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Accurate assessment of exposure using tracer gas measurements

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ABSTRACT

Room airflow interaction, particularly in the breathing zone, is important to assess exposure to indoor air pollution. A breathing thermal manikin was used to simulate a room occupant with the convective boundary layer (CBL) generated around the body and the respiratory flow. Local airflow against the face of the manikin was applied to increase the complexity of the airflow interaction. CO_2 was released at the armpits and N_2O at the groin to simulate the respective bio-effluents generated at these two body sites. The tracer gas concentration at the mouth/nose of the manikin was measured with gas analyzers with short and long response times, respectively. The tracer gas concentration was characterized by the mean, standard deviation and 95th percentile values. The results revealed that the measurement time needed to determine, with sufficient accuracy, these parameters decreased substantially with a decrease in the response time of the gas analyzer. When only CBL was present, shorter measurement time was needed for the accurate concentration measurement of the tracer gas released close to the breathing zone. For more complex flow, as a result of CBL interaction with the exhalation flow, the needed measurement time was longer. It has been concluded that the accurate exposure assessment requires that the concentration measurements are performed only during the inhalation period. Therefore, gas analysers with low response time and sampling time that is considerably shorter than the inhalation period have to be used.

1. Introduction

Indoor air quality affects occupants' health, comfort and performance. Building materials, office equipment, and occupants are some of the indoor pollution sources. Occupants pollute indoor air by continuous body released bio-effluents and by the exhaled air as well as by bioaerosol shedding from their skin, clothes and hair [1,2]. Various human activities like cooking, smoking, vacuuming, cleaning, walking, etc. are also major contributors to the indoor air pollution burden [3–8]. The released pollution may cause SBS symptoms [9]. Therefore, the exposure assessment is important.

One of the paths of the occupants' exposure to the indoor pollution is respiration, i.e. inhalation of the polluted air. Airflows in rooms and around a human body transport pollution to the breathing zone and thus, modify the exposure. The convective boundary layer (CBL) around the human body in a calm environment, the transient flow of respiration and the flow generated by ventilation are some of the flows interacting in the breathing zone of the occupants. The convective boundary layer has been studied and described [10–17]. The importance of the CBL with respect to the transport of pollution to the breathing zone has been documented [10,11,18]. The contaminated exhaled air disturbs the CBL, can penetrate it, and spreads to other occupants [19]. Depending on the air distribution method the ventilation flow may be assisting, transverse, or opposing the CBL [20]. In general, the airflow interaction in a person's micro-environment is one of the most important factors influencing the exposure to the pollution released close to the body [10,11,19–24]. The interaction of flows around the human body is complex and transient in time [25,26]. Understanding the characteristics of different airflow interactions in the breathing zone will contribute to the accurate assessment of the exposure to the indoor pollutants and to a better design of efficient air distribution systems providing the occupants with high quality of the inhaled air and thermal comfort. Therefore, the accurate measurement of the flow characteristics such as air speed, temperature, and the gaseous contaminants concentration is important.

The concentration of gaseous contaminants that people are exposed to indoors changes randomly in time. It can be described by time averaged concentration, standard deviation of the concentration fluctuations, and their 95th percentile. Most often, the exposure and its impact on the occupants' health is assessed from the mean concentration measurements. However, it is still not clear whether the 95th percentile of the concentration should be considered as more relevant

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for the exposure assessment.

In previous studies the physical experiments were typically performed in full-scale test rooms, and the human body was simulated by using breathing thermal manikins [27,28]. A tracer gas was used to simulate the gaseous contaminants, e.g., a tracer gas mixed with the exhaled air was used to simulate respiratory pollution or it was released either from different sites on the manikin's body to simulate bio-effluents or in different locations in room to simulate particular pollution sources. Typically, to assess the transport and the exposure, the tracer gas concentration measurements were performed in the breathing zone of the manikin (close to the nose or the mouth). Two important factors have to be considered for the accurate exposure assessment, namely, the complex airflow interaction around the human body, particularly in the breathing zone, and the characteristics of the measuring instruments and the method of data analyses. The breathing thermal manikins with complex body shapes and the average person size allow for the mimicking of the CBL around the body and the human breathing cycle and mode with sufficient accuracy required for many studies. Different ventilation flows can also be organized in the full-scale rooms. This allows us to simulate with good approximation, the airflow interaction around the human body and to study its impact on the exposure. Furthermore, the measurement of the tracer gas concentration may be critical for the exposure assessment. Since the nature of the flow characteristics is stochastic, the dynamic characteristics of the measuring instruments are important. In general, the instruments used for the concentration measurements are slow and their response time and sampling period are considerably longer than the breathing cycle of a sedentary person (approx. 2.5 s inhalation, 2.5 s exhalation and 1 s pause). This may lead to an inaccurate exposure assessment because concentration measurements are performed during the entire breathing cycle instead of only during the inhalation period, i.e. the tracer gas concentration is measured also during the exhalation phase of the breathing cycle when an the airflow clean of tracer gas is generated. It has been shown that an open-path Fourier transform infrared (OP-FTIR) spectrometer can be used to ensure faster spatial tracer gas distribution in an empty room when compared to multipoint-sample concentration measurements [29]. However, the data at a particular point cannot be obtained faster than one sample per 6 min, which is too slow, and the measurement principle requires that the optical path between the emitter of the infrared radiation and the detector should be ensured which is often impossible in practice. This method can be used to measure spatial concentration distributions of one or two gases emitted from sources with either constant emission or with a simple pattern of emission, such as a short impulse or constantly increased/decreased emission.

The aim of the paper is to identify the importance of the sampling frequency, of the response time of the tracer gas analyzer and of the tracer gas sampling only during the inhalation cycle for the tracer gas concentration measurements. Another goal is to assess the required measurement time and develop a data analysis method for the accurate exposure assessment.

2. Methods

2.1. Experimental set-up

Experiments were performed in a climate chamber with the dimensions 4.7 m × 6 m × 2.5 m (W × L × H). The chamber was ventilated and air-conditioned by an upward piston flow. The air was supplied through a porous textile covering the entire floor area of the chamber on the top of which there was a steel coarse grid with square openings (2 × 2 cm). The supply air in the chamber was 100% outdoor air, with no recirculation. The supply airflow rate was controlled by an electronic fan speed control software and the fan was kept to operate constantly throughout the experiment. The air was exhausted through a square opening (the area of which was 0.144 m^2) in the ceiling above the manikin. The chamber construction ensured conditions with uniform temperature and negligible radiant temperature asymmetry. The air temperature in the room was kept 23 °C during all the measurements.

During the measurements, a breathing thermal manikin was used to realistically simulate a sitting person. The manikin resembled an average Scandinavian woman, 1.7 m tall. The manikin had 23 body segments and each had an individual control to maintain surface temperature equal to the skin temperature of an average person in a state of thermal comfort. The average surface temperature of the manikin's individual segments ranged from 32.0 to 34.8 °C during the experiments. The manikin was dressed in thin-tight outfit (a T-shirt, underwear, tight-fitting trousers, socks, and shoes). The thermal insulation of the clothing together with the chair was equal to 0.55 clo. The manikin had a short-haired wig. The thermal manikin's breathing process was simulated with an artificial lung located outside the chamber. The device was connected by two plastic tubes and connectors (situated on the lower back of the manikin) to the manikin's mouth and nose. The breathing frequency, pulmonary ventilation rate, and the temperature of the exhaled air were set to be the same as those of a person engaged in light sedentary activity. The manikin was set to inhale the air through its nose and exhale through its mouth, and vice versa. The pulmonary ventilation rate was 6 L/min. The breathing frequency was 10 times per minute with a cycle of 2.5 s of inhalation, 2.5 s of exhalation and 1 s of the pause [30]. The exhaled air was heated to 34 °C but not humidified. The thermal manikin's nostrils were round openings, each with the cross-sectional area of 38.5 mm^2. The jets emerging from the nostrils were deflected 40° downwards from the horizontal [31]. The mouth of the manikin was an ellipsoidal opening with the cross-sectional area of 158 mm^2.

The manikin was located approximately in the middle of the chamber, seated on a computer chair in front of a desk with the arms resting on the table (Fig. 1). A wooden plate (2 m × 1.21 m) was placed below the manikin to prevent the supply airflow to disturb the CBL produced by the thermal manikin. The mean air speed was measured at several locations in the chamber and around the manikin when it was unheated. The air speed was measured with a multichannel low velocity thermal anemometer with spherical sensor (the accuracy of the readings was ± 0.02 m/s ± 2%). It was lower than 0.05 m/s, i.e. a quiescent environment was present in the chamber [10]. The manikin was leaned 10° backwards from the vertical axis. There was a 10 cm gap between the edge of the desk and the manikin's abdomen. The desk was equipped with personalized ventilation (PV) supplying clean air towards the face of the manikin from a round movable panel diffuser (RMP). The RMP had a circular outlet with diameter of 0.185 m. A detailed description of the RMP can be found in Ref. [32]. Previous study showed that the personalized flow supplied by the RMP against the face could penetrate the CBL and provided clean air for breathing when its target velocity was higher than 0.3–0.35 m/s [32]. The supply

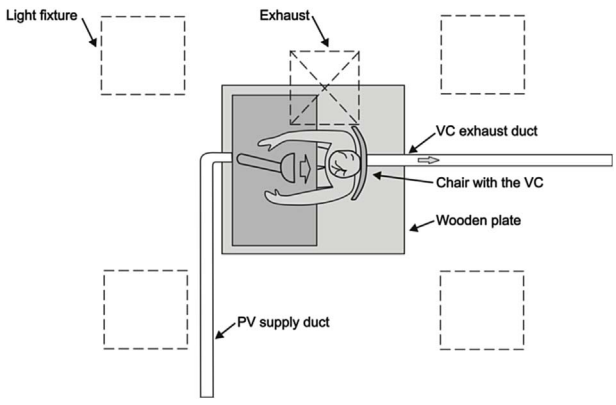

Fig. 1. Experimental set-up.