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Applicability of whole-body heat balance models for evaluating thermal sensation under non-uniform air movement in warm environments

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ABSTRACT

In ASHRAE Standard 55-2010, the comfort effects of elevated air movement are evaluated using the SET index as computed by the Gagge 2-Node model of whole-body heat balance. Air movement in reality has many forms, which might create heat flows and thermal sensations that cannot be accurately predicted by a simple whole-body model. This paper addresses two of such potential inaccuracies: 1) indoor airflows may affect only a portion of the body surface (e.g., above desktop), and the affected body surface might be variably nude (e.g., face) or clothed, 2) the turbulence intensity (TI) in some typical airstreams (e.g., those created by fans) might have a different impact on heat transfer than the TI implicit in 2-Node's single convective heat transfer coefficient. For both these issues, can a whole-body index like SET represent such a wide range of possible exposures to airflow?

Measurements of thermal sensation were obtained from human subjects using face-level fans in warm environments. Previous laboratory studies of a range of airstream sources were also analyzed. The effects of turbulence intensity were examined with manikin tests.

The results show that indices derived from the 2-Node model of whole-body heat balance are effective at predicting thermal sensation under most non-uniform air movement. In contrast, the PMV index underestimates cooling in warm conditions. Turbulence increases the cooling effect of air movement, but by amounts that might be neglected for most design purposes.

1. Introduction

Air movement has a significant cooling effect, increasing the acceptable range of indoor temperatures [1–4]. ASHRAE Standard 55-2010 uses the model PMV to determine comfortable temperatures under still air, and uses the SET (standard effective temperature) index as the basis for extending this still-air comfort zone under elevated air speeds [5].

The SET index is derived from Gagge's 2-Node model, which was introduced in 1970 [6]. The model considers a human as two concentric thermal compartments representing the skin and core of the body, producing a minute-by-minute simulation of the status of the human thermoregulatory system [7,8]. The model predicts skin temperature, skin wettedness, and thermal status for any combination of environmental and personal variables, including those outside the neutral range, and can be used to find the loci of environmental conditions that produce equal levels of heat loss. Therefore it appears reasonable to use SET as an index to evaluate cooling effect of elevated air movement.

However the environmental surroundings of a simplified model like 2-Node are assumed to be uniform. It is a 'whole-body' model, in which the entire body surface is represented by one average heat transfer coefficient, unlike a 'multi-segmented model', in which body segments are treated individually, and which are necessarily more complex. Recognizing the whole-body nature of SET, ASHRAE Standard 55 specifies that 'average air speed' be used as input to the model, which for sedentary occupants is defined as an average of airspeed measurements at 0.1, 0.6, and 1.1 m above the floor.

There are many ways that air movement may be distributed across the body, uniform or non-uniform. The airflow from fans typically reaches only parts of the body surface. The airspeed across these exposed parts is higher than the average airspeed, and the physical and psychological effects may be sensitive to this difference.

In addition, whole-body models use an average clothing resistance value for the whole body surface [9]. But the airflow from fans

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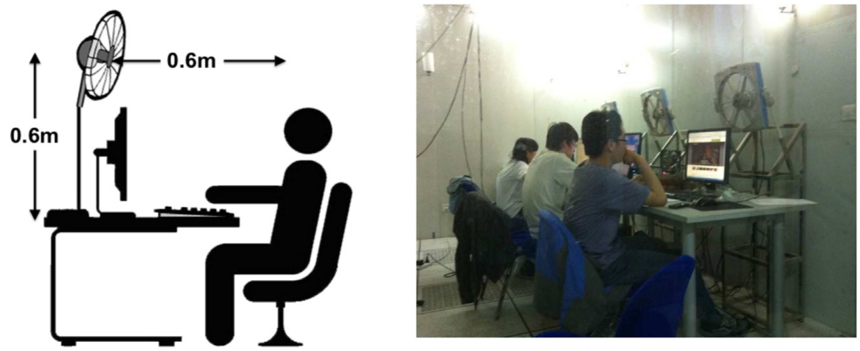

(a) (b)

Fig. 1. The relative position with the subject and fan.

passes over both clothed (e.g., trunk) or unclothed (e.g., face) portions of the body. While the heat loss from clothed and nude surfaces might be linearly related to clothing resistance, the psychological sensitivity may not be.

