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DESIGN AND CALCULATION POSSIBILITIES FOR THE HEAT EXCHANGE CONDITIONS OF THE HUMAN BODY

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Abstract

The calculation of the heat exchange conditions of the human body is a complex task. However, this is the basis of the indoor thermal comfort designing. In the frame of this paper starting from the basic equation of heat balance of the human body we will overview the possibilities for the calculation and modelling of convective and radiant heat exchange.

Keywords: thermal comfort, heat balance, heat exchange.

1. Introduction

The modern indoors design methods are based on the heat exchange conditions of the human body. The ideal situation is when the heat production (metabolism) and heat output of the human body are balanced. In the beginning of the last century the physiologists defined the heat generation of the human body – depending on the activity. The ultimate methods for the calculation of heat exchange of the human body, however, were developed only 30-40 years ago. Several tasks could only be solved with the help of special thermal modelling methods (thermal manikin) as well as experiments on the human body in many cases.

In the following we are going to review the designing modelling and calculation possibilities of the heat exchange conditions of the human body.

2. Heat Balance of the Human Body

The calculation of the heat exchange of the human body can be executed with the help of the so-called heat-balance equation, as studies have proved that the subjective heat sensation is pleasant and the work concentration ability is optimal if the heat generated in the human body and the heat dissipated in various ways are in balance. According to this the generally applied heat-balance equation is as follows

$$H - E_d - E_{sw} - E_{re} - L = K = R + C, \tag{1}$$

where H = the internal heat production in the human body
E_d = the heat loss by water vapour diffusion through the skin
E_{sw} = the heat loss by evaporation of sweat from surface of the skin
E_{re} = the latent respiration heat loss
L = the dry respiration heat loss
K = the heat transfer from the skin to the outer surface of the clothed body (conduction through the clothing)
R = the heat loss by radiation from the outer surface of the clothed body
C = the heat loss by convection from the outer surface of the clothed body

The double *Eq.* (1) expresses that the internal heat production H minus the heat loss by evaporation from the skin $(E_d + E_{sw})$ and by respiration $(E_{re} + L)$ is equal to the heat conducted through the clothing (K) and dissipated at the outer surface of the clothing by radiation and convection $(R + C)$. It is assumed that the evaporation corresponding to E_{sw} and E_d takes place at (or underneath) the skin surface.

In the following section first the internal heat production of the human body will be discussed in more detail.

3. Internal Heat Production of the Human Body

An oxidation (burning) process happens in the human body, and the energy transformed in the course of this evolves partly in the form of internal body heat and partly used for mechanical (muscle) work and active output in a physical sense.

For this burning the human body needs to take on oxygen, the degree of which will determine the intensity of the work. The oxygen consumption of an adult human body in stationary position is the so-called basic metabolism 0.25 l/min (4.2 10^{-6}m^3/s). The heat evolving as a result of the burning of this is 88 W.

The oxygen consumption is multiplied in case of mechanical work compared to stationary position. In case of an average person it can be 12 times as much as the stationary position for a short time, which is 3 l/min ($0.051 \cdot 10^{-3}$ m^3/s) that equals 1060 W.

According to BÁLINT [1] and WINSLOW and HARRINGTON [2] the efficiency of the so-called efficient work in the course of metabolism is 20%, therefore the human body works on a higher degree of efficiency than an average steam machine (14%). Beside this, metabolism is carried out on a constant level of heat, on 37 ± 0.5 °C. This is the fundamental difference between simple burning – the temperature of which is not constant – and metabolism.

There are only approximate data available as regards the average working ability. According to these the working ability of an average young man is – in case of regular working – 1 l/min ($17 \cdot 10^{-6}$m^3/s), which equals a power of 350 W. Deducting the degree of basic metabolism of 88 W we get the result of 262 W.

According to FANGER [3] the so-called metabolic heat generated in the course of the oxidation process in the human body comprises two parts: the outside mechanic labour (W) and the inside heat demand (H).

In this case the outside mechanic labour considered as the heat necessary for the mechanical work carried out by the person is also assured by the oxidation process of the human body.

W is positive if the energy needed for the physical work has to be covered by the value M (e.g.: climbing a stair) but W is negative when we are descending on a slope.

