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COUPLING OUTER-BODY AIRFLOW AND INNER-BODY THERMOREGULATION MODELS TO PREDICT THERMAL COMFORT IN NON-UNIFORM ENVIRONMENTS

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ABSTRACT

In this study, we developed a numerical thermal manikin (NTM) with inner-body thermoregulation functions to investigate the local and overall thermal comfort in non-uniform thermal environments. The effect of interaction between human body and his/her environment was modeled by transferring air condition data from computational fluid dynamics (CFD) simulation into a thermoregulation model, feeding back the body surface temperatures from the inner-body model as boundary conditions to CFD, and then iterating until convergence. Application of this approach in the evaluation of two kinds of personalized ventilation systems was demonstrated. Comparison with some of the experimental results showed that it was able to predict the thermal comfort level with reasonable accuracy.

INTRODUCTION

Developments of heating, ventilation and air-conditioning (HVAC) have created many types of non-uniform indoor environments for better air quality while keeping low energy consumptions. For example, personalized ventilation (PV) was proposed for individual control of micro-environments and fresh inhalation in the breathing zone. To evaluate thermal comfort levels in these asymmetric environments, the well-known comfort model developed by Fanger is not appropriate since it is inherently one-node and steady-state model. For another instance, in modern metropolises, glass-curtain walls and large windows are used more and more for day-lighting and beautiful outside views. Although generally glass walls and windows are not the primary element affecting the indoor thermal comfort of the occupants, for the people sitting/standing close to them, applications of glass-curtain walls and large windows may still cause some comfort problems, such as radiant asymmetry, draft caused by cold glass temperature, positive or negative effect of direct solar radiation falling on a building occupant.

In such built-environments, evaluation of thermal comfort level is essential for HVAC systems or architecture components design. Human subject survey and application of heated thermal manikins are two popular experimental approaches. However, given their high time- and money- costs, numerical methods should be developed to effectively assess the comfort level in these kinds of non-uniform environments, not only in the design stage, but also in the parametric optimization.

In this paper, a numerical approach is developed considering the air condition around the occupant and his/her physiological response. Through coupling outer-body airflow model and inner-body thermoregulaion model at various body segments, the sensation and comfort at both local parts and overall body could be predicted.

To the best of the author's knowledge, there are very limited studies on the coupled simulation of inner-body thermoregulation model and outer-body airflows although some preliminary investigations have been practiced. Murakami et al (2000) combined Gagge's two-node model with room air flow simulation. The sensible and latent heat loss from the human body was calculated. But the physiological difference of body parts was not included. Xue et al (1999) coupled three-dimensional flow field and a modified 25-node model of human thermoregulation. Distributions of air velocity, temperature, and moisture content were demonstrated in a crowded enclosure with 280 people sitting in 4 blocks. But the geometry of the human body was very simple. Recent works by Zhu et al. (2007, 2008) realize the full coupling of CFD and two kinds of thermal physiological models. The skin temperatures and heat fluxes are well predicted. However, thermal sensation and comfort are not evaluated.

METHODOLOGY

Inner-body thermoregulation models

A complete heat balance type thermal comfort model should include three components (Guan et al. 2003): a physical heat exchange model and a clothing model, a physiological thermoregulation model, and a physiological thermal sensation model. Heat exchange model provides information on heat and mass transfer between the human body and the surrounding environment. Thermoregulation component takes account of the physiological reaction to the environment. Based on subject tests and statistic methods the physical parameters obtained from previous two models are bridged with human thermal sensations.

Huizenga et al. (2001) have developed an advanced thermoregulation model. Their model is able to predict human physiological and psychological response to transient, non-uniform thermal environment. Based on Stolwijk's 25-node model of human thermal regulation (Stolwijk 1971), their model allows an unlimited body segments, each of which consists of four body layers (core, muscle, fat, and skin tissues) and a clothing layer. Countercurrent heat exchange between the artery and vein, as well as heat exchanges between the blood vessels and the contacting tissues are simulated. A separate series of nodes represent blood and provide for conductive and convective heat transfer between segments and tissue nodes. The model calculates heat transfer between each node using a standard finite-differencing algorithm with variable time-stepping to optimize computational resources while preserving numerical stability. Validations of this model through several steady state conditions and three transient environments show that it is able to predict both core and skin temperatures with reasonably accuracy under a range of environmental conditions. Therefore this model is selected as the inner-body thermoregulation model in this study. More detailed information can be found in Huizenga et al. (2001).

Thermal comfort models

We adopt the thermal sensation and comfort model set up by Zhang (2003). In Zhang's tests, local body segments of the subjects were independently heated or cooled while the rest of the body was exposed to a warm, neutral, or cool environment. Based on the physiological and subjective parameters: skin and core temperatures and their change rates, and perceptions of local and overall sensation and comfort, the following sensation and comfort predictive models were developed (Figure 1):

- A local sensation model for each of the 19 body parts
- A local comfort model for each of the 19 body parts
- An overall thermal sensation model
- An overall thermal comfort model

The thermal sensation scale used is a continuous scale and can be translated into the numerical values, i.e., "very cold" is -4, "cold" is -3, "cool" is -2, "slightly cool" is -1, "neutral" is 0, "slightly warm" is 1, "warm" is 2, "hot" is 3, "very hot" is 4. The thermal comfort scale ranges from very uncomfortable (-4) to very comfortable (+4). In the middle the scale is broken, between "just uncomfortable (-0)" and "just comfortable (0)".

Model coupling

The model coupling is realized on a numerical thermal manikin (NTM) with the real body shape. Detailed information of air temperature and air velocity can be simulated using computational fluid dynamics (CFD) at each body segment of the NTM. Model coupling means transferring the air condition data from CFD into the thermoregulation model to obtain surface temperatures, heat flux, and sweat loss, and then feeding back the surface temperatures to CFD as boundary conditions at body surfaces. The iteration loop is shown in Figure 2. The following steps are the main components in this numerical method:

- Create a numerical thermal manikin with the real geometry of human body
- Set up thermoregulation model with multi-node function
- Establish thermal sensation and comfort model for non-uniform environment
- Obtain the environment parameters using CFD, such as temperature and velocity
- Couple CFD and thermoregulation model to obtain physiological data
- Use physiological parameters as inputs to predict thermal sensation and comfort

RESULTS AND ANALYSIS

Faulkner et al. (2004) tested the ventilation effectiveness and thermal comfort level of one personalized ventilation system in which personalized air was served at desk edge and was directed upward impinging firstly at the chest of the occupant (Figure 3a). The cases where the personalized air is supplied at the direction of 45^0 upward are simulated in this paper. In experiments (Faulkner et al. 2004) the room air was maintained at approximately 25 ℃ and personalized air was supplied iso-thermally at 25 ℃ or at a temperature about 5-6 ℃ less than the ambient room temperature and at the flow rate of 3.5, 4.8, 6.5 l/s. In experiments eleven subjects participated in the study of thermal comfort. Most (90%) of the subjects selected an overall thermal sensation between +1 and -1 on the ASHRAE thermal sensation scale. The supply air jet was not objectionable since 67% of the subjects reported that no change in air movement was wanted.

Figure 4 shows that both the whole-body and the local thermal comfort are acceptable. No clear draught sensation is caused. The cooling effect focuses mainly at the head, chest, and arms and the sensations at the other body parts almost do not change (Figure 4a). Even at the strongest cooling condition (6.5 l/s and 20 ℃) personalized air only decreases the whole-body thermal sensation by 0.17 and thermal comfort by 0.15 when compared with no personalized air supply. The clothing insulation at the chest makes the human body not so sensitive to personalized air cooling from desk edge as in the case where personalized air is directed at the naked body parts from desk top, such as the head.

Melikov et al. (2002) tested the performances of five different air terminal devices (ATDs) using a breathing thermal manikin. One of them named movable panel (MP) with rectangular opening ($240mm \times 75mm$) is simulated in this paper (Figure3b). Isothermal (winter) conditions with an indoor operative temperature of 20 ℃ and a personalized air temperature of 20 ℃ and non-isothermal (summer) conditions with an operative temperature of 26 ℃ and a personalized air temperature of 20 ℃ are simulated. An upward plug-flow with a velocity less than 0.06 m/s supplied uniformly from the floor is formed to maintain the room air temperature. The ATD is positioned 0.2 m in front of the manikin's face and 0.3 m above the nose. The flow rate of personalized air is changed from 0 to 20 l/s.

Thermal sensation, and thermal comfort in summer and winter conditions are shown in Figure 5. Clearly the cooling from personalized air focused at the head and chest, which are directly exposed to personalized air. Both in summer and winter conditions personalized air can bring a "cool head" (Figure 5a, 5c) and improve comfort level at the head and the overall thermal comfort (Figure 5b, 5d) when the flow rate is in the range from 5 l/s to 15 l/s. It is in line with the survey results that most subjects selected the local air velocity in a wide range from below 0.15 m/s (about 3 l/s) up to almost 0.8 m/s (about 15 l/s) if room air temperature was 23 ℃ and personalized air temperature was from 20 ℃ to 23 ℃ (Kaczmarczyk 2003).

DISCUSSION AND CONCLUSIONS

The present study demonstrates the applications of the coupled inner- and outer- body simulation in helping to understand the thermal comfort in non-uniform environments. A NTM is able to "tell" us the overall and local thermal sensation and thermal comfort with reasonable confidence. This numerical method can also be used in many other areas, such as analysis of thermal comfort in vehicles, and investigation of temperature difference limitation in vertically stratified indoor environments.

There are still some limitations in this study. For example, airflows in the personal micro-environment are influenced by the body movement. This dynamic process need to be taken into account in the simulations. On the other hand, the numerical stability and convergence analysis is valuable in the coupling, given that the time scales in airflow models and body thermal models are different.

ACKNOWLEDGEMENT

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FIGURES

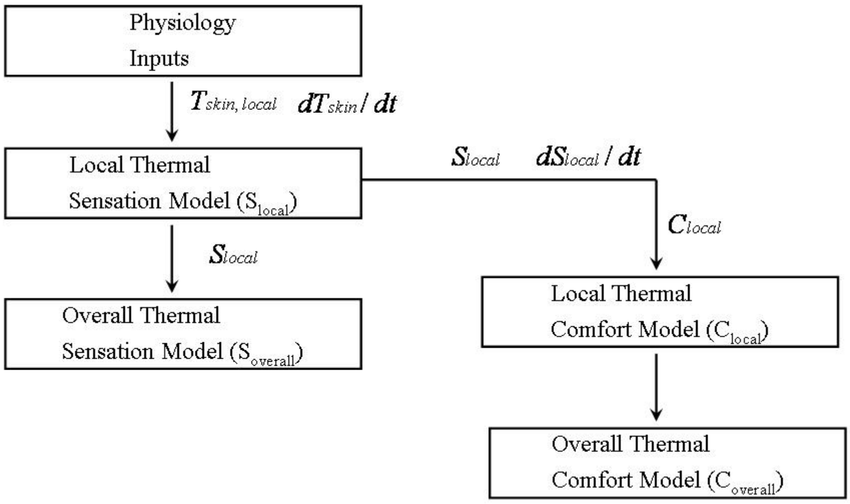


Figure 1 Flow chart of models relationships

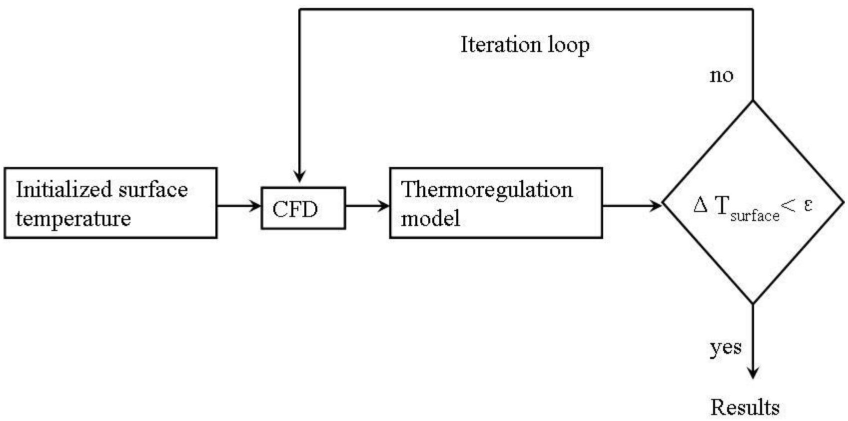
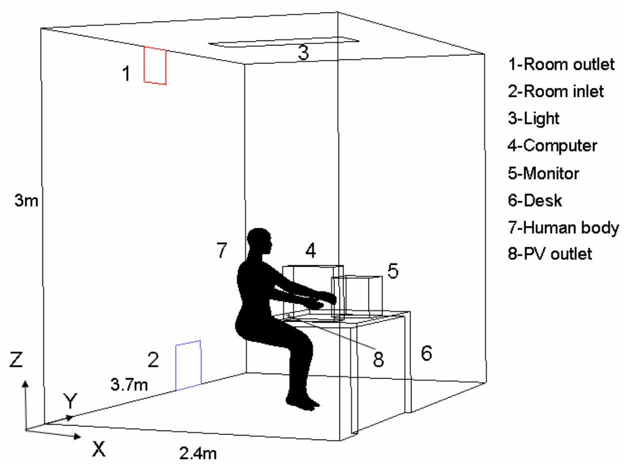
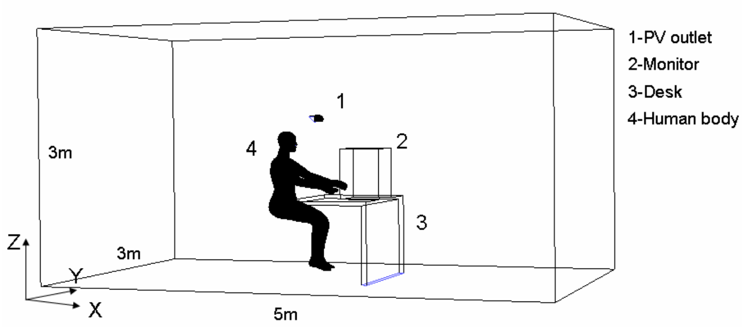


Figure 2 Coupling of CFD and Berkeley Comfort Model (ε controls the coupling accuracy and it is set to 0.1 ℃ in present simulations)

