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An improved experimental method for local clothing ventilation measurement

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ABSTRACT

A clothing local ventilation measuring device based on the Lotens–Havenith steady state tracer gas method was developed and an improved experimental method for understanding local ventilation mechanisms was proposed. The local ventilation system can measure the arm, chest and back ventilation rates at the same time. Local ventilation mechanisms of an impermeable garment at two activities (static, walking) and two wind speeds (no wind, 1.2 m/s) were studied, with a focus on determining the pathways of ventilation through the different garment openings. The results showed that local ventilation rates of chest, back and arm varied considerably over locations and conditions. As expected, ventilation rates were highest for all locations at walking with wind conditions. Ventilation mechanism changed at different walking and wind conditions. The main air exchange pathway for all locations was through the garment bottom. Wind had a greater impact on clothing local ventilation than walking.

Relevance to industry: Clothing ventilation impacts worker's thermal comfort and safety directly both in the cold and heat. The new clothing local ventilation measuring device developed in this paper can measure both clothing local and whole ventilation. It can also help us to separate the different pathways for heat loss through clothing.

1. Introduction

Clothing microclimate ventilation is an effective way for the human body to lose heat. Especially for workers in the hot dry conditions, it is an efficient cooling avenue. Over the years, three methods have been developed to measure clothing ventilation: one by Crockford (CR) – unsteady state method (Crockford et al., 1972), one by Lotens and Havenith (LH) – steady state method (Lotens and Havenith, 1988) and one by Reischl and Stransky, (1980). The first two methods are used to measure whole garment ventilation, while the third method is intended for local ventilation at a single point only. Havenith et al. (2010) compared the first two methods on reproducibility, validity, sensitivity and applicability for the determination of microclimate ventilation and vapor resistance. Both methods worked well. However, Crockford's method requires the measurement of the clothing microclimate volume, which is complicated and error prone (Havenith et al., 2010). The 3D scanning method is the most accurate to measure microclimate volume (Lee et al., 2007). But the equipment is costly and laborious 'repair' work has to be done to the scans to get a closed model. So the LH method (Lotens and Havenith, 1988) is easier used in research and industry (Havenith et al., 1990a; Satsumoto and Havenith, 2010).

The air space between the human body and the garment is a main factor influencing ventilation rates. But this always changes according to different activities and locations (Ghaddar et al., 2003). Therefore the clothing microclimates (air gap thickness and microclimate volume) of local regions are always different (Zhang et al., 2010). In addition local sweat rates are also different (Havenith et al., 2008; Smith and Havenith, 2011), interacting with local ventilation rates to deliver cooling (Ueda et al., 2006; Havenith et al., 2003; Ueda and Havenith, 2002; Ueda et al., 2005). Therefore local ventilation rates need to be evaluated separately to enable designers to optimize clothing design for improved thermal comfort. Recently two local ventilation systems have been developed. One was built by Satsumoto and Havenith, (2010), and the other was developed by Ueda et al., (2006). SH used the LH steady state method (Havenith et al., 1990a, 1990b) to evaluate four regions' local ventilation rates of diapers. But the method needed to control the inlet and outlet flow rate precisely the same which can be difficult technically. In addition, the SH system can only measure

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one part's ventilation at one time, which wastes trace gas and extends testing time. UI used the CR unsteady state method to evaluate chest, back and upper arm ventilation separately, approximating clothing microclimate using a cylinder model (Lotens and Havenith, 1991), thereby increasing potential uncertainty and error. Satsumoto also evaluated the local ventilation in diapers using the CR unsteady state method before (Satsumoto et al., 2008). They demonstrated that the steady state method was better than the transient method (Satsumoto and Havenith, 2010).

Air exchange between a specific garment location and the environment includes three parts: 1:air exchange between local body parts' microclimates, 2: air exchange through the fabric with the environment and 3: through garment apertures with the environment. Of these, only air exchange between the microclimate and the environment directly helps heat loss, which can be called effective ventilation. The air exchange between different clothing sections may not be effective as the air coming in from other sections may already be heated and have absorbed moisture there. Therefore it is of high importance to understand the local ventilation mechanism as this may give some suggestions to garment apertures design especially for functional garments that can only have one or two apertures.

In the present study, a local clothing ventilation system was developed based on the LH steady state tracer gas method to measure local microclimate ventilation rates in different locations. Using this setup, a study was designed to better understand local ventilation mechanism at two activities (stand, walking) and two wind conditions (no wind, 1.2 m/s), giving specific attention to air exchange via the different apertures of the clothing.

2. Method

We divided the upper body garment into 4 areas – right arm, left arm, chest and back. The upper body has approximately vertical symmetry. Therefore for vertical symmetry garments only local ventilation rates of the right arm (or left arm), the chest and the back need to be measured.

