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Unsteady-state human-body exergy consumption rate and its relation to subjective assessment of dynamic thermal environments

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ABSTRACT

Few examples studied applicability of exergy analysis on human thermal comfort. These examples relate the human-body exergy consumption rate with subjectively obtained thermal sensation votes and had been based on steady-state calculation methods. However, humans are rarely exposed to steady-state thermal environments. Therefore, the first objective of the current paper was to compare a recently introduced unsteady-state model with previously used steady-state model using data obtained under both constant and transient temperature conditions. The second objective was to explore a relationship between the human-body exergy consumption rate and subjective assessment of thermal environment represented by thermal sensation as well as to extend the investigation towards thermal acceptability votes. Comparison of steady-state and unsteady-state model showed that results from both models were comparable when applied to data from environments with constant operative temperature. In contrast, when applied to data with temperature transients the prediction of particular models differed significantly and the unsteady-state model resulted in better prediction of mean skin temperature. The results of the present study confirmed previously indicated trends that lowest human body exergy consumption rate is associated with thermal sensation close to neutrality. Moreover, higher acceptability was in general associated with lower human body exergy consumption rate.

1. Introduction and background

Human thermal cognition and perception based on thermal sensation have been usually statistically analyzed in relation to measured physical quantities such as room air temperature, mean radiant temperature, operative temperature or outdoor air temperature. In the case of in vitro experiments, in which a number of subjects are exposed to a controlled chamber that usually have no windows, the subjective votes taken in the experiment are usually investigated in terms of whether or how they are correlated to the measured indoor environmental parameters. On the other hand, in the case of in vivo experiment or field survey, the subjective votes are usually investigated in terms of whether or how they are correlated to the change in outdoor air temperature [1].

These conventional approaches to thermal-comfort study have revealed a lot, but there are still a number of issues that have not yet been fully investigated. One of them is the aspect of heat-transfer mechanism with respect to the 2nd law of thermodynamics; that is, human-body exergy balance.

In general, exergy analysis clarifies where and how much of exergy, not energy, is consumed in a whole chain of working systems ranging from man-made systems such as heating or cooling systems to human-body systems [2]. It has been applied in various disciplines for qualitative and quantitative analysis of chemical, biological, mechanical, environmental or industrial processes. Use of exergy concept in the built environment was first introduced in the field of solar-energy utilization by Oshida [3] and further in building heating systems by Shukuya [4,5].

The application of exergy analysis is the investigation of human body exergy balance was introduced by Isawa et al. [6] and Shukuya et al. [7]. In the following years, several studies related to the analysis of human body exergy consumption have been published [7–24]. Authors of these studies generally concluded that there is an optimal combination of indoor air temperature and mean radiant

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temperature that provides the lowest possible human body exergy consumption rate.

One of the aspects that have become clear is that for winter condition thermal environments with higher mean radiant temperature and lower air temperature resulted in lower human-body exergy consumption rate than that with lower mean radiant temperature and higher air temperature, even if the operative temperature is the same in both cases [2,8,11].

The relation between human body exergy consumption rate and subjectively assessed thermal sensation was analyzed by Simone et al. [14]. The results showed that the minimum exergy consumption rate was associated with thermal sensation votes (TSV; "vote" in this context means a point of time when particular human subject filled out a thermal sensation scale during the exposure) close to thermal neutrality, but tending to the slightly cool side of thermal sensation [14]. Such results suggest that when human body consumes the least of exergy, the human brain assesses thermal neutrality.

The studies mentioned above focused on human body exergy consumption rate with the assumption of steady-state conditions.

However, real human thermal environments can rarely be described as steady-state. Temperature, humidity, air velocity and other thermo-environmental parameters vary both spatially and with time. These variations affect human thermal behaviour and should be taken into consideration when analysing the effect of the thermal environment in buildings on the human body. To account for the aforementioned phenomena, a model of human body exergy balance under transient conditions was developed by Shukuya [25]. Note that in the present paper human body exergy consumption rate based on the assumption of steady state thermal conditions will be abbreviated $E_{x\text{-st}}$, while E_x that related to transient conditions.

