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Human body exergy consumption and thermal comfort of an office worker in typical and extreme weather conditions in Finland

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ABSTRACT

Finding the way to predict optimal thermal conditions for an office worker would contribute to sustainable building design: the environmental effects would be reduced, the economics of the organization and whole society would improve and there would be indisputable social benefits for the individual and the global community. These benefits stem from the improved productivity of the office worker in most favorable thermal environment and the possibilities to achieve this with lower energy demand. This study uses a new approach, exergy analysis, to recognise the optimal conditions by looking for the combination of mean radiant temperature and room air temperature giving the lowest human body exergy consumption rate. All of the commonly used thermal comfort prediction methods use energy analysis, and it seems that exergy analysis could give more accurate prediction of the conditions giving optimal thermal comfort. The new method is applied to the case of office worker in typical and extreme weather conditions in Finland. The results agree well with the previous analyses, and moreover, the points giving minimum human body exergy consumption rate coincide with the points usually regarded as most comfortable in summer conditions. According to recent studies, people are also most productive at these conditions.

1. Background

The energy use in buildings, accounting for 36% of the energy use and related CO_2 emissions as well in Europe [1] as worldwide [2], is mainly due to the need to maintain comfortable indoor environment for us humans. Most of this energy is used for heating and cooling, aiming at thermal comfort. Finding an optimal way to control the thermal environment would help in using only the necessary amount of energy for this purpose, and nothing more.

According to many studies [e.g. 3–8] people also work best in optimal thermal conditions, being most productive. Although the human performance also depends on many other things than thermal comfort, reaching the best possible thermal environment would improve possibilities in reaching the best performance or productivity. Increasing the productivity of people in the working space will cover many times the costs for any additional effort in planning or energy use [e.g. 5]. It is estimated that a half to one percent increase in productivity could cover the costs of all energy use over the year [9]. Also on individual level, using the working hours in most productive way would release more time and personal energy for other activities, like different hobbies or spending time with family and friends. It is also claimed [10] that loss of productivity may be one of the major routes for negative economic effects of climate change.

Consequently, finding the way to predict optimal thermal conditions for an office worker (and finding the right technical solutions for that) would present a promising solution for sustainable building design: the environmental effects would be reduced, the economics of the organization and whole society would improve and there would be indisputable social benefits for the individual and the global community.

Many approaches to measure and calculate the optimal conditions for thermal comfort has been proposed, such as the widely used PMV method [11] or adaptive model [12], but all of them seem to have had a number of shortcomings, which will be discussed below, where some of the methods are briefly presented. A new approach is proposed by a research group at Tokyo City University and the LowEx co-operation [13], based on the idea of the human body as exergy–entropy system. According to the first results, human body exergy balance calculations seem to be a promising way to evaluate the thermal comfort provided by different

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heating and cooling systems (e.g. in [14–18]). The new method uses the outdoor conditions as environmental conditions for the calculations, and therefore it is interesting to compare the results of the thermal comfort calculations with the human body exergy consumption (HBEC) rate in some chosen weather conditions.

This paper first reviews some work from other researchers to find out to what extent the human body exergy balance calculations could tell us where to find the optimal conditions for thermal comfort, compared to some other ways to predict thermal comfort. Calculations on the human body exergy consumption have been conducted in some typical and extreme weather conditions in Finland (which has characteristics of both a maritime and a continental climate), and these are discussed and compared with the results in similar cases in other countries with different climates calculated by other researchers.

2. Thermal comfort and methods to predict or assess it

2.1. Thermal comfort

Human thermal comfort is defined by ANSI/ASHRAE Standard 55-2010 [19] as "that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation".

The perceived thermal comfort is not only a result of the thermal environment, but a combination of many physical, physiological and psychological factors related to the environmental and personal qualities. Environmental factors include e.g. noise level, IAQ (Indoor Air Quality), air temperature and velocity, radiant temperature, visual environment, availability of daylight and humidity or enthalpy of the air. Personal factors include not only the clothing insulation or metabolic rate, but also age, gender, thermal sensitivity and ability to control the thermal environment [20–22]. According to many studies [e.g. 12,17,23] also the short and long term thermal history has an effect on the way people perceive their thermal environment. Many of these factors are also interrelated, and they seem to affect the perceived intensity of each other [3], although not many studies have been conducted on this field.

