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A methodology for the comprehensive evaluation of the indoor climate based on human body response: Evaluation of the hygrothermal microclimate based on human psychology

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ABSTRACT

In this paper a new methodology for the comprehensive evaluation of the thermal condition of environment based on operative temperature thermal levels, so called decitherms, is presented. It allows an assessment based on the perception of the environment by man. It stems from the impact of the environment on human psyche as described by the Weber–Fechner law. One of its strengths is that it takes into account the fact that a decrease in operative temperature is perceived the more strongly at lower temperatures. The concept of the decitherm allows a direct numerical comparison with decibels, used for noise evaluation, and with deciodors, used for odor assessment, and additionally the total environment can be assessed by adding the individual levels multiplied by corresponding impact factors. Further, concrete values for SBS can be estimated, rating of air-conditioning systems efficiency defined and the degree of danger to man whether by overheating (hyperthermia) or undercooling (hypothermia) can be estimated. This methodology has already been used in the preparation of European standard prEN 4666:2011 Aerospace Series, Aircraft integrated air quality and pressure standards, criteria and determination methods.

1. Introduction

The environment accounts for over 70% of discomfort in the workplace, of which the hygrothermal microclimate alone accounts for almost 30%. Thus the importance of the hygrothermal constituent is evident as is its correct evaluation.

The evaluation should be both from the point of human physiology and also from the impact of the environment on human psychology, which is the subject of this part.

The physical criterion of the interaction of human psychology and the hygrothermal constituent is established by the Weber–Fechner law (WF):

$$R = k \times \log S \tag{1}$$

where R—the response of human body; S—the stimulus of impacting environment; k—the coefficient of proportionality.

2. The proposed system of evaluation

Weber–Fechner law can be applied to the thermal condition of the environment in the form

$$L\text{th} = k\text{th} \times \log\left(\frac{T}{T_{\text{threshold}}}\right) \quad [\text{dTh}] \tag{2}$$

where Lth—operative temperature thermal level [decitherm], [dTh]; T—operative temperature [°C], $T_{\text{threshold}}$—threshold operative temperature, i.e. in this case optimal; operative temperature [°C].

This formula (2) is analogous with the equation for the noise evaluation by acoustic pressure level

$$L_p = 20 \times \log\left(\frac{P}{P_0}\right) \quad [\text{dB}] \tag{3}$$

where stimulus has the shape of acoustic pressure ratio of the investigated space (P) and threshold acoustic pressure (P_0) (the lower limit of perceived pressure, i.e. 20 μPa). For the acoustic level the decibel is the unit (dB), for the thermal level the decitherm unit (dTh) has been proposed.

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3. Experimental verification

Formula (2) is acceptable both from the point of man's psychology and from the point of the theory of similarity [1,2]. However, experimental confirmation was desirable to be sure that decitherms really correspond to human sensations.

Thermal environment level impact on man's sensations can be assessed by the well tested ASHRAE scale (ANSI/ASHRAE 55-1992) [3] cold, cool, slightly cool, neutral, slightly warm, warm, hot. These values resulting from the experimental work should be proportional to thermal levels in dTh; that is it must be proven

$$Lth = k_1 \times (\mathrm{AV}) \quad (4)$$

where AV—ASHRAE values; k_1—coefficient.

Simultaneously formula (2) should be valid and therefore from the experimental data it must be proven

$$\mathrm{AV} = k_2 \times \log\left(\frac{T}{T_{\mathrm{opt}}}\right) \quad (5)$$

to be $Lth = k_1\mathrm{AV}$

After substitution we get

$$Lth = k_1 \times \mathrm{AV} = k_1 \times k_2 \times \log\left(\frac{T}{T_{\mathrm{opt}}}\right) = kth \times \log\left(\frac{T}{T_{\mathrm{opt}}}\right) \quad [\mathrm{dTh}] \quad (6)$$

In Fig. 1, the result of measurements by Fishman and Pimbert [4] are presented. On the horizontal axis operative temperatures are plotted, on the vertical axis corresponding average votes according to the ASHRAE scale). ASHRAE values were estimated in a narrow temperature range of ±0.2 °C for each temperature, e.g. for 20 °C the range was 19.8–20.2 °C. Mean physical activity was 80 W/m^2. 26 subjects recorded their sensations 8 times per day between 9.30 and 16.30 h during the whole year, i.e. the total of recorded values was 54080.

