OPERATIVE TEMPERATURE AND GLOBE TEMPERATURE

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Thermal comfort is defined as the mental condition that expresses satisfaction with the thermal environment. It is easy to understand this definition but it is difficult to express it by mathematical equations, because it is needed to take into account many of environmental and personal parameters. The Czech standards contain the equations that describe the thermal comfort through Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) indexes, also describe the thermal state by the operative temperature. The objective of this article is to prove, if it is possible to estimate the thermal comfort of the environment by using the globe temperature.

Keywords: *thermal comfort, operative temperature, globe temperature*

1. Introduction

Air temperature, radiant temperature, humidity and air velocity are the four basic environmental variables which define the thermal state of environment. Combined with the metabolic heat generated by human activity and clothing worn by a person, they provide the six fundamental factors that define human thermal environments [1]. Many instruments have been designed which give the effects of air temperature, mean radiant temperature and air velocity on the thermal state of environment. One such instrument is the globe thermometer. In this paper it had shown the possibility of using the globe temperature for evaluating the thermal state of an environment through make comparison between globe temperature and the operative temperature in a wide range of air temperature, mean radiant temperature and air velocity.

2. Thermal comfort

The Thermal comfort has been defined by The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) as the condition of the mind in which satisfaction is expressed with the thermal environment [2]. The thermal comfort describes a person's psychological state of mind and it is usually referred to in terms of whether someone is feeling too hot or too cold [3]. When we want determination what will make someone feels comfortable we need to take into account a range of environmental and personal parameters which make very difficult to definition thermal comfort [4].

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3. Operative temperature

The operative temperature T_o is defined as a uniform temperature of a radiantly black enclosure in which an occupant would exchange the same amount of heat by radiation and convection as in the actual non uniform environment. According to ČSN EN ISO 773 [5] is

$$t_\mathrm{o} = t_\mathrm{a} + (1 - A)\,(t_\mathrm{r} - t_\mathrm{a}) \qquad \text{or}$$
$$T_\mathrm{o} = T_\mathrm{a} + (1 - A)\,(T_\mathrm{r} - T_\mathrm{a}) \; . \tag{1}$$

$$A = \frac{\alpha_\mathrm{c}}{\alpha_\mathrm{c} + \alpha_\mathrm{r}} \tag{2}$$

where: α_c, α_r [$\mathrm{W\,m^{-2}\,K^{-1}}$] are the coefficients of heat transfer by convection and radiation, respectively, on the body surface; t_a, t_r [°C] are the air temperature and mean radiant temperature, respectively.

The air velocity of an environment affects the coefficient of heat transfer; when the air velocity increases then the coefficient of heat transfer by convection α_c increase, and the change of coefficient of heat transfer by radiation α_r can be neglect, then the coefficient A only depends on air velocity w, see Tab. 1.

w [m/s]	< 0.2	0.2 to 0.6			> 0.6 to 1	
A [—]	0.5	0.6			0.7	
w [m/s]	< 0.2	0.3	0.4	0.6	0.8	1

Tab.1: Depending the coefficient A on the air velocity w [5]

It is possible to calculate the coefficient A from the following equation [5]:

$$A = 0.73\,w^{0.2} \; . \tag{3}$$

According to law in Czech Republic: For low air velocity $w < 0.2\,\mathrm{m\,s^{-1}}$ the operative temperature equal to the globe temperature [6].

$$T_\mathrm{g} = T_\mathrm{o} \tag{4}$$

where: T_g is globe temperature in unite of [K], T_o is operative temperature in unite of [K].

On the other hand, according to reference [5]: For low air velocity $w < 0.2\,\mathrm{m\,s^{-1}}$ and small difference of temperature $|T_\mathrm{a} - T_\mathrm{r}|$, it is possible assess the operative temperature as arithmetic mean of air and mean radiant temperature

$$T_\mathrm{o} = \frac{1}{2}\,(T_\mathrm{a} + T_\mathrm{r}) \; . \tag{5}$$

4. Globe temperature

The globe temperature T_g is quantity, which measures directly by globe thermometer. The globe thermometer is one of the most common radiant temperature measurement tool, introduced by Vernon (1930). It consists of a hollow copper sphere of diameter 150 mm (or 100 mm), coated with matt black paint and containing an ordinary thermometer with its bulb fixed at the center of the sphere, without source of heat [7].

