# Effects of Air Temperature, Mean Radiant Temperature, and Air Velocity on the Globe and Operative Temperatures

Mohammad Kazkaz, Mousa Sattouf

***Abstract*****—**In this paper is presented a theoretical comparison between the globe and operative temperature, to determine if it is possible to use the operative temperature instead of globe temperature for appraisal of the thermal comfort, for that matter each of the relation of globe temperature, the relation of operative temperature, the relation of the difference between operative and globe temperature as function of air velocity, men radiant temperature and air temperature are presented.

***Keywords*****—**Thermal environment, thermal comfort, globe temperature, operative temperature.

## I. Introduction

Thermal comfort is defined as the condition of mind in which satisfaction with the thermal environment is expressed. The definition is easy to understand but it is hard to express it by mathematical relation, because it is required to take into account number of environmental and personal parameters. Air temperature, radiant temperature, humidity and air velocity are the four basic environmental parameters which define the environmental thermal state. Together with the metabolic heat rate generated by human body activity and clothing worn by a person, they supply the six fundamental parameters that define human thermal environments [5]. Several instruments have been designed which give the effects of the six fundamental parameters on the thermal state of environment. The globe thermometer is one of these instruments. In this paper is shown the possibility of replacing the globe temperature instead of operative temperature for assessment thermal state of environment.

## II. 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'' [1]. The thermal comfort describes a person's psychological case of mind and is usually referred in terms of whether someone is feeling too hot or too cold. When it is needed to determinate what will make a person feels comfortable, then we need to take into account a number of environmental and individual parameters, which make the definition of thermal comfort very difficult.

So for simplifying evaluation of the thermal comfort, indexes and derived quantities are used, including the combined effect of many or all of the factors determining the thermal state of the environment, including for example; The globe temperature, the operative temperature (temperature measured by globe thermometer), equivalent temperature, index PMV (Predicted mean vote), index PPD (predicted percentage dissatisfied) and index DR (draught rate).

In this article the globe temperature and operative temperature are mainly discussed to evaluate the thermal state of the environment.

## III. Globe Temperature

The globe temperature is quantity that measured directly by globe thermometer. The globe thermometer is one of the most common mean radiant temperature measurement devices. the globe thermometer consists of a blank copper sphere of diameter 150 mm (or 100 mm), coated with matt black color, the blank copper sphere contains an ordinary thermometer with its bulb fixed at the center of the sphere, without source of heat. In steady state the globe thermometer reaches the thermal equilibrium when 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[9][10].

$$q_c = q_r \tag{1}$$

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

$$q_r = \sigma.\varepsilon(T_r^4 - T_g^4) \tag{2}$$

Where:

$\varepsilon$ 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 .

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$\sigma = 5.67 \times 10^{-8}$ is Stefan – Boltzmann's constant (W/m$^2$.K$^4$).

$T_r$ is mean radiant temperature of the surrounding surfaces (K).

$T_g$ is temperature of the sphere surface (K).

The convection heat transfer between the environment and the globe thermometer is given by (3):

$$q_c = \alpha_{cg}(T_g - T_a) \quad (3)$$

Where:

$T_a$ is air temperature (K).

$\alpha_{cg}$ is the convection heat transfer coefficient between air and the globe thermometer (W/m$^2$.K).

For natural heat flow is:[4]

$$\alpha_{cg} = 1.4\left(\frac{|t_a - t_g|}{D}\right)^{0.25} \quad (4)$$

In case of forced heat flow; according to ISO 7726 is: [4]

$$\alpha_{cg} = 6.3\frac{w^{0.6}}{D^{0.4}} \quad (5)$$

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 (m/s).

The thermal equilibrium equation is written as following:

$$\alpha_{cg}(T_g - T_a) = \sigma.\varepsilon(T_r^4 - T_g^4) \quad (6)$$

In this research the forced 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:

$$6.3\frac{w^{0.6}}{D^{0.4}}T_g + \sigma.\varepsilon.T_g^4 = 6.3\frac{w^{0.6}}{D^{0.4}}T_a + \sigma.\varepsilon.T_r^4 \quad (7)$$

For globe thermometer the following conditions are applied: Diameter of sphere $D$=0.15 m. All physical properties are constant, emissivity of sphere $\varepsilon$=0.95 and Stefan – Boltzmann's constant is $5.67 \times 10^{-8}$ (W/m$^2$.K$^4$), then:

$$13.46 \cdot w^{0.6} \cdot T_g + 5.3865 \cdot 10^{-8} \cdot T_g^4 = 13.46 \cdot w^{0.6} \cdot T_a + 5.3865 \cdot 10^{-8} \cdot T_r^4 \quad (8)$$

From last equation it is difficult to write the globe temperature as function of air velocity, mean radiant and air temperature, because it is transcendental equation, which requires an iterative solution. In this article the Mathcad program was used to solve this equation and found the globe temperature as function of other variables as (9):

$$t_g = f(w, t_r, t_a) \quad (9)$$

Fig.1 and Fig.2 show the globe temperature as function of velocity, mean radiant temperature and air temperature (two viewpoints). Where these figures show three surfaces, each one represents the relation between globe temperature and air velocity for a constant air temperature.

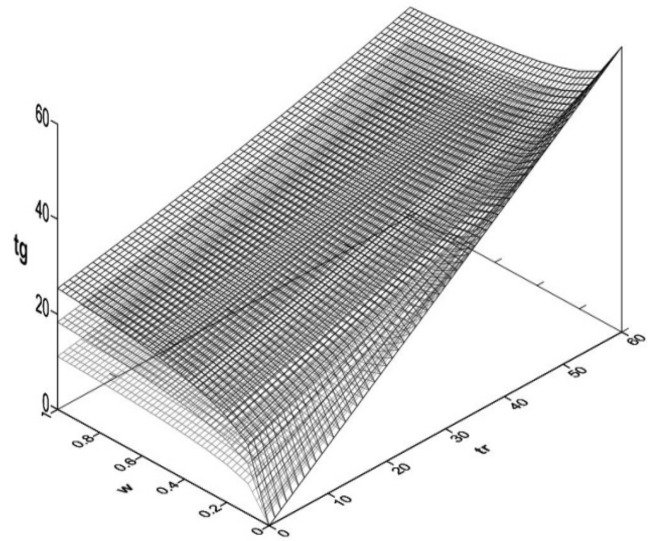


Fig.1 Globe temperature for $t_a$=15°,25°,35° (right side view)

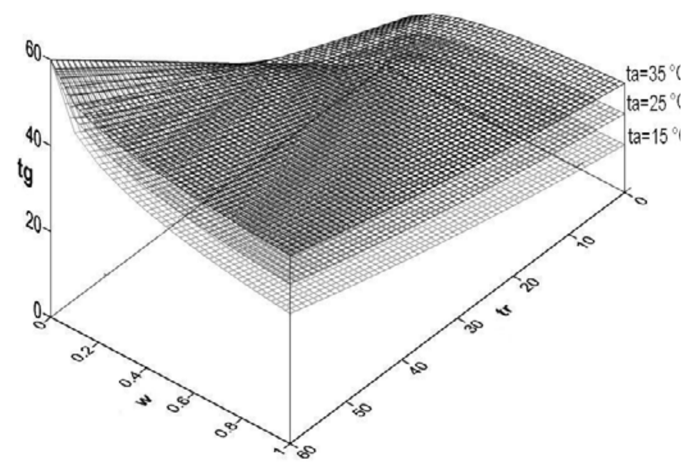


Fig.2 Globe temperature for $t_a$=15°,25°,35° (left side view)

## IV. OPERATIVE TEMPERATