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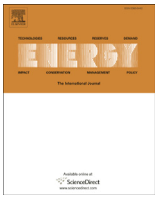

Assessment of thermal comfort conditions during physical exercise by means of exergy analysis

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ABSTRACT

Some authors have been applying the exergy analysis to thermal comfort, where the environmental conditions for minimal exergy destruction are claimed to correspond to thermal comfort conditions. Herein, the exergy destroyed rate of the human body will be determined as a function of temperature and humidity for three levels of exercise. For the sake of comparison, thermal comfort will also be assessed by means of *PMV* (Predicted Mean Vote) index. Results indicate that, the higher the relative humidity, the lower the temperature of thermal comfort and, for the same humidity, the higher the exercise intensity, the smaller the temperature of thermal comfort. On the other hand, the values of *PMV* do not vary much with relative humidity, what indicates that the effect of this parameter is almost neglected by this method. Besides, the difference between the three levels of exercise was not as pronounced as in the exergy method. During activity, the values of the exergy flow rate due to evaporation for thermal comfort are smaller in the exergy method than in the conventional one. Thus, it can be said that, under physical activities, the exergy method for thermal comfort seems to be a reliable alternative to the conventional one.

1. Introduction

Exergy analysis results from a combination of First and Second Laws of Thermodynamics and is a tool to evaluate the quality of energy conversion processes, including those that take place in the human body, as first performed by Batato et al. [1]. In the past decade, this kind of analysis has been extensively applied to the human body to correlate destroyed exergy and thermal sensation, in an attempt to develop a new method for thermal comfort evaluation.

The classical thermal comfort analysis is guided by the results of the studies performed by Fanger [2], which are also the foundation of the ASHRAE standard for thermal comfort [3]. The main breakthrough of his work was the combination of energy balance equations and empirical data, which resulted from the evaluation of subjective thermal comfort sensations with a group of people in laboratory and climate chamber. Then, those results were used to create the best-known thermal comfort indexes: *PMV* (Predicted Mean Vote) and *PPD* (Predicted Percentage of Dissatisfied). The former evaluates the thermal sensation provided by a given environment. The latter, as suggested by its name, indicates the percentage of people dissatisfied with the thermal sensation produced by the environment. The assessment of thermal comfort by means of these indexes, which is known as Fanger's method, associates thermal comfort sensation to three main points, namely, the temperature of the skin, the sweat evaporation through the skin and the energy balance of the body.

Despite of its extensive application, the method established by Fanger [2] presents some limitations, being more suitable for artificially ventilated buildings. *PMV* and *PPD* estimation is valid only for a limited humidity range, between 30% and 70%. Furthermore, it does not take into account the discomfort due to draught [4], adaptive aspects [5] and the outdoor environment [6]. In an attempt to find a more comprehensive thermal comfort model, Saito & Shukuya [7] were the first authors to investigate the relation between the destroyed exergy in the human body and thermal comfort sensation.

A few years later, Prek [8,9] achieved some progresses in this

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Nomenclature

$\mathbf{B}$	exergy, J
B	exergy rate and flow rate, W
c	specific heat capacity, J/(kg K)
h	specific enthalpy, J/kg
m	mass flow rate, kg/s
Q	heat transfer rate, W
P	pressure, Pa
PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied
R	gas constant, J/(K kg)
s	specific entropy, J/(K kg)
T	temperature, °C or K
t	time, s
v	velocity, m/s
W	performed power, W
w	weight, kg
y	mass fraction

Greek symbols

ϕ	relative humidity (%)

Subscripts and superscripts

0	reference
body	body
c	convective
d	destroyed
ev	evaporative
ex	expired
i	index for gas exchange
k	index for exergy transfer
in	inflow
lv	liquid-vapor
M	metabolic
out	outflow
r	radiative
rc	radiative-convective
res	respiration
sk	skin
ΔT	due to body temperature variation
w	water vapor

kind of analysis and enunciated that the destroyed exergy reaches its minimum value in a point close to thermal comfort sensation. This idea was extensively analyzed by other authors [10–16], among them Simone et al. [13], who collected thermal sensation data from the literature of thermal comfort and compared them to the values of exergy destruction in the human body for the same environmental condition range. The authors concluded that the minimum destroyed exergy was close to the thermal neutrality, tending to a slightly cool sensation. Schweiker & Shukuya [14] evaluated experimentally the effects of adaptive aspects on the exergy destruction in the human body.

Dovjak et al. [15] used the values of the destroyed exergy in the body to determine optimal conditions in hospital environment for healthcare and treatment of burn patients. Wu et al. [16] compared the destroyed exergy and the mean human performance in an office with the thermal sensation and observed that, although the slopes of the curves were different and minimum did not coincide, there was a point where the functions intersected. Besides, Caliskan [17] performed both energy and exergy analysis of the human body during the summer in order to identify the contribution of each component of the balances. Aiming at assessing the efficiency of a building, Dovjak et al. [18] performed an integrated exergy analysis of the human body and the building envelope.

Mady et al. [19] calculated the destroyed exergy and exergy efficiency of the body as a function of operative temperature and relative humidity. In accordance with the results obtained by Refs. [8–13], for relative humidity between 40% and 60%, the points of minimum exergy destruction and minimum exergy efficiency occurred at the thermal neutrality condition, which, in that case, was also the thermal comfort condition. Nevertheless, the authors also found out that, for low relative humidities and high temperatures, the exergy destruction is also minimal, what differ from the thermal comfort assessment by means of *PMV* and *PPD*. Therefore, they suggested that the use of the exergy destruction as a thermal comfort index would have limited validity. However, the traditional method, as elucidated previously, has its own limitations. It was developed based on experimental results, which is, simultaneously, an advantage and a disadvantage, since it has already a practical validation but, on the other hand, it assumes the thermal comfort sensation of a group of Danish students as representative for every human being. Moreover, it was developed focused on closed air-conditioned buildings, presenting a narrow range of environmental parameters and is not the best method to assess thermal comfort in naturally ventilated buildings. Furthermore, it is not suitable for some practical cases, like some industrial facilities, where the thermal comfort is difficult to reach, due to extreme environmental parameters and high activity levels, but the discomfort can be minimized. For that reason, the exergy analysis emerges as an alternative to assess thermal comfort conditions for a wider range of environmental parameters.

In the present work, destroyed exergy rate in the human body will be determined as a function of relative humidity from 10% to 90%, at intervals of 10%, and temperature from 5 °C to 45 °C, at intervals of 5 °C, for three levels of activity: at rest, walking and running at 10 km/h. Air velocity is assumed as zero, minimizing the effects of forced convection. Since the main goal of the present work is to evaluate the effects of relative humidity and physical exercise, this assumption will not impair the results. The results will be confronted with those presented by the method developed by Fanger [2]. Moreover, the components of the exergy balance will also be evaluated as a function of those parameters. Additionally, the magnitude of these variables in the points of minimum exergy destruction will be confronted with those obtained for $PMV = 0$. Thus, it will be possible to investigate how contrasting are the exergy interactions between the body and the environment in the points of thermal comfort defined by both methods. Finally, from the points of minimum destroyed exergy rate, it will be possible to assess, for example, the temperature that leads to less discomfort for a worker performing a certain level of physical activity in an industrial facility with controlled humidity. The exergy model of the human body developed by Mady et al. [20] will be used together with the thermal model of Ferreira & Yanagihara [21], which will provide the data concerning the energy balance of the body. The latter is composed of both thermoregulatory and passive systems and is divided into 15 cylindrical segments with elliptical cross section, each of them presenting a combination of seven types