In steady state the radiant heat flux from the environment into the sphere is in balance with the convective heat flux from the surface of sphere to the environment. The globe thermometer reaches thermal equilibrium when the heat gain by radiation equals the heat loss by convection

$$q_\mathrm{c} = q_\mathrm{r} \; . \tag{6}$$

By Stefan-Boltzmann's law, the radiation gain may be expressed by the equation

$$q_\mathrm{r} = \sigma\,\varepsilon\,(T_\mathrm{r}^4 - T_\mathrm{g}^4) \tag{7}$$

where ε is a numerical constant depending on the emissivity of the sphere, for a surface painted matt black the value of ε is about 0.95; $\sigma = 5.67\times10^{-8}\,\mathrm{W\,m^{-2}\,K^{-4}}$, is Stefan-Boltzmann's constant, T_r is mean radiant temperature of the surrounding surfaces [K], T_g is temperature of the sphere surface [K].

The convection heat transfer between air space and the sphere is given by the equation

$$q_\mathrm{c} = \alpha_\mathrm{cg}\,(T_\mathrm{g} - T_\mathrm{a}) \tag{8}$$

T_a is air temperature [K]; α_cg is the convection heat transfer coefficient between air and globe thermometer [$\mathrm{W\,m^{-2}\,K^{-1}}$].

For natural flow [8] :

$$\alpha_\mathrm{cg} = 1.4\left(\frac{|t_\mathrm{a} - t_\mathrm{g}|}{D}\right)^{0.25} \; . \tag{9}$$

In case of forced flow [8] :

$$\alpha_\mathrm{cg} = 6.3\,\frac{w^{0.6}}{D^{0.4}} \tag{10}$$

where : t_a is air temperature [°C]; t_g is temperature of the sphere surface [°C]; D is diameter of sphere [m]; w is air velocity [$\mathrm{m\,s^{-1}}$].

The thermal equilibrium equation is written

$$\alpha_\mathrm{cg}\,(T_\mathrm{g} - T_\mathrm{a}) = \sigma\,\varepsilon\,(T_\mathrm{r}^4 - T_\mathrm{g}^4) \; . \tag{11}$$

In this article, the forced heat convection has been used because it is easier to express the globe temperature as a function of air velocity. Then the globe temperature can be written as following :

$$6.3\,\frac{w^{0.6}}{D^{0.4}}\,T_\mathrm{g} + \sigma\,\varepsilon\,T_\mathrm{g}^4 = 6.3\,\frac{w^{0.6}}{D^{0.4}}\,T_\mathrm{a} + \sigma\,\varepsilon\,T_\mathrm{r}^4 \; . \tag{12}$$

For globe thermometer the following conditions are applied : Diameter of globe thermometer $D = 0.15\,\mathrm{m}$; Emissivity of sphere $\varepsilon = 0.95$; Stefan-Boltzmann's constant is $5.67\times10^{-8}\,\mathrm{W\,m^{-2}\,K^{-4}}$; then :

$$13.46\,w^{0.6}\,T_\mathrm{g} + 5.3865\times10^{-8}\,T_\mathrm{g}^4 = 13.46\,w^{0.6}\,T_\mathrm{a} + 5.3865\times10^{-8}\,T_\mathrm{r}^4 \; . \tag{13}$$

The last equation is transcendental equation, and it is need to use iterative method to solve it. In this article the Mathcad program has been used to solve this equation and found the globe temperature as function for the other variables

$$T_\mathrm{g} = f(w, T_\mathrm{r}, T_\mathrm{a}) \; . \tag{14}$$

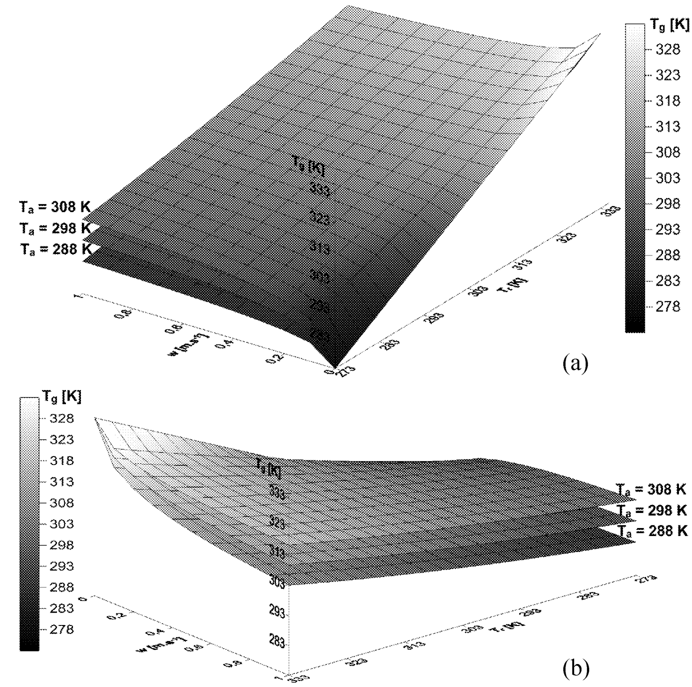

Fig.1: Globe temperature as function of air velocity, mean radiant temperature, and air temperature: (a) front view, (b) side view

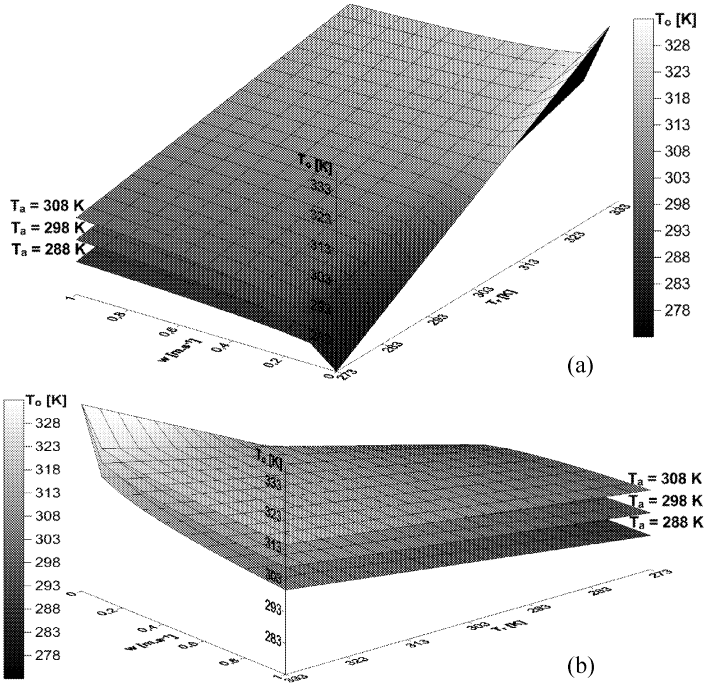

Fig.2: Operative temperature as function of air velocity, mean radiant temperature, and air temperature: (a) front view, (b) side view

Fig. 1a and 1b show the globe temperature as function of air velocity, mean radiant temperature and air temperature (two viewpoints a and b). Where the in each figures are three surfaces, each one represents the relation between globe temperature and air velocity for a constant air temperature.

The operative temperature can be found as function of air velocity, mean radiant temperature and air temperature from the equations (1) and (5)

$$T_\mathrm{o} = f(w, T_\mathrm{r}, T_\mathrm{a}) \; . \tag{15}$$

Fig. 2a and 2b show the relation of operative temperature with air velocity, mean radiant temperature and air temperature (two viewpoints). Where the in each figures are three surfaces, each one represents the relation between operative temperature and air velocity for a constant air temperature.

Because of globe temperature is obtained easier than operative temperature (by reading it directly from the globe thermometer), so a comparison between globe temperature and operative temperature is made in a wide range of air temperature, mean radiant temperature and air velocity.

Fig. 3a and 3b show a comparison between operative temperature and globe temperature, each one represents the difference between operative and globe temperature as function of air velocity and mean radiant temperature for a constant air temperature (308 K and 288 K, respectively).

