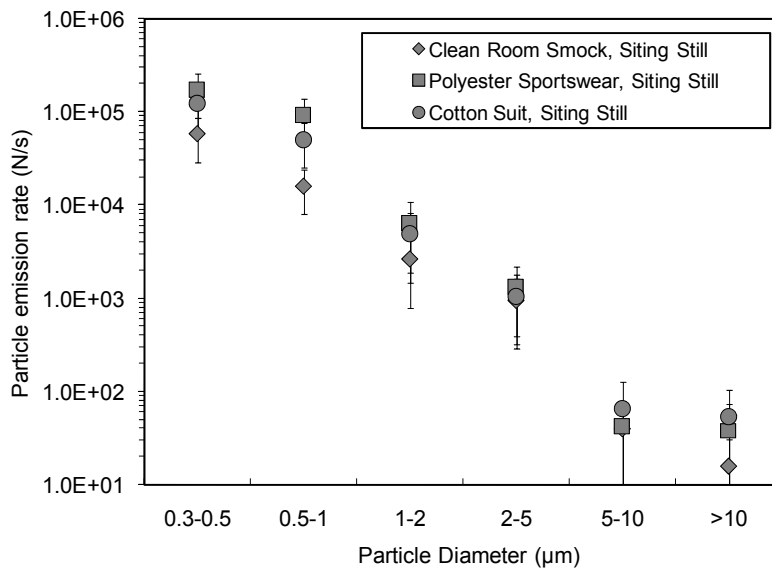
Fig. 7. Comparison of size-dependent emission rates of particles from a human body sitting still with different clothes on (logarithmic vertical axis).
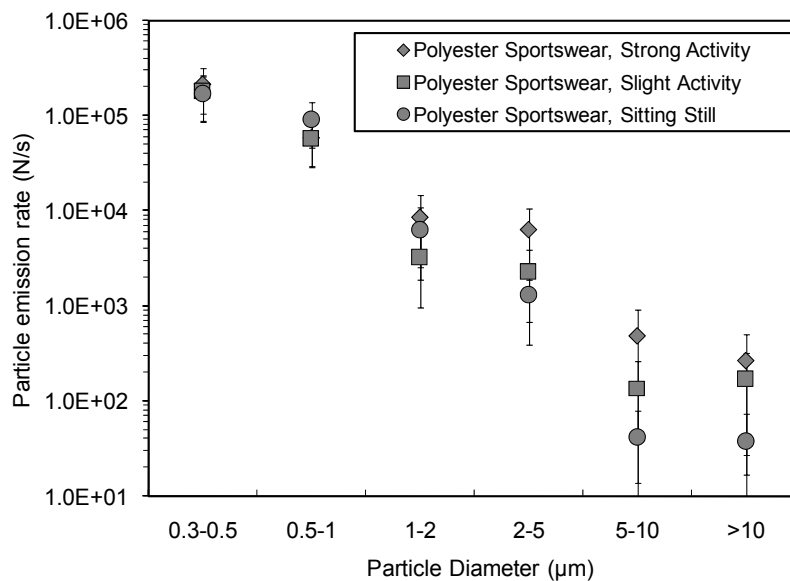

Fig. 8. Comparison of size-dependent emission rates of particles from human body with polyester sportswear with the participant performing various activities (logarithmic vertical axis).

1 μm, human activities did not display such a significant impact on particle emission rates as for particles with a diameter larger than 1 μm. For instance, for particles with a diameter ranging from 0.3 to 0.5 μm, the difference between the emission rate at strong activity and sitting still was not statistically significant. Subsequently, for particles with a diameter larger than 2 μm, the particle emission rates were positively correlated with the activity intensity. For instance, for particles with a diameter between 5 and 10 μm, the emission rates of particles from the clothed human body with slight and strong activity levels were respectively 3.3 and 11.6 times higher than those from the clothed human body sitting still.