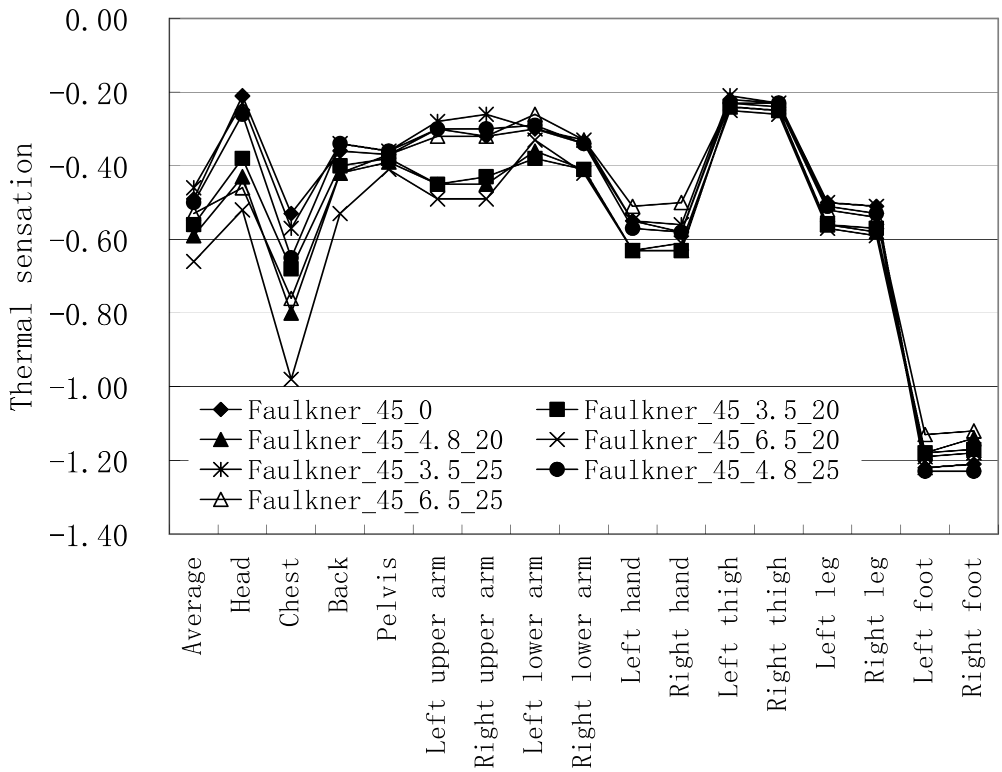


(a)

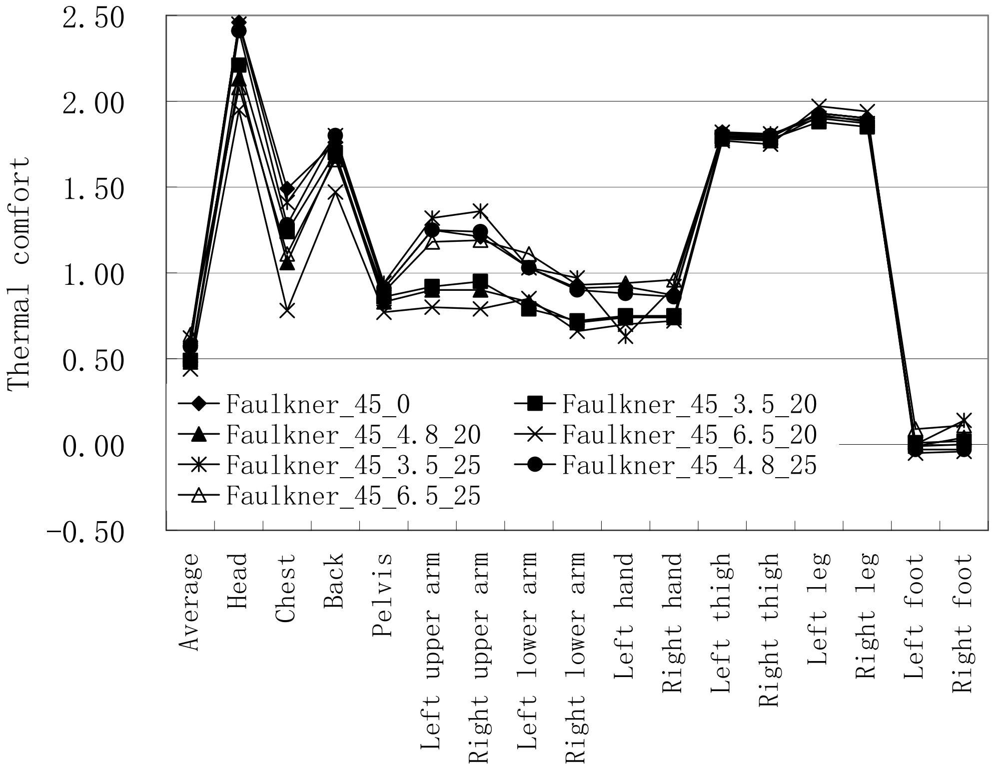


(b)

