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Experimental investigation of the human convective boundary layer in a quiescent indoor environment

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ABSTRACT

This study aims to characterize human convective boundary layer (CBL) in a quiescent indoor environment. The study has two objectives: first, to characterize the velocity field around the thermal manikin under two ambient temperatures and body postures; and secondly, the influence of clothing insulation/design, chair design, table positioning and seated body inclination on airflow characteristics in the breathing zone of a sitting manikin is examined. The increase of the ambient temperature from 20 to 26 °C widens the CBL flow in front of the sitting manikin but do not influence the shape of the CBL in front of the standing manikin. The same temperature increase causes the reduction of the CBL mean peak velocity from 0.24 to 0.16 m/s in front of the sitting manikin. Dressing the nude manikin with thin-tight clothing ensemble reduces the peak velocity in the breathing zone from 0.205 m/s by 17%, and by 40% for thick-loose ensemble. Removing the wig increases the peak velocity from 0.17 to 0.187 m/s. Clothing and chair design have a minor influence on the velocity profile beyond 5 cm distance from the body. Closing the gap between the table and the manikin reduces the peak velocity from 0.17 to 0.111 m/s. Manikin leaned backwards induces the peak velocity of 0.185 m/s, which is 45% above the case when manikin is leaned forward. PIV measurements complemented with Pseudo color visualization (PCV) technique provide a good synergy between quantitative and qualitative airflow characteristics and can be adequately employed for the CBL investigation.

1. Introduction

As part of the thermoregulatory process, the human body is constantly exchanging heat with its surrounding environment. Recommended indoor temperature range is 20–26 °C [1], which is approximately 7–13 °C lower than the temperature of the human skin. Consequently, the convective heat loss from a human body induces upward movement of the surrounding air, thus forming a convective boundary layer (CBL) around it and a free-convection thermal plume above the human head. The driving force of the convective flow is the buoyancy force caused by the difference in the temperature between a warm human body surface and cooler surrounding air.

Lewis et al. [2] were the first to conduct a systematic analysis of the air movement in the vicinity of the human body using a Schlieren photography and hot wire anemometer. They found that at a background temperature of 15 °C, the flow in front of a standing nude man begins to change from laminar to turbulent at the height of 1 m and becomes fully turbulent at about 1.5 m from the floor. Other studies [3,4] documented that surrounding air is entrained into the laminar free-convection flow around the human body which after some distance accelerates progressively developing into a thicker turbulent flow with a relatively high velocity at the mouth level. As a result of entrainment, mass flow in the plume above a standing human increases inducing as much as 60 l/s of surrounding convection flow at 20 °C ambient temperature [4,5]. In that regard, the volume flux of the human thermal plume is comparable to the total ventilation flow, thus having a prominent role in formation of the airflow patterns in an indoor environment. It has been documented how important human convection flow is for indoor air quality, thermal comfort and spread of airborne diseases, in the indoor environment [5,6].

Apart from the temperature gradient between warm surface of the body and the surrounding air, there are number of factors which influence the development of the human CBL such as room

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air distribution, thermal stratification, metabolic rate, posture of the body, clothing insulation and design, as well as furniture arrangement [6–8]. Understanding the extent to which these factors affect air distribution around the human body is important since the CBL has the ability to transport pollution and potentially infectious particles around the human body that may be entrained from the ambient air or that may be shed from the skin or clothing [9]. This transport applies to pollutants such as formaldehyde released from furniture, products of chemical reactions of bioeffluents produced by the body and especially to the particles smaller in size that are proven to be more severe, compared to larger particles.

Several numerical studies of the airflow enveloping the human body were documented. Some of them were performed in quiescent indoor conditions [6,10], while others investigated the human convection flow exposed to a various combinations of the free stream velocity [11,12]. Several researchers [13,14] employed Schlieren photography technique to visualize the development of the CBL under three body postures: standing, sitting and lying. The visualization showed that a supine body position generates a weaker convection flow compared to the standing posture, and consequently, different heat output rates from the human head. Sedentary occupants might not be necessarily seated in the upright position, but may lean backwards or forwards depending on their preference. Understanding the physics of the flow around a sedentary person is more important as most of the building occupants are predominantly found sitting throughout the day. Detailed quantification of this flow has not been performed so far.