Finally, a given airspeed's transient flow characteristics (intensity and scale of turbulence) are likely to be different from the fixed level of turbulence assumed in the 2-Node model. Nishi and Gagge [10] experimentally developed the model's forced-convection equation by having subjects walk through still air at a fixed speed. Turbulence was not measured in their experiment, and is not an input variable to 2-Node. In reality, however, turbulence from different air movement sources will differ, and will affect heat transfer. Mayer's research with a manikin head [11] showed an increase in heat transfer with increasing turbulence intensity (TI) when TI is above 40%. It would be desirable to know whether the differences in turbulence intensity found in typical air movement sources like ceiling or desk fans significantly affect body cooling, and whether 2-Node predictions using only one implied turbulence level accurately predict these differences.

This paper examines each of the above issues as follows:

1) In a study in which fans provided non-uniform frontal air flow to the upper body, subjects' actual thermal sensation votes (TSV) could be compared to SET values calculated for the experiment's test environmental conditions. The calculations were done in two ways: using only the air speed around the face, and using the average air speed of three heights next to the subjects: 0.1 m, 0.6 m, and at face level (1.1 m). If the calculated indices represent the subject's responses well even under non-uniform flow and non-uniform clothing coverage, then the general use of a whole-body model is supported.
2) A number of published human subject experiments provide TSV results for other types of airflow sources and exposures of the body surface. These experiments involved airflow exposures to a variety of body parts that have differing thermal sensitivity (e.g., face vs. chest vs. back) [12]. Differences in subjects' thermal sensations should appear, even at the same air velocity. The regression relationship of TSV against SET value is therefore likely to differ among various types and extent of exposure.
3) Finally, we determined the turbulence intensity that had occurred in the Nishi/Gagge experiment [10], since this TI is inherent in the 2-Node convection algorithm. We repeated the conditions of the Nishi and Gagge experiment and directly measured the TI. The heat loss from this TI was then measured with a manikin, and compared with heat losses from a range of TI values occurring from fans and other indoor sources. A relationship describing the difference in heat loss and thermal comfort could be developed from this.

2. Methods

2.1. Test of cooling under non-uniform air flow

A subjective experiment was conducted in a climate chamber in Tsinghua University in Beijing. 30 subjects took part in the experiment, experiencing warm environments with fan-generated frontal air flows to the face and upper body. They wore summer clothing of 0.57 clo. The temperature ranged from 28 °C to 34 °C with relative humidity 40%–50%. At each temperature, air speed ranged from 0.6 m/s to 2 m/s. All the fans were placed in front of the subjects at a horizontal distance of 0.6 m and a vertical distance of 0.6 m from the desk (Fig. 1). The experiments were designed orthogonally with different temperatures and air speeds. Each experiment lasted about 2 h at a fixed temperature. At the beginning, the subjects were given no air flow for 45 min, and then they voted their thermal sensation. After that, the fans provided air flows with four randomly sequenced speeds in turn, with each air flow lasting for 15 min, for a total duration of 60 min. Subjects' TSV were collected at the end of each 15-min period, using the ASHRAE seven-point thermal sensation scale (−3 cold, −2 cool, −1 slightly cool, 0 neutral, +1 slightly warm, +2 warm, +3 hot). Using the environmental parameters of each experiment, SET values for

Table 1
Studies of air movement using different air movement devices [14–23].

Researcher	Location	RH (%)	Local control	Air movement supply device	Body part directly exposed to the air movement
D. McIntyre (1978) [14]	UK	50	Yes	Ceiling fan	Head
Y. Zhai (2013) [15]	USA	60/80	No	Ceiling fan	Head
M. Fountain (1994) [16]	USA	50	Yes	Desk fan	Face and chest
S. Atthajariyakul (2008) [17]	Thailand	45–80	No	Desk fan	Face and chest
T.T. Chowa (2010) [18]	Hong Kong	50	No	Tower fan	Back
S. Tanabe (1994) [19]	Japan	50	Yes	Wind box	Back
H. Kubo (1997) [20]	Japan	50	Yes	Wind box	Front
N. Gong (2006) [21]	Singapore	40–55	No	Nozzle	Face
B. Yang (2010) [22]	Singapore	–	No	Nozzle	Head
H. Zhang (2010) [23]	USA	50	Yes	Nozzle	Head