The objective behind the introduction of unsteady state exergy analysis method was to investigate interactions between the dynamic processes inside the human body and those in the environment. So far, the studies on unsteady state exergy analysis of the human body and its relation to thermal comfort are very limited. Tokunaga and Shukuya performed unsteady-state human-body analysis for summer cases [26] and for winter cases [27]. In summary, what they found so far is that the exergy consumption rate varies quite sharply with time-related changes of the thermal environment, to which the human body is exposed. In summer-case analysis, there was a sudden change in the human-body exergy consumption rate right after entering the mechanically air-conditioned room, where the air temperature and relative humidity are significantly lower than the outdoor air temperature and humidity. In contrast there was no such change in the case of entering a naturally-ventilated room, where indoor environmental conditions are less distinct to outdoor conditions [28]. In contrast, there was no significant difference in the human-body exergy consumption rate between a room with air-heating and the other with floor heating in winter, since these two room spaces were enveloped by thermally-well insulated walls, floor and ceiling. But, as a window was opened for a short period of time, there was an apparent difference in the rate of exergy transfer by convection due to the effect of ventilation with cold air entering from outside. Since these findings so far were based on a few trial analyses with respect to unsteady-state human-body exergy balance and are therefore not conclusive, a further series of the analyses are necessary.

Therefore, the general aim of the present paper was to deepen the insights to the relation between human body exergy consumption and human perception of thermal environment. This was done by comparing subjective votes obtained by three laboratory studies [29–31] with calculated human body exergy consumption rates based on the thermal conditions prevailing during these studies. All three studies focused on thermal comfort of human subjects exposed to drifts of operative temperature. Thereby, this work had two specific objectives. For the first, two types of models for determination of human body exergy consumption rate, namely the steady state model and the non-steady state model, were compared. For the second, the observed relationships between the TSV and E_x or $E_{x\text{-st}}$ as well as between the thermal acceptability vote (TAV) and E_x or $E_{x\text{-st}}$ were analyzed statistically.

2. Methods

2.1. Details regarding studies that provided original data sets

Kolarik et al. [29] studied the influence of operative temperature ramps ranging from 0.6 up to 4.8 K/h on thermal comfort and office work performance of 52 college age subjects. The exposure took place in the climate chamber providing uniform thermal environment, thus air and mean radiant temperatures were equal during both steady state reference exposures and thermal transients – ramps [32]. The study was divided into two phases – the first addressed summer conditions: temperature range 22–26.8 °C while the second addressed winter conditions: 17.8–25 °C. Only the second phase of the study was included in the present analysis (see Table 1) – referred to in the following as Kolarik data. Air and operative temperature, air velocity, and relative air humidity were logged in 10 s intervals at the centre of the chamber 0.6 m above the floor. The accuracies of the measuring instrumentation were ±0.5 K for air temperature, ±0.3 K for operative temperature, ±0.02 m/s for air velocity (in the range 0.05–1 m/s). The temperature-humidity transmitter measured relative humidity with an accuracy of ±2% RH in the 0–90% RH range. All measurements complied with requirements in and recommendations given in ISO 7726 [33]. Subjects wore their own clothing during all experimental sessions. Garments were selected during preliminary exposures to constant operative temperature of 24.4 and 21.4 °C (50% RH, 2 h) for the first and the second phase respectively. The water vapour pressure of 1.53 kPa, corresponding to 50% RH at 24 °C, was maintained constant during all exposures. During the exposures the subjects were performing simulated office work tasks on PC and filling out questionnaires dealing with thermal comfort, air quality and health related symptoms. Continuous 7-point thermal sensation scale and two-part acceptability scale were used to assess thermal sensation and thermal acceptability respectively. The subjects made the assessment twice every hour of exposure.

The study of Toftum et al. [30] – referred to in the following as Toftum data – was conducted in the same experimental set-up as the study of Kolarik et al. [29]. However, subjects were allowed to arbitrarily modify their clothing to keep thermal neutrality. The study comprised summer and winter temperature ranges of 22.0–26.8 °C and 19.0–23.8 °C respectively. Altogether 25 college age students participated in the study. Subjects performed simulated office work and regularly filled out questionnaires dealing with thermal comfort, air quality and health related symptoms. The questionnaire set was the same as in the case of the study by Kolarik et al. [29]. In addition, subjects had to indicate every change of clothing using a separate part of the questionnaire. The changes of the clothing insulation were included in the data set used for the present study.

The study of Kitazawa et al. [31] – referred to in the following as Kitazawa data – was conducted in the same climate chamber as studies by Kolarik et al. [29] and Toftum et al. [30]. The focus was on seasonal differences in human responses to increasing temperature. Experiments were conducted in late summer and winter with altogether 128 subjects (either <30 or >60 years old, see Table 2). The subjects were exposed to operative temperature ramp in a range 24.0–35.2 °C at a rate of 3.7 K/h (for details see Table 1) as well