2.1. Local ventilation rates measuring system

Fig. 1 shows the schematic diagram of the local ventilation system for one location. A steady state tracer gas method based on the LH principle was used (Lotens and Havenith, 1988; Havenith et al., 2010). Argon was chosen as tracer gas, as it constitutes a compromise between similarity with water vapor in molecular diameter, low background concentration, lack of absorption and safety considerations (Havenith et al., 1990b; Lotens and Havenith, 1988). But it is still need to mention that the diffusion constants of Argon and water vapor are different. The respective diffusion constant of Argon relates to that of water vapor in air is 0.7 (Havenith et al., 2010). In addition, the absorption capability of the two gases also differed. The main tracer gas concentration measuring device is a mass spectrometer (Spectra, Crewe, UK).

Argon was premixed with air before going into clothing microclimate. The pump connected to garment outlet flow (sampling tubing) was for circulation of air through the system, back into the garment after enriching it with pure Argon. A second, smaller pump connected to the mass spectrometer was for sampling. All sampling connections to the mass spectrometer were placed on the positive pressure side of the main circulation pump to reduce pressure differences in the sampling line. This aimed to reduce the impacts of pressure differences in the system on mass spectrometer values, as this is very sensitive to pressure differences.

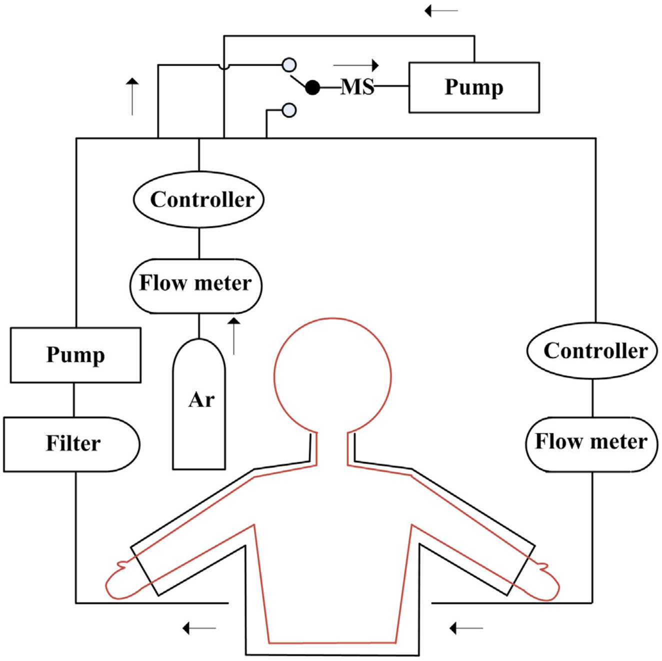

Fig. 1. Schematic diagram of the local ventilation system for one location.

One improvement of the system compared to Lotens and Havenith (1988); Havenith et al. (2010) is that all sampling flow was returned to the main flow after sampling (rather than being discarded), which decreases the impacts of the sampling process on the testing precision. Due to this improvement, there was no need to strictly limit the sampling flow rate theoretically (For Havenith et al.'s system (Havenith et al., 2010) the whole garment sampling flow rate is controlled below 1 l/min compared to a main flow rate of 20 l/min, but due to the lower measurement volumes of the local zones compared to a full body system, the total flows needed to be reduced (<2 l/min per area) to reduce the impact of the measurement flow on the ventilation process itself, while the sampling flow rate could not be reduced to a similar ratio to maintain stability and speed).

Argon distribution and sampling took place via tubing systems. Both systems were branched with same diameter tubes(arm – 4 tubes, chest and back – 6 tubes) for even Argon distribution and sampling. These tubes were sealed and perforated every 100 mm by orthogonal pairs of 1 mm i.d. holes. Tubes supplying to and sampling from the arms were not perforated for the first 170 mm (The distance from about the waist to the shoulder) to avoid excessive Argon distribution across chest or back. The distance of the tubes from the shoulder to the end was about 60 cm.

2.2. Ventilation computational methods

For each location i, microclimate ventilation rate ($\mathrm{Vent_i}$) is (Havenith et al., 2010, 1990b):

$$\mathrm{Vent}_i = V_i \times \left(C_{\mathrm{in},i} - C_{\mathrm{out},i}\right) / \left(C_{\mathrm{out},i} - C_{\mathrm{air},i}\right) \tag{1}$$

where i stands for different locations, from 1 to 4, V is the flow rate of local circulating system (l/min),C_{in} is Argon concentration of the garment inlet flow (%),C_{out} is Argon concentration of the garment outlet flow (%), C_{air} is the Argon concentration of the atmosphere around the ith clothed body (%).

In addition, the system can also measure whole ventilation ($\overline{Vent}$) indirectly. That is: