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Effect of airflow interaction in the breathing zone on exposure to bio-effluents

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ABSTRACT

The influence of the complex interaction of three airflows - breathing flow, convective flow around the human body and ventilation flow directed against the face - on the exposure to dermally-emitted effluents from a person's own body was examined together with the effects of source location and control. A breathing thermal manikin was used to simulate a seated person in a full size climate chamber. Bio-effluents released at the armpits and groin were simulated with two tracer gases. It was found that the flow of exhalation substantially affected the exposure to dermally-emitted bio-effluents released close to the breathing flow, e.g. armpits. The exposure in the case of exhalation through the nose was higher than when exhalation took place through the mouth. Breathing did not influence the exposure to gaseous pollutants emitted from the lower part of the body, in this case, the groin. Local pollution source control by exhaust ventilation integrated into the seat reduced the exposure. Airflow imposed against the face can substantially reduce the exposure regardless of the pollution source location. However, when this flow is combined with local source control the exposure may paradoxically increase, depending on the airflow interaction at the breathing zone and the source location.

1. Introduction

The human body emits particles (bio-aerosols) and gases (bio-effluents). Human respiration activities (exhalation, coughing, sneezing) generate bio-aerosols that may carry viruses and bacteria [1] that may cause airborne transmission of infection in confined spaces [2]. Human body movement and friction between the clothing and the skin generate skin flakes that contain a wide variety of contagious pathogens [3]. The flakes can be transported by air, inhaled and infect other occupants. The bio-effluents are volatile and non-volatile organic compounds that may be detected by the human olfactory system as odours. Oral cavity, armpits, groin, head and feet are the sites where bio-effluents are mostly generated [4]. Sweating is important for human body thermal regulation. The sweat is accumulated by the skin microbiome and further metabolised into volatile and non-volatile odours compounds [5]. The odour emanating from the human groin area is from the skin and from human excreta (e.g. urine). The compounds found in human excreta are acids, ammonia, sulphur, nitrogen compounds and other volatile metabolites [4]. Flatus also contributes to body odour and smells mainly because it contains a combination of volatile sulphur compounds [6]. Ozone reacts readily with squalene (found in skin oil) on occupants' skin, clothing and hair [7–9]. The reactions produce sub-micron particles and volatile products which may cause headaches, eye and respiratory irritation and increased susceptibility to respiratory illness [10]. Studies report that dermally-emitted pollutants have a higher odour intensity compared to the pollutants in exhaled air and may have a negative impact on occupants' health, well-being and productivity [11,12].

The micro-environment around the human body plays a major role for the heat and mass exchange between the body and the indoor environment and in exposure to indoor pollution [13]. A building occupant can be exposed to his/her own bio-effluents as well as to bio-effluents emitted from others. The importance of the separate and combined impact of the free convection flow and the flow of respiration on the exposure of bio-effluents released by an occupant's own body was the focus of the present study.

The Convective Boundary Layer (CBL) develops due to a temperature difference between the air surrounding the body and the surface of the body [14,15]. The CBL develops in the thermal plume above a person [16]. Gaseous and particulate pollutants generated

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from the body and in the immediate surroundings of the legs and trunk are entrained into the CBL of a seated person and are transported to the breathing zone [15,17–19]. The concentration of bio-effluents from a seated body in the breathing zone is highest when it is released at the chest and lowest when it is emitted at the upper back or behind the chair. It increases when the room air temperature decreases or the body is inclined backward [20]. The exposure is also influenced by the position of a desk in front of the body, the chair and the clothing design. However, the cited studies did not take into account the respiratory flow and the impact of its interaction with the CBL on personal exposure.

Breathing is transient and most often consists of inhalation, then exhalation, followed by a pause. The dynamics of the inhalation flow very close to the nose and to the mouth are similar [21]. Large variations in the spread of exhaled flows occur between people [22]. Exhalation generates jets with relatively high velocity, 1–2 m/s [21,23,24], which depending on the head position can penetrate the CBL resulting in a small amount of the exhaled air being re-inhaled [25]. The velocity in the exhaled jets decreases rapidly with the distance from the face. However the flow of exhalation through the nose and mouth is different [25,26]. Two independent jets deflected downward from the horizontal are exhaled from the nostrils [22,23,27]. In a calm environment and with an upright position of the head the jet is exhaled almost horizontally from the mouth with a temperature of approximately 34 °C and a relative humidity close to 100% [28] moves upward at some distance from the face [24,29]. An occupant with a low activity level inhales air mostly from the front areas of the CBL, and little from the back and sides of the body [30].