Fig. 9 shows a comparison of size-dependent emission rates of particles from the human body wearing a cotton suit with a participant performing various levels of activity. Generally speaking, for particles with a diameter smaller than 2 μm, human activities did not have an impact as significant as for particles with a diameter larger than 2 μm. For particles with a diameter over 2 μm, the distinctions between the emission rates of particles from clothed human body when sitting still and with slight activity were still not significant. However, the emission rates of particles from the clothed human body with a strong activity level were much larger than the other two. For instance, the emission rate of particles with a diameter in the range 5–10 μm from the clothed human body with a strong activity level was 12.5 times larger than that from the clothed human body sitting still.
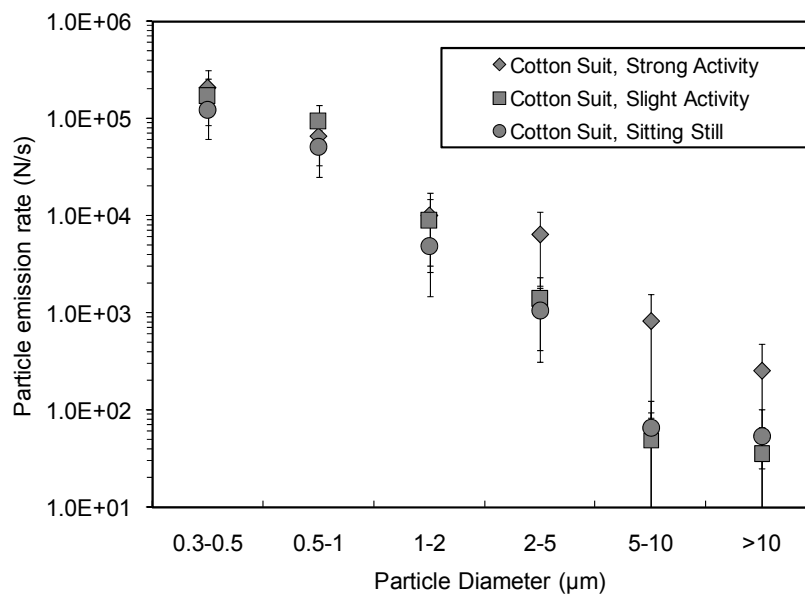
Fig. 9. Comparison of size-dependent emission rates of particles from human body with cotton suit with the participant performing various activities (logarithmic vertical axis).

DISCUSSION

Potential Explanations for the Experimental Results

Generally speaking, the size-dependent emission rates of particles from human body wearing a clean room smock were the lowest and those from human body with a cotton suit on were the highest among the selected clothing. The clean room smock, made of special polyester, is electric-proof and dust-proof, making it difficult for particles to emit from the surface of the smock. The polyester sportswear is smooth on the surface, while the cotton suit is relatively rough. Thus the adherence capacity of particles to the cotton suit is higher than that of the polyester sportswear, so that the particles emit more easily from the polyester sportswear than from the cotton suit.

Results show that particle emission rates are positively correlated with the activity intensity. One potential explanation is that an increase of the activity intensity may enhance the air speed near the surfaces of the clothed human body, which may result in an increase of particle resuspension rates (Zhu *et al.*, 2012). Therefore, particle emission rates in cases with stronger activity intensity may increase due to higher particle detachment rates from the surfaces of the clothes.

The results showed that human activity tended to have a more significant impact on the emission rates of particles from clothed human body for particles with larger diameter than for particles with smaller diameter. According to a former study, when air speed increases, the particle resuspension rates increase more significantly for particles with larger diameter than for particles with smaller diameter (Zhu *et al.*, 2012). As the emission rate of particles from clothed human body is strongly related to particle resuspension, the difference of impacts of activity intensity on emission rates between fine and coarse particles may account for the results.

Influence of Exhaled Droplets

In this study, the particle emission from human included the exhaled droplets through breathing. It has been proved that exhaled droplets can be a significant particle source from human, whose emission characteristics have been reported in many studies (e.g., Fabian *et al.*, 2008; Chao *et al.*, 2009; Morawska *et al.*, 2009b). Therefore, it is important to assess the influence of exhaled droplets on the emission rates of particles from clothed human body measured in this study. Gupta *et al.* (2011) indicated that the typical amount of exhaled droplets for a breath can be set as 525 per breath. The duration of a breath is about 4 s (Gupta *et al.*, 2010). Thus, the total emission rate of exhaled droplets for breathing can be calculated as 525/4 = 131 N/s. Fabian *et al.* (2008) indicated that the percentages of exhaled droplets for a breath were: 0.3 to 0.5 μm, 70%; 0.5 to 1 μm, 16%; 1 to 5 μm, 14%. Therefore, the size-dependent emission rates of exhaled droplets for breathing were 0.3 to 0.5 μm, 92 N/s; 0.5 to 1 μm, 21 N/s; 1 to 5 μm, 18 N/s. Comparing these values with the emission rates of particles from clothed human body presented in this study, it may be concluded that the influence of exhaled droplets on the emission rate of particles from clothed human body was negligible.

Influence of other Factors

Except particle resuspension from the clothes and exhaled droplets through breathing, another emission mechanism was the secondary organic aerosol (SOA) generation from reaction of ozone and human skin (Wisthaler and Weschler, 2010). Several studies indicated that large portion of SOAs were particles with diameter smaller than 0.4 μm (Fan *et al.*, 2003; Destaillats *et al.*, 2006), it was expected that this factor may not influence the results in a major way since the particle diameters measured in this study were larger than 0.3 μm.

The increase in temperature may have an impact on the airflow field, which could directly affect the particle

concentration distribution. However, a mixing fan was employed in this study to maintain the uniformity of the particle concentration distribution, whose capability has been assessed in our previous study (Chen *et al.*, 2011), thus, the raise in temperature may not be that crucial. However, it should be noted that the temperature differential between the clothed human body and the air definitely existed and created the thermal plume to serve as a driving force for the particle resuspension. On the other hand, the thermophoretic force, which is related to the temperature gradient, may change when the temperature increases (Hinds, 1999). Although we do not expect that the thermophoresis would significantly affect indoor particle dispersion (Zhao *et al.*, 2009), the influence of thermophoretic force on particle emission from clothed human body was not thoroughly clear and needs further study.

The relative humidity was related to the moisture evaporation amount of the clothed human body, thus it can only affect the emission and deposition of exhaled droplets (a kind of aerosol particle). However, our previous study indicated that relative humidity does not have a significant impact on the characteristics of motion of droplets (Chen and Zhao, 2010), thus the raise in the relative humidity may not be that crucial. However, there is a possibility that the relative humidity may affect the droplet generation in the respiratory system, which needs to be further assessed by measuring the exhaled droplets under different relative humidity.

It should be noted that breathing is deeper and more frequent during the physical exercises than during sitting. Therefore, physical exercises may produce more particles. However, since the measured particles were larger than 0.3 μm, this factor may not influence the results in a major way.

Limitations

The measuring method is based on the assumption that the air in the chamber was well-mixed. To make particles distribute as uniformly as possible, a mixing fan was installed as described in the Methods section. The use of multiple particle counters at different heights could indeed contribute to the accuracy of the results. However, only one particle counter was available due to the restrictions of our experimental facilities. If the use of multiple particle counters were possible, the uniformity of particle distribution by this method could be further checked. Should the particles not distribute uniformly, measures should be taken to meet the well-mixed assumption, such as enhancing the mixing of the indoor air.

The measurement methods used in this study were based on the assumption that the emission rates of particles from clothed human body were constant. Given that this study relies on short-term emission (within 1 hour), that it focuses only on the starting part of the particle emission process, the assumption is substantiated to some degree. If the whole process of particle emission was to be analyzed, with particle emission monitored for a longer period of time, the emission rates of particles from the clothed human body may not remain constant. Therefore, a novel analytical method for estimating long-term particle emission rates deserves further

study.

In this study, only the emission rates of particles with a diameter larger than 0.3 μm were measured. However, since ultrafine particles are strongly related to adverse health effect (Delfino *et al.*, 2005; EPA, 2005), there is a need to investigate further the emission rates of ultrafine particles from the clothed human body, for example by using the method proposed in this study.

The human subject employed in this study may represent the typical characteristics of young males. However, we acknowledge that the characteristics of the human subjects, such as gender, age and race, may affect the particle emission rates. For instance, if it can be proved that a person with higher metabolic rate tends to have higher particle emission rate, males, young and Chinese people tend to have higher emission rates than females, old and Caucasians do, respectively. Therefore, the influence of the characteristics of human subjects on particle emission rates deserves further exploration. Additionally, particle emission rates of clothed human body were measured in a sealed chamber, a relatively ideal setting compared with real indoor environments such as clean rooms or aircraft cabins. Therefore, further research must be conducted to validate the applicability of this measurement method to actual engineering cases.

In this study, the tested clothes were exposed to outdoor particles over night, which may indirectly imply that the emitted particles in the test chamber were from the particles deposited on the clothes during the night. However, there may be other potential reasons for the particles emitting from the clothes. For instance, the emitted particles may be generated by breakage of the clothing fibers. In addition, the washing powder reminders may be resuspended from the clothes, which indicates that the time from last laundry may be another influencing factor. Novel experimental approach deserves further study to assess these potential influencing factors.

In this study, the measured deposition rates were used for determining the emission rates. However, since the moving human body entered the chamber, the surface inside the chamber as well as the intensity of mixing would increase. Therefore, the deposition rates when measuring particle emission may be higher than the measured ones, which may cause the under-prediction of the particle emission rates. As the surface of human body is relatively smaller than the inner surface of the tested sealed chamber, it is expected that the under-prediction may not be obvious.

This study was solely based on experimental investigation. However, a novel model for describing the emission of particles from clothed human body for simulation purposes needs to be developed, which could contribute to better analysis of the experimental data.

Scanty studies on particle emission from human body with street clothes have been carried out. This study is a tentative exploration on this issue, and it is far from perfect. More experimental studies are needed to obtain new and more comprehensive results that are truly applicable in other indoor environments. Novel physical-based models need to be developed for simulation and analysis purposes. We hope that more studies could be carried out on this topic.

CONCLUSIONS

We measured the short-term emission rates of particles in the "personal cloud" with various clothes and activity intensities in a sealed chamber. Within the scope of this research, the following conclusions can be made:

(1) Generally speaking, in this study the size-dependent emission rates of particles from the human body wearing a clean room smock were the lowest, while those from the human body wearing a polyester sportswear were the highest among the selected clothing.

(2) The emission rates of particles from the clothed human body were positively correlated with the human activity intensity. Furthermore, human activities tended to have a more significant impact on emission rates from the clothed human body for coarse particles than that for fine particles.

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