Figure 3 Configurations of different personalized ventilation (PV) systems: (a) desk-edge based PV system from Faulkner et al. (2004); (b) movable panel (MP) from Melikov et al. (2002);

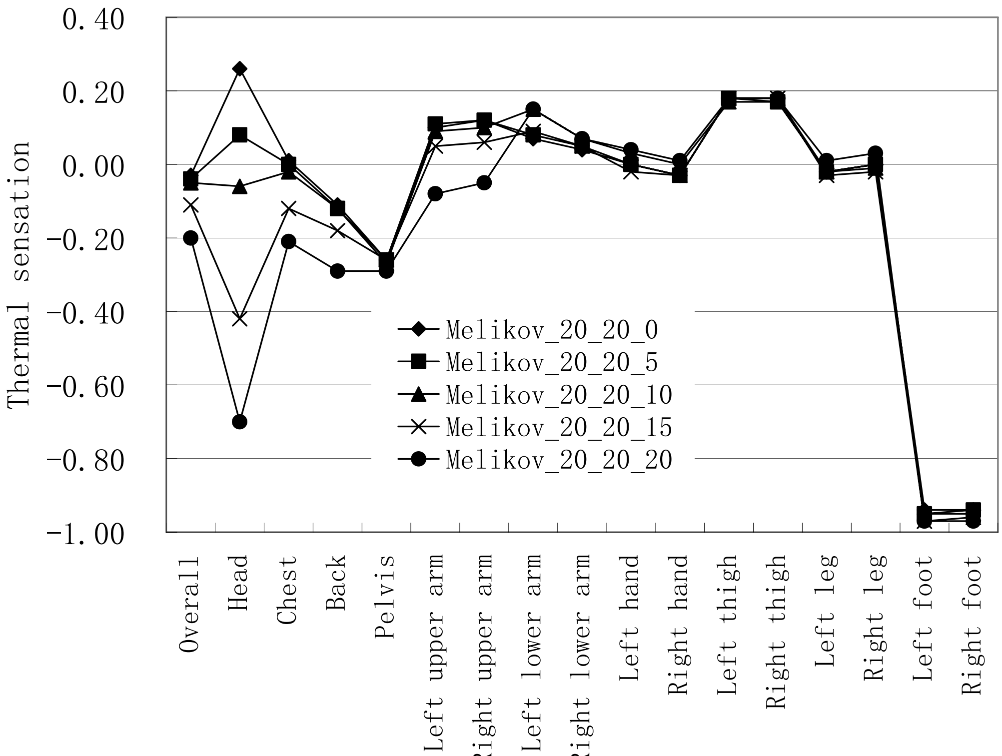


(a)