Therefore the metabolic heat can be divided into two parts:

$$M = H + W \qquad [\mathrm{W}]. \tag{2}$$

According to this the work efficiency can be expressed from the following equation:

$$\eta = \frac{W}{M}. \tag{3}$$

Putting back this into the equation:

$$H = M(1 - \eta) \qquad [\mathrm{W}]. \tag{4}$$

Or expressing it for one unit of body surface:

$$\frac{H}{F_{Du}} = \frac{M}{F_{Du}}(1 - \eta) \qquad [\mathrm{W/m^2}].$$

F_{Du} is the so-called Dubois surface of the body, which considers the most important individual ‘metric’ characteristics and can be defined on the basis of the following correlation:

$$F_{Du} = 0.203\, G^{0.425} L^{0.725} \qquad [\mathrm{m^2}] \tag{5}$$

where: G is the weight of the individual (kg),
L is the height of the individual (m).

Eventually, it is important to mention that for the numerical definition of the heat equivalent value of the different labours the unit of ‘met’ is applied in the international practice, and 1 met = 58 W/m^2.

The design data to be considered have been processed in a tabular form.

4. Conditions for Thermal Comfort

The next question is: which conditions are necessary for the optimal thermal comfort. By the theory there are three basic conditions for it. The first condition necessary for thermal comfort for a person under long exposure to a given environment is the existence of a heat balance, a condition which is naturally far from sufficient. Man’s thermoregulatory system is quite effective and will therefore create heat balance within wide limits of the environmental variables, even if comfort does not exist.

With the establishment of a double heat balance an equation of the following form can be obtained (only the main variables have been taken into consideration):

$$f\left(\frac{H}{F_{Du}}, I_{cl}, t_a, t_{mrt}, p_a, v, t_s, \frac{E_{sw}}{F_{Du}}\right) = 0, \tag{6}$$

where $\frac{H}{F_{Du}}$ = internal heat production per unit body surface area (F_{Du} = DuBois area) W/m^2

I_{cl} = thermal resistance of the clothing m^{2}K/W

t_a = air temperature °C

t_{mrt} = mean radiant temperature °C

p_a = pressure of water vapour in ambient air Pa

v = relative air velocity m/s

t_s = mean skin temperature °C

$\frac{E_{sw}}{F_{Du}}$ = heat loss per unit body surface area by evaporation of sweat secretion W/m^2

For a given activity level, the skin temperature, t_s, and the sweat secretion, E_{sw}, are seen to be the only physiological variables influencing the heat balance in *Eq*. (6). The sensation of the thermal comfort has been related to the magnitude of these two variables. Experiments involving a group of subjects at different activity levels have been performed to determine mean values of skin temperature and sweat secretion, as functions of the activity level, for persons in thermal comfort. The results have the following form:

$$t_s = f\left(\frac{H}{F_{Du}}\right), \tag{7}$$

$$E_{sw} = F_{Du} = f\left(\frac{H}{F_{Du}}\right). \tag{8}$$

Eqs. (7) and (8) are presented as the second and third basic conditions for thermal comfort.

The quantitative evaluation of *Eqs*. (7) and (8) and the theoretical foundation for relating the sensation of thermal comfort with skin temperature and sweat secretion are set out in the second part of this chapter.

By substituting conditions (7) and (8) in (6), the desired comfort equation takes the following form:

$$f\left(\frac{H}{F_{Du}}, I_{cl}, t_a, t_{mrt}, p_a, v,\right) = 0. \tag{9}$$

Using the comfort *Eq.* (1), it is possible for any activity level (H/F_{Du}) and any clothing (I_{cl}) to calculate all combinations of air temperature (t_a), mean radiant temperature (t_{mrt}), air humidity (p_a) and relative air velocity (v) which will create optimal thermal comfort.

We have to mention that the exact calculation of the heat transmission through the clothing on the outer surface of the skin is almost impossible. The several layers of clothing on the human body, the air layers randomly formed between these layers, the change of these when the person is moving and air speed are all such aspects that do not make the direct and exact calculation possible. Therefore, the so called thermal manikins have been developed, which model the different temperatures on the surface of the human body with the help of electric heating. From the changes of the heating performance and the summarisation of the results of certain parts of the skin surface the dry heat emission can be determined. [4]