2.2. PMV method to predict thermal comfort in artificially conditioned spaces

Fanger [11] created a mathematical model to predict the way people perceive their thermal environment. It is called the Predicted Mean Vote or PMV method. The method is based on the human body heat balance equation which was adjusted according to considerable amount of measurement results from large group of human subjects. It predicts the mean value of the Thermal Sensation Votes (TSV) given by a large group of people in certain environmental conditions.

PMV method is by far the most applied method for assessing the thermal comfort provided by environmental conditions of an indoor space, although it is sometimes severely criticized and its applicability is claimed to be limited [24]. It is used in national and international standards as basic method for the indoor thermal comfort calculations, e.g. in ISO Standard 7730 [25] and ANSI/ASHRAE Standard 55-2010 [19]. In these standards, it is stressed that also the local thermal discomfort must be considered in determining conditions for acceptable thermal comfort.

Fanger's PMV model was initially intended for application by HVAC industry in creation of artificial climates in controlled spaces [11]. However, it has been widely applied to all kinds of buildings in many types of environments. In his analysis of the applicability of PMV method [24], van Hoof assessed the results of several studies which seem to show that significant number of people prefer conditions that are in the non-neutral vote area, and even the TSV votes outside the three central categories do not necessarily mean that people would feel discomfort. The preferred conditions are often influenced by the season. It also seems that PMV model is not very well applicable to naturally ventilated buildings. [12] Many experienced designers and scientists have noticed that the best thermal comfort in winter situation is usually found in conditions, where the mean radiant temperature is slightly higher than the air temperature (e.g. [26]). However, this is not shown by the PMV method, as it predicts thermal neutrality with many combinations of mean radiant temperature and air temperature.

2.3. Adaptive model to predict the thermal comfort in naturally ventilated spaces

Due to the limited ability of PMV model to predict the thermal comfort in naturally ventilated buildings, de Dear and Brager developed an Adaptive model of Thermal Comfort and Preference [12], which is currently presented as an alternative method in ASHRAE Standard 55-2010 [19] for evaluating the thermal comfort in naturally ventilated buildings. They also noted the results that the preferred temperatures are on slightly cool side of neutral vote in summer and slightly warm side in winter. The Adaptive model uses the outdoor temperature for predicting the optimum thermal comfort temperature.

This model is based on the assumption that the contextual factors and person's thermal history affect her expectations and preferences. It is derived from an impressive amount of raw data from field-experiments around the world. Based on this data de Dear and Brager concluded that occupants in naturally ventilated buildings tend to be tolerant to wider range of temperatures, due to both behavioral adjustment and physiological adaptation. This observation is supported by the findings by Tokunaga and Shukuya in their experiments [17]. Their results show that the subjects in a group who are accustomed to take passive strategies became comfortable effectively with a smaller sweat secretion rate than the subjects in a group usually exposed to convective cooling. From point of view of the current paper it is interesting that the human-body exergy consumption rate of the subjects in the former group was generally smaller than that of the subjects in the latter group in both everyday life and in the experimental room.

Both the advantages and disadvantages of the adaptive model seem to basically be due to the limited number of input values: while it is very simple and straight forward to use and the result is easily understandable, it ignores many of the central parameters of the heat balance equation, especially the air velocity. This limits its applicability to different situations, and therefore it should only be used for offices and workspaces and for regular levels of metabolism and clothing insulation. Local discomfort should also be assessed separately. [27–29]

2.4. Other ways for predictive assessment of thermal comfort

In addition to the above mentioned methods, there are many other ways suggested to predict the thermal comfort, but they are not as widely used as the PMV method or adaptive model. Many of the new methods are based on PMV, like the method which uses the Standard Effective Temperature (SET*) instead of operative temperature in the calculation of PMV, resulting in calculation of PMV* [30]. This method was claimed to improve the responsiveness to relative humidity and vapor pressure changes as well as the vapor permeability of the clothing, and this is why it is chosen for the comparisons of PMV method vs. Human Body Exergy Consumption rate method in this paper.

To improve the applicability of PMV method for warm climates, Fanger and Toftum suggested the use of expectancy factor 'e' in