Depending on several factors (head position, breathing rate, strength of the CBL, etc.) the flow of exhalation may or may not penetrate the CBL [14,24,25,29,31–33]. The interaction of the exhalation flow from the nose and the CBL increases the turbulence in the breathing zone [29,34,35]. Rim and Novoselac [17] reported that simulating the breathing activity of a seated thermal manikin (inhalation/exhalation through the nose) has a noticeable impact on the airflow distribution in the breathing zone and may increase or decrease the particle concentrations measured at the mouth and above the head, depending on the source location in the room.

The interaction of the CBL with the surrounding airflow and the spread of exhaled air depend on several factors including the strength and direction of the airflow, location and size of the body exposed to the flow, etc. [27,30,36,37]. Laverge et al. [38] reported that in a room with low velocity floor-mounted diffuser (i.e. with the supply airflow distributed over the floor) the CBL remained the dominant flow at the inhalation zone. However, the CBL and the ventilation flow in spaces may interact differently depending on whether they are assisting, opposing or transferring pollutants to each other [37,39,40]. Advanced air distribution, such as Personalized Ventilation (PV), that supplies clean air directly to the breathing zone can penetrate the CBL and have a great impact on exposure [41,42].

The interaction of flows around the human body has been studied mainly with a focus on the spread of pollution between people. The reported research on airflow interaction at the breathing zone and its effect on the exposure of persons to their own bio-effluents are limited and incomplete. Local source control has been studied very little. Bivolarova et al. [43,44] showed that it is possible to apply efficiently source control and remove bio-effluents through local exhaust before it is mixed with the surrounding air.

Tracer gas has been used to simulate bio-effluents [20,39,40,43,44]. The tracer gas concentration used to assess exposure has been measured with instruments with a slow response time. The measurements have been performed for relatively long periods that included many inhalation and exhalation phases. This may have had an impact on the accuracy of the assessment because in reality the exposure depends on the inhaled air contamination only and not on the exhaled air.

The objective of the study was to show the impact of interaction between the breathing flow, the CBL and airflow from directed at the face from in front, together with local exhaust on the exposure to dermally-emitted pollution.

2. Methods

2.1. Experimental setup and facilities

Full-scale experiments were carried out in a climate chamber with dimensions of 4.7 m × 6.0 m x 2.5 m (W x L x H). The chamber was ventilated by an upward piston airflow without recirculation, supplied from the entire floor area with an air velocity of less than 0.05 m/s. The upward piston flow of outdoor air ensured uniform air temperature and air velocity distribution in the chamber without recirculation of the tracer gases. The air was exhausted through a square opening (0.38 × 0.38 m^2) in the ceiling (Fig. 1). The chamber had been constructed to ensure a mean radiant temperature equal to the room air temperature and negligible radiant temperature asymmetry.

A breathing thermal manikin with a realistic female body shape (size 38, 1.68 m height) was used to simulate the dry heat loss of a seated occupant [45]. The manikin had 23 body segments, each with individually controlled heat output. The surface temperature of the segments was controlled to be similar to the skin temperature of the body parts of an average human in a state of thermal comfort when exposed to the same room conditions and wearing the same clothing. The average surface temperature of the individual segments varied within the range of 32.0–34.8 °C. The

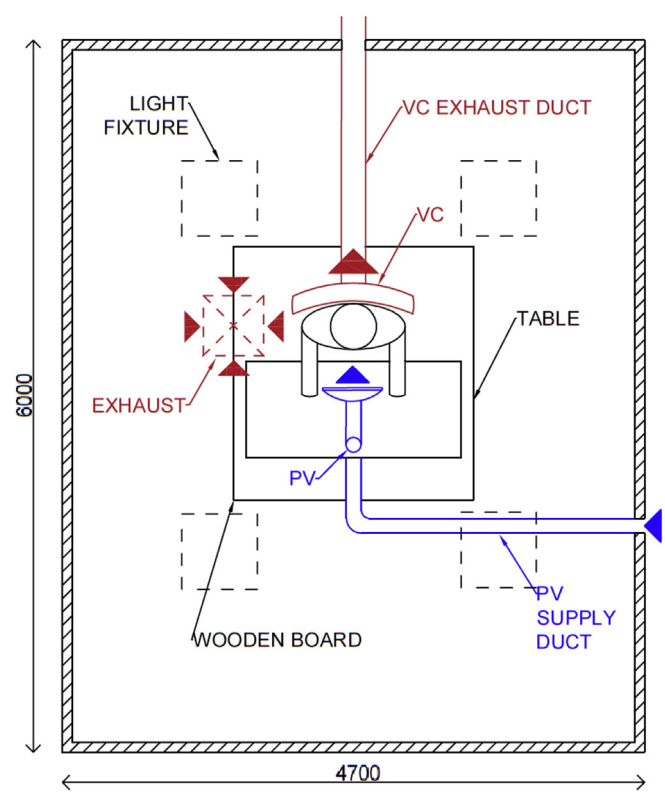

Fig. 1. The climate chamber arrangement.