5. Heat Balance and Comfort Equation

Substituting all the heat loss terms derived above into the double heat balance *Eq.* (1) and dividing by F_{Du} gives

$$\begin{aligned} &\frac{M}{F_{Du}}(1-\eta) - 0.35[1.92t_s - 25.3 - p_a] - \frac{E_{sw}}{F_{Du}} - 0.0023\frac{M}{F_{Du}}(44-p_a) \\ &\quad -0.0014\frac{M}{F_{Du}}(34-t_a) = \frac{t_s - t_{cl}}{0.18I_{cl}} \\ &= 3.4\cdot 10^{-8} f_{cl}[(t_{cl}+273)^4 - (t_{mrt}+273)^4] + f_{cl}h_c(t_{cl}-t_a). \end{aligned} \tag{10}$$

Substituting the expressions for $\overline{t_s}$ and $\overline{E_{sw}}$ in the double heat balance *Eq.* (10)

$$\begin{aligned} &\frac{M}{F_{Du}}(1-\eta) - 0.35[43 - 0.061\frac{M}{F_{Du}}(1-\eta) - p_a] - 0.42\left[\frac{M}{F_{Du}}(1-\eta) - 50\right] \\ &-0.0023\frac{M}{F_{Du}}(44-p_a) - 0.0014\frac{M}{F_{Du}}(34-t_a) = \frac{35.7 - 0.032\frac{M}{F_{Du}}(1-\eta) - t_{cl}}{0.18I_{cl}} \\ &= 3.4\cdot 10^{-8} f_{cl}[(t_{cl}+273)^4 - (t_{mrt}+273)^4] + f_{cl}h_c(t_{cl}-t_a). \end{aligned} \tag{11}$$

Solving the left part of the double *Eq.* (11) gives the following expression for t_{cl}:

$$\begin{aligned} t_{cl} &= 35.7 - 0.32\frac{M}{F_{Du}}(1-\eta) - 0.18I_{cl}\left\{\frac{M}{F_{Du}}(1-\eta)\right. \\ &-0.35\left[43 - 0.061\cdot\frac{M}{F_{Du}}(1-\eta) - p_a\right] - 0.42\left[\frac{M}{F_{Du}}(1-\eta) - 50\right] \\ &\left.-0.0023\frac{M}{F_{Du}}(44-p_a) - 0.0014\cdot\frac{M}{F_{Du}}(34-t_a)\right\} \qquad {}^\circ\mathrm{C}. \end{aligned} \tag{12}$$

Setting the left side of double *Eq.* (11) equal to the right side gives:

$$\begin{aligned}\frac{M}{F_{Du}}(1-\eta) - 0.35\left[43 - 0.061\cdot\frac{M}{F_{Du}}(1-\eta) - p_a\right] - 0.42\left[\frac{M}{F_{Du}}(1-\eta) - 50\right]&\\ -0.0023\frac{M}{F_{Du}}(44-p_a) - 0.0014\cdot\frac{M}{F_{Du}}(34-t_a)&\qquad(13)\\ = 3.4\cdot 10^{-8} f_{cl}[(t_{cl}+273)^4 - (t_{mrt}+273)^4] + f_{cl}h_c(t_{cl}-t_a).&\end{aligned}$$

Eq. (13) is the desired general comfort equation, in which t_{cl} is given by *Eq.* (12)

The comfort equation contains the following variables:

I_{cl}, f_{cl},	M/A_{Du}, η, v,	v, t_a, p_a, t_{mrt}
A function of the type of clothing	A function of the type of activity	Environmental variables

I_{cl} and f_{cl} are functions of the type of clothing (values for different clothing ensembles are shown in tabies). M/F_{Du}, η, and partially v, are functions of the type of activity t_a, p_a, t_{mrt} and partially v, are thermal environmental variables.

The comfort equation being obtained by inserting in the heat balance equation the comfort expressions found for skin temperature and sweat rate, satisfaction of the comfort equation therefore means at the same time satisfaction of the three basic comfort conditions. Satisfaction of the comfort equation is thus a necessary condition for optimal thermal comfort.

Using the comfort *Eq.* (13) it is possible, for any type of clothing (clo) and any type of activity (W/m^2), to calculate all reasonable combinations of air temperature (°C), air humidity, mean radiant temperature (°C), and relative velocity (m/s) which will create optimal thermal comfort for persons under steady state conditions.

Comfort Diagrams

The comfort equation is quite complex, since the involved heat transfer processes are relatively complicated. Solution by hand would be laborious as multiple iteration is necessary. It has, therefore, been solved by digital computer, for all relevant combinations of the variables, and 9 diagrams for direct practical application have been prepared. Since the diagrams, and not the equation itself, should be used in practice, it was not necessary – at the expense of accuracy – to simplify the comfort equation in order to make hand calculations easier.

The curves in the figures represent comfort lines, i.e. lines through points (conditions) which satisfy the comfort equation and thus will provide optimal thermal comfort. In all the figures the mechanical efficiency η is set equal to zero, covering the great majority of practical applications.

The comfort diagrams are well known and they could be found in the different literatures [3], [5], [6], [7].

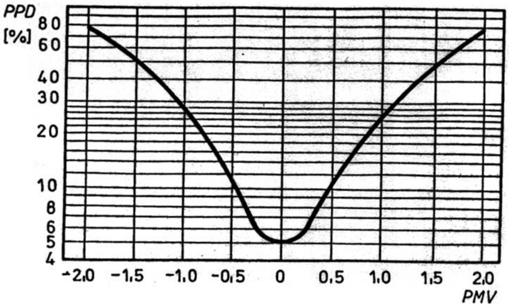

Fig. 1. Operation of the main ventilation system

6. PMV-PPD Value

Fanger developed the above calculation approach by working out a theory and a practical method, on the basis of which an expected sense of heat as regards to a given point in space can be determined with the help of the available parameters. These are the so called PMV, the Predicted Mean Vote value and the PPD value, which stands for the proportional probability of disadvantageous sense of heat Predicted Percentage of Dissatisfied. The knowledge of the theoretical development of these two indicators is indispensable.

In the course of the development of PMV Fanger started from the basic equation of heat balance and the scale of subjective psychophysical sense of heat by ASHRAE [8].

Assuming an environment of discomfortable conditions the thermostatic mechanism of the body changes the average value of skin temperature, starts sweating if necessary in order to maintain the thermo-balance of the body. This thermal load is the physiological accelerator of the thermostatic mechanism, therefore the assumption that the degree of the load determines the sense of heat at the same time is justified. In a simplified form it can be expressed with the following equation:

$$Y = f\left(\frac{H}{F_{Du}} \cdot L\right), \tag{14}$$

where Y is the expected sense of heat
L is the thermo-load on the body
H/F_{Du} is the thermal-load on 1 m^2

Functionality can be verified only if the votes of sense of heat and the equation of heat balance have been compared with an appropriate number of field or laboratory experiments.

In respect of comparing the data Fanger considered the experiments of Nevins and McNall partly, as regards four levels of activities for those cases where the values of air and mean radiation temperature were the same and the relative degree of humidity was 50%. The resulting Y value is the so called PMV value.

With the application of the measurements on people and these correlations tabular values were worked out first, then Fanger developed a diagram, which can be seen in *Fig. 1*. This figure is the basis of the practical evaluation of the thermo-environment according to Fanger. The PMV value of the diagram is symmetrical and has a minimum level. This minimum is 5% according to Fanger implying that the best result is that we can get when forming a microclimate in respect of the sense of heat if 95% of those who are there have a pleasant sense of heat.

7. The Possibilities for the Practical Application of the Calculation Method in Hungary

For the practical application of the calculation method Fanger developed the so-called comfort diagrams, which – as we have mentioned – can be found in numerous Hungarian and foreign publications [3] [5] [6] [7]. However, when applying the calculation method the following aspects have to be considered usually:

a.) The factor of dissatisfaction of 5% is considered. As the admissible PPD value is economy-dependent the demands of the given country (or contractor) have to be respected at all times. This however necessitates the calculation of the PMV value.

b.) The design theory of Fanger assumes that the sense of heat is independent of age, sex and ethnical characteristics. This is often disputed, numerous experiments – domestic ones, too [9] [10] [11] – have tried to define more accurate values.

c.) The theory also provides an explanation for the method of calculation if the parameters of the microclimate are different in the various parts of the given space. These are the so-called local aspects of discomfort, two of which are draft and asymmetric radiation. However, a separate article should be devoted to the elaboration of this subject, although there are plenty of foreign and domestic experiments and publications e.g. [12], [13], [14] available in this respect.

Conclusion

The subjective sense of heat of a person in an interior, his/her working and concentrating ability are primarily determined by the heat exchange conditions of his/her body. The so- called thermo-balance equation and the PMV-PPD method are suitable for the calculation of this. The paper has overviewed the theoretical design of the calculation method and the possibilities for practical application. Our work and results in Hungary on this special field could be perceptible from the mentioned papers too.

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