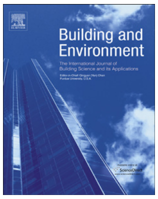
Building and Environment 81 (2014) 388–395

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv



Deposition velocity of fine and ultrafine particles onto manikin surfaces in indoor environment of different facial air speeds

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ARTICLE INFO

Article history:
Received 15 May 2014
Received in revised form
18 July 2014
Accepted 19 July 2014
Available online 31 July 2014

Keywords:
Deposition velocity
Fine and ultrafine particles
Human body
Indoor environment

ABSTRACT

Indoor airborne particles deposit onto human body surfaces. This deposition process not only changes indoor particle concentration, but affects indoor particle size distribution as well. Additionally, various air pollutants bound with indoor airborne particles, of which the deposition onto human body causes dermal exposure to air pollutants. Air speed is one of the key factors influencing particle deposition velocity onto human body surfaces. Air speed is also an important parameter for indoor thermal comfort. This study focused on particle deposition velocity (v_d) onto human body due to an increase in facial air speed in indoor environment. Deposition velocities of fine and ultrafine particles (30–500 nm) onto a sitting and a standing manikin, which experienced facial air speed of 0.4, 0.8 and 1.2 m s^{-1}, were experimentally measured in a well-sealed steel chamber. The heat dissipations of the manikins were set as 50 W and 100 W. The results showed that for the studied particles, deposition velocity onto different manikin surfaces increased from 0.048–2.68 m h^{-1} to 1.19–8.79 m h^{-1} as facial air speed went up from 0.4 to 1.2 m s^{-1}. The change of facial air speed had a stronger effect on smaller particles than on larger particles. The results of this study may well be helpful in further studies on dermal exposure estimation, indoor particle distribution analysis and even airflow design.

1. Introduction

Deposition is one of the important aerodynamic features of airborne particles. Indoor airborne particles deposit onto indoor surfaces, such as building walls and furniture, as well as human body. Deposition influences the indoor concentrations and size distribution of airborne particles. Moreover, multiple pollutants, such as heavy metal, semi-volatile organic compounds (SVOCs) and bacteria, can adsorb onto airborne particles. Deposition of these pollutants-bound particles onto human skin in indoor environments can lead to dermal exposure and may cause adverse health risks. For example, research based on occupational exposure scenarios has recognized that the increasing dermal exposure to polycyclic aromatic hydrocarbons (PAHs), which can adsorb onto airborne particles due to its low vapour pressure, contributed to an increase of the incidence of skin cancer [1]. Therefore, research on particle deposition onto human body surfaces in different indoor environments has profound meanings.

To quantitatively characterize the mass flux of particles depositing onto human body surfaces, deposition velocity is an indispensable parameter. Studies have claimed that indoor air speed is one of the most influencing factors for indoor particle deposition [2,3]. Thus, it is necessary to study particle deposition velocity onto human body surfaces in indoor environments under different indoor air speeds. Schneider et al. [4] developed a semi-empirical model to study particle deposition velocity on forehead and eyes of human beings. The model was based on wind tunnel studies and included the effects of electric field and air current. Gudmundsson et al. [5] measured deposition rates of particles with diameters of 2–30 μm onto dummy eyes under different wind velocities, wind directions and turbulence intensities. Nielsen and Schneider [6] investigated particle deposition velocity onto facial skin and eyes of two facial shapes under two scenarios with different turbulence conditions and aerosol charge distributions. Schneider and Bohgard [7] described the influence of turbulence, gravitational settling, electrical fields and thermophoresis on deposition velocity onto ocular surfaces. Andersson et al. [8] measured particle deposition velocity onto specific anatomic parts of human beings and analysed the influences of electrophoresis, moisture, temperature and physical movement. However, these researches only considered particle deposition velocity onto a specific part of human body

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http://dx.doi.org/10.1016/j.buildenv.2014.07.017

Nomenclature

A	surface area of human body (m^2)
C_c	Cunningham coefficient
C_{in}	indoor particle mass concentration ($\mu g\ m^{-3}$)
C_0	initial indoor particle concentration ($\mu g\ m^{-3}$)
D	Brownian diffusivity of the particle ($m^2\ h^{-1}$)
d_p	particle diameter (μm)
J	coagulation rate (h^{-1})
K	particle deposition rate (h^{-1})
k	Boltzmann constant
k_s	skin roughness height (μm)
m	particle mass (μg)
N	indoor particle number concentration (m^{-3})
P	coagulation coefficient ($m^3\ h^{-1}$)
T	temperature (K)
t	time (h)
V	volume of the chamber (m^3)
v_d	particle deposition velocity ($m\ h^{-1}$)
Greek symbols	
μ	air dynamic viscosity ($N\ h\ m^{-2}$)

rather than overall human body surfaces. Additionally, they did not provide the range of particle deposition velocity onto overall human surface under a general range of indoor air speed. Shi and Zhao [2] established an improved three-layer model to predict particle deposition velocity onto human body surfaces. The model, incorporating the effects of Brownian and turbulence diffusion, gravitational settling, turbophoresis, thermophoresis, and diffusiophoresis, was validated with manikin-based experiments. This study took overall human body surfaces into consideration, and concluded that for fine particles, friction velocity influenced deposition velocity onto human body surfaces significantly. However, the experiments were based on bald and unclothed manikins, which was divorced from reality to some extent. And they modelled particle deposition velocity onto overall human body surfaces with a typical indoor air speed rather than experimentally studying the varying trend of particle deposition velocity onto overall human body surfaces within a general range of indoor air speed. Consequently, the primary goal of our study is to figure out the particle deposition velocity onto overall human body surfaces in indoor environment with different air speeds. It should be noted that to better specify the indoor air speed, we chose facial air speed as an indicator as mentioned later in section “Methods”.

Researches on thermal comfort have studied the preferred indoor air speeds of human beings in hot and humid indoor conditions. Kubo et al. [9] reported the averages of the preferred air speeds of participants wearing 0.3–0.4 clo cloths at several temperatures and relative humidity, the results of which are shown in Table 1. Gong et al. [10] measured facial region air movement with different temperatures. The most often selected air speeds by the participants are also shown in Table 1. Surat and Charoenporn [11] placed a 15 cm diameter electric fan in front of each student who was wearing 0.55–0.6 clo cloth. Table 1 shows the preferred local air speeds of students of this study. Candido et al. [12] did field studies in Brazil and concluded from questionnaires that minimum air speed values that achieved 90% thermal and air movement acceptability were 0.4 m s^{-1} when temperature rose from 24 to 27 °C, 0.41–0.8 m s^{-1} when temperature rose from 27 to 29 °C and over 0.8 m s^{-1} when temperature rose from 29 to 31 °C. In conclusion, the most preferred air speed of general hot and humid conditions is from 0.4 to 1.2 m s^{-1}, which was chosen as the general range of indoor facial air speed in this study.

Table 1
The preferred air speeds at several temperature and relative humidity from previous studies.

Indoor temperature (°C)	Indoor relative humidity (%)	Preferred air speed (m s^{-1})	Reference
26.0	50	0.53	Kubo et al. [9]
26.0	80	0.58	
28.0	30	0.66	
28.0	50	0.87	
28.0	80	1.02	
30.0	30	1.06	
30.0	50	1.07	
30.0	80	1.27	
23.0	–	0.39	Gong et al. [10]
26.0		0.42	
26.0	–	0.20	Surat and Charoenporn [11]
26.6		0.50	
27.4		1.00	
28.3		1.50	
29.2		2.00	

To achieve the goal of this study, experiments were conducted to quantify the particle deposition velocities onto overall human body surfaces under the general indoor facial air speed. Heated manikins of two postures, standing and sitting, were utilized in the experiments as substitutes for living person to avoid the uncertain and unstable airborne particle source effect of living human.

2. Methods

2.1. Chamber, fan, manikin

The experiments were conducted in a cubic stainless steel chamber. The dimension of the chamber was Length × Width × Height = 2 × 2 × 2 m^3. The entrance door of the chamber was surrounded by a rubber strip. When the chamber was sealed, the air exchange rate measured by CO_2-decay method was lower than 0.04ACH. Thus, the chamber was considered to be well-sealed, under which circumstances the influence from outdoor particles on indoor particle concentrations is negligible. The temperature and humidity inside the chamber were continuously measured and recorded by a recording device (TJHY, Model WSZY-1) during each experiment. We utilized ambient particle to study the deposition velocity to represent a more realistic condition. Cao et al. [13] have measured atmospheric $PM_{2.5}$ in Beijing and provided detailed information about physical and chemical features of local airborne particles, which helped us learn the characteristics of the experimental particles. It is noteworthy that, particle coagulation is another potential reason leading to particle concentration decline in real conditions. To avoid the effect of particle coagulation on measuring particle deposition rate, the experiments were chosen to conduct when ambient particle concentrations were comparatively low. The highest initial particle concentration was 12033 cm^{-3}. The impact of particle coagulation will be introduced in detail in the following section.

The arrangement of the components in the chamber is shown in Fig. 1. Living human beings can generate fine and ultrafine airborne particles due to respiration, decrustation and physical movements. However, it is quite challenging to correctly quantify the strength of such human particle sources. Therefore, manikin is an appropriate substitute which avoids uncertain source effects and meanwhile possesses the main features of human being, such as the overall shape and the heat dissipation. Two manikins, one standing and the other sitting, were used in our experiments to represent the most