For ASHRAE values from graph in Fig. 1 the following relationship can be derived

$$\mathrm{AV} = 14.469 \log T - 19.172 = 14.469 \log T - 14.469 \log 21.14 = 14.469 \times \log\left(\frac{T}{21.14}\right) \quad (7)$$

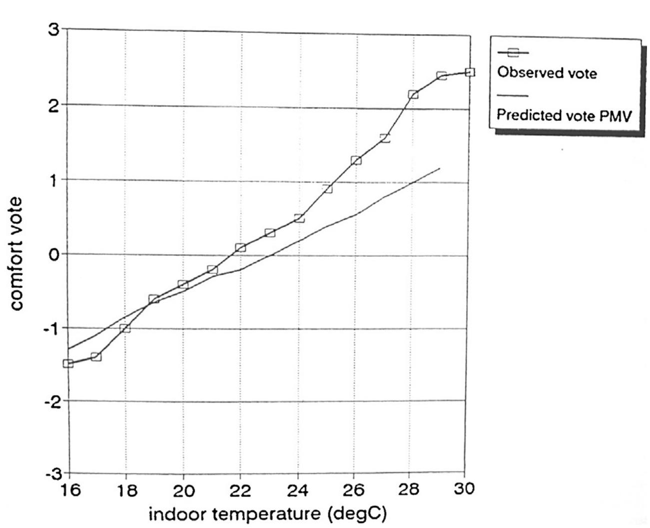

Fig. 1. Comfort votes (ASHRAE scale) in relationship to indoor temperature. Activity 80 W/m^2, clothing 0.64 up to 0.82 clo [4]

i.e. in a generalized form

$$\mathrm{AV} = k_2 \times \log\left(\frac{T}{T_{\mathrm{opt}}}\right) \quad (8)$$

Therefore the following is also valid

$$Lth = k_1\mathrm{AV}$$

i.e. it is evident that dTh corresponds to human sensations. It is also obvious that operative temperature alone does not correspond to them.

4. Derivation of operative temperature thermal levels estimation

Having proven above that operative temperatures correspond to human sensations, it is now possible to estimate optimal, long-and short-term tolerable thermal levels for operative temperatures.

4.1. Optimal operative temperature thermal levels

Optimal operative temperatures are defined by a neutral thermal equilibrium of human body for the activity and clothing at the time. dTh = 0 corresponds to optimal operative temperatures (log 1 = 0), as is the case with noise and odors. Human body thermoregulation then results in an optimal range dTh = 0–22.5 corresponding to an optimal range of operative temperatures (also Jokl [5]).

4.2. Long-term tolerable operative temperature thermal levels

They begin at maximal values of optimum rising up to operative temperatures reaching mean skin temperature as higher operative temperatures can cause hyperthermia produced by heat transfer from the air to the body surface. Range is 23–90 dTh, see Table 1 and Fig. 2.

Long-term tolerable operative temperatures can be allowed only in the warm area as the disturbed thermal equilibrium is compensated for by sweating. In the cold area shivering is the analogous mechanism to sweating but it cannot be taken into account as not all people are capable of shivering, perhaps a few. Therefore in the cold area only short-term tolerable values must be used.

The area of long-term tolerable values is also the area SBS (Sick Building Syndrome) because it is already outside the optimal values but still tolerable for a longer time.

4.3. Short-term tolerable operative temperature thermal levels

In the warm area they begin at maximal long-term tolerable values, in the cold area at the minimal values of optimum. They terminate with the operative temperature before the threshold of pain (about 42 °C). The range is 91–134 dTh.

There is a problem in the cold area. For hard work operative temperature cannot be based on the thermal equilibrium of the human body. The limiting factor is fatigue that requires breaks in the activity over the period of a shift; therefore the need for higher temperatures in the respite period. The limiting temperatures are 10 °C in the Czech Republic and higher at 15 °C in USA.

4.4. Intolerable operative temperature thermal levels

For their definition only the starting values are available—the chosen threshold of pain at about 42 °C or 135 dTh. This is analogous with noise and odors where the threshold of pain is identified as 135 dB and 135 dOd.