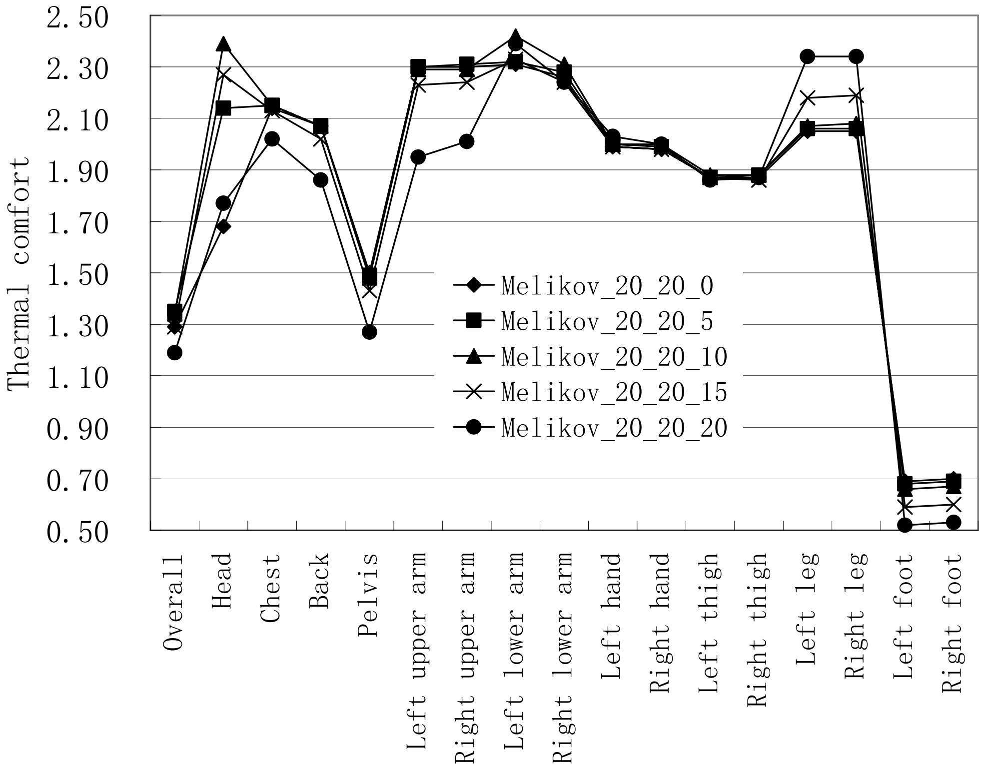


(b)

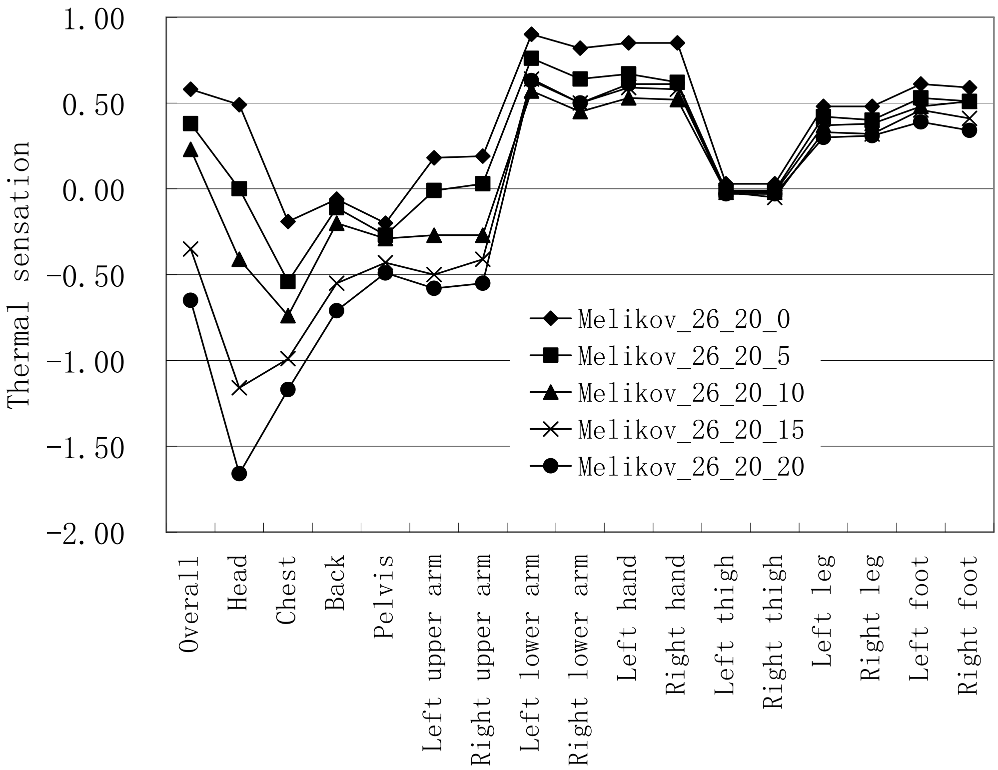
Figure 4 Thermal sensation (a), and thermal comfort (b) at different body segments in the desk-edge based PV system. The legend shows the air supply angle, flow rate, and temperature. For example, Faulkner_45_4.8_20 means personalized air is served 45^0 upward at 4.8 l/s and 20 ℃.



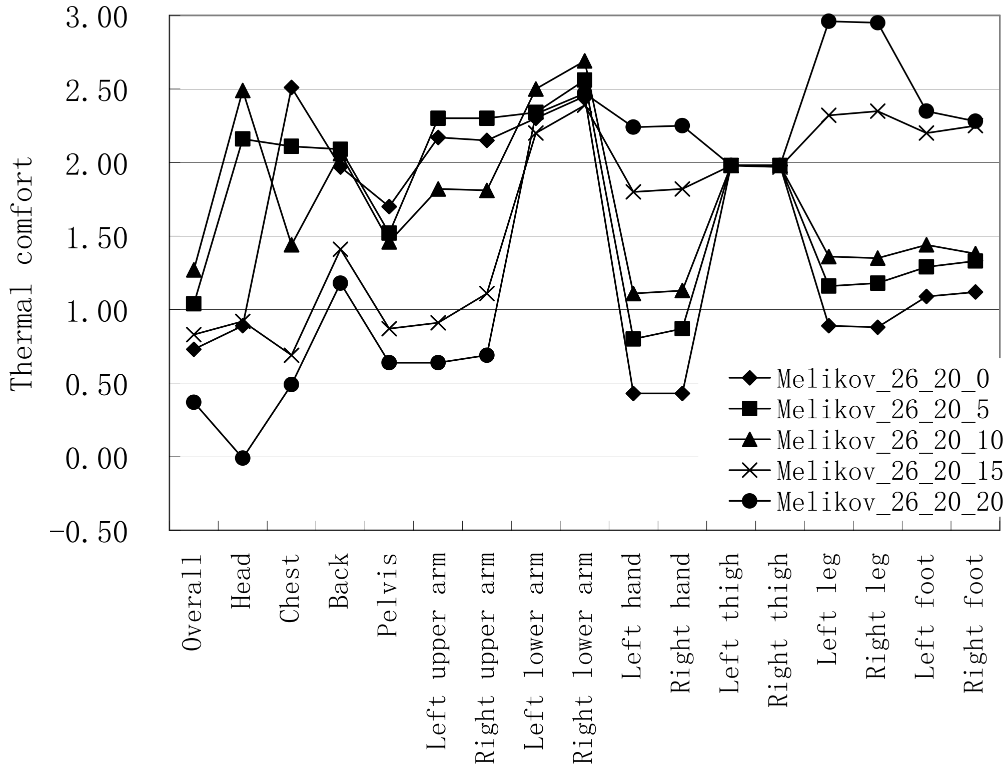
(a)


2.50
2.30
2.10
1.90
1.70
1.50
1.30
1.10
0.90
0.70
0.50
Thermal comfort
Melikov_20_20_0
Melikov_20_20_5
Melikov_20_20_10
Melikov_20_20_15
Melikov_20_20_20
Overall
Head
Chest
Back
Pelvis
Left upper arm
Right upper arm
Left lower arm
Right lower arm
Left hand
Right hand
Left thigh
Right thigh
Left leg
Right leg
Left foot
Right foot

(b)


1.00
0.50
0.00
-0.50
-1.00
-1.50
-2.00
Thermal sensation
Melikov_26_20_0
Melikov_26_20_5
Melikov_26_20_10
Melikov_26_20_15
Melikov_26_20_20
Overall
Head
Chest
Back
Pelvis
Left upper arm
Right upper arm
Left lower arm
Right lower arm
Left hand
Right hand
Left thigh
Right thigh
Left leg
Right leg
Left foot
Right foot

(c)



(d)

Figure 5 Thermal sensation and thermal comfort at different body segments in the PV system with movable panel when room air is replenished from the floor at 20 ℃. The legend shows personalized air temperature, flow rate, and room air temperature. For example, Melikov_20_20_10 means personalized air temperature and flow rate is 20 ℃ and 10 l/s individually, and room air temperature is 20 ℃.