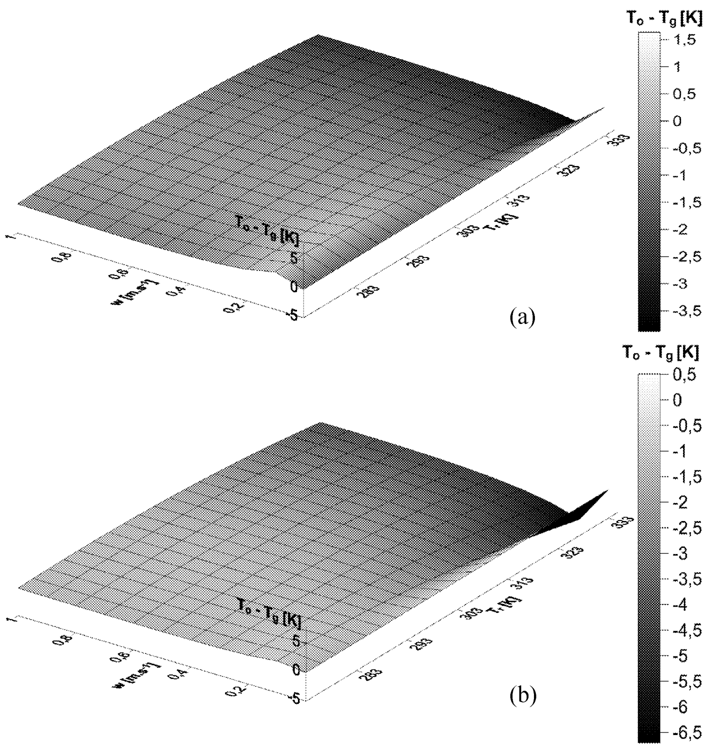

Fig.3: The difference between operative and globe temperature for constant air temperature: (a) 308 K, (b) 288 K

5. Discussion

The results appear that the difference between the operative temperature and the globe temperature depends on the air velocity and further on the difference between mean radiant and air temperature, where for air velocity more than $0.2\,\mathrm{m\,s^{-1}}$ and the difference $|T_\mathrm{r} - T_\mathrm{a}| < 10\,\mathrm{K}$, then the difference between operative temperature and globe temperature is less than $0.6\,\mathrm{K}$, as it is shown on Fig. 4a and 4b.

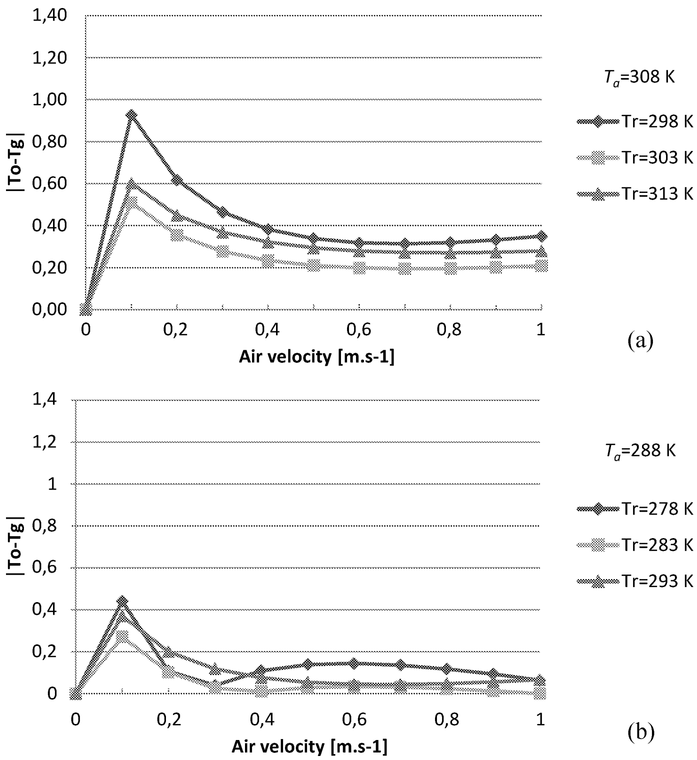

Fig.4: The difference between operative and globe temperature for constant air temperature: (a) 308 K, (b) 288 K and difference between mean radiant and air temperature less than 10 K

6. Conclusion

Depending on the discussion (for air velocity more than $0.2\,\mathrm{m\,s^{-1}}$ and the difference $|T_\mathrm{r} - T_\mathrm{a}| < 10\,\mathrm{K}$, then the difference between operative temperature and globe temperature is less than $0.6\,\mathrm{K}$) it is possible to say that the globe temperature is equal to the operative temperature in the range for air velocity $> 0.2\,\mathrm{m\,s^{-1}}$ and the difference $|T_\mathrm{r} - T_\mathrm{a}| < 10\,\mathrm{K}$. And this corresponds with the Czech standards [8] (the accuracy in the globe temperature measurement is $\pm 0.5\,\mathrm{K}$).

Former conclusion disagrees with the Statute-book [6], where is written that for air velocity less than $0.2\,\mathrm{m\,s^{-1}}$, the operative temperature can be replaced by the globe temperature.

Another reference, the Society of Environmental Engineering [9], they had the same conclusion like in this article.

By analyzing the results it is possible to say that the large difference between the operative and globe temperature in range of velocity of $0 < w < 0.2\,\mathrm{m\,s^{-1}}$ is due to omit the effect of free convection in this range.

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