In indoor spaces, seated occupants are customary surrounded with the furniture that can alter the airflow characteristics around their body. It has been documented how the table in front of the occupant impacts the flow characteristics of the thermal plume above the head [15]. Bolashikov et al. [16] used Particle Image Velocimetry (PIV) to study the strength of the human CBL and its interaction with personalized ventilation jet. The results show that weakening the human convection flow by placing the cardboard between the front edge of the desk and abdomen of the manikin allowed the personalized ventilation jet to penetrate the breathing zone at the lower flow rate. The influence of the table positioning on the airflow characteristics around the human body has not been explored comprehensively enough in the past.

Previous research attempted to investigate the effects of the clothing and chair insulation on the flow field around the human body. Homma & Yakiyama [4] found that the thickness of the CBL at the chest level was 7.5 cm for the nude standing person, whereas a clothed person increased the thickness to 15 cm. The impact of clothing and chair design on the characteristics of the thermal plume above seated person has been studied [15]. Findings showed that tight clothing and chair design need not be considered in full-scale experiments, since they have no influence on the thermal plume. The impact of the clothing design on the airflow characteristics enveloping the human body has not been studied. Seated occupants have part of the thighs, buttocks and back in the contact with a chair, which increases the clothing insulation differently, depending on the design of the chair, material, clothing ensemble, as well as surface area against the body. McCullough et al. [17] documented that replacing a real chair with a net chair decreased clothing insulation values from 0.3 to 0.1 clo. The impact of chair design on the CBL characteristics at the breathing zone is unknown.

The first objective of this study was to characterize the human CBL in the quiescent indoor environment under two ambient temperatures and body postures. The second objective was to study the impact of factors such as clothing insulation and design, chair design, table positioning and seated body inclination on airflow characteristics in the breathing zone of a sitting manikin. While some of the parameters have already been studied in the past, most of them are lacking comprehensive data on airflow characteristics obtained with global-wise measurement technique. For the purpose of this study, the Particle image velocimetry (PIV) results were complemented with Pseudo color visualization (PCV) technique to improve overall understanding of airflow distribution around the human body. The PCV technique has not been previously used for CBL studies.

2. Methods

2.1. Experimental setup

An environmental chamber with dimensions of 11.1 × 8 m^2 and height of 2.6 m was used for the purpose of this study. The chamber was equipped with displacement ventilation system composed of four supply diffusers located in the corner of the room and six ceiling mounted exhaust diffusers. To simulate the behavior of the human CBL, a non-breathing thermal manikin with complex female body shape was used to resemble human body. The manikin had a height of 1.68 m in the standing posture and 1.23 m in the sitting posture. Manikin's body consisted of 26 body segments with a constant surface temperature kept at 32 °C. This theoretical scenario was chosen to precisely determine the effect of each parameter studied. Future studies will involve non-uniform temperature distribution of the manikin that resembles the skin temperature of an average person in a thermally comfortable state. Thermal manikin was calibrated prior to the experiments.

During the experiments, ventilation system was turned off with the aim to provide quiescent indoor conditions. The chamber was periodically ventilated (i.e. between each measurement) in order to maintain the constant room air temperature and remove heat loads introduced by the manikin and measuring equipment. Prior to the experiments, tests were performed to establish how much time is necessary for environment to become quiescent from the moment air delivery was turned off. Results indicated that 5 min is enough for this transition and that time was adopted as a part of the experimental protocol. Velocity measurements were performed with DANTEC omnidirectional thermal anemometers (probe type 54T33) that are capable of measuring velocity (±0.02 m/s accuracy) and the ambient temperature (±0.2 K). Both velocity and temperature recordings took place at 4 locations around the thermal manikin at 1.2 m distance, vertically placed at 0.5 m, 1 m, 1.5 m and 1.9 m from the floor at each of the locations (Fig. 1). Based on 300 recordings, each measurement took 5 min to obtain the mean velocity. The magnitude of the mean velocity was low, below 0.05 m/s, indicating that quiescent indoor environment had been achieved [10]. Measurement equipment was placed at far enough distances from the manikin in order not to interfere with the natural convection flow. All the external walls were insulated and heat from the light sources was eliminated, which made all surrounding walls adiabatic. Ambient temperature was measured to indicate that the effect of the thermal stratification on the CBL was acceptable. Temperature recordings closely followed the set point temperature with insignificant level of thermal stratification compared to the vertical air temperature difference recommended by ASHRAE [1]. The maximum thermal gradient between the lowest and the highest measurement point was about 0.5 °C.

Given the objectives of this study, two sets of experiments were conducted:

- Set 1: The first set of experiments aimed to characterize the velocity field around a thermal manikin under two ambient temperatures (20 and 26 °C) at two body postures (sitting and standing). A nude (0 clo) thermal manikin with no hair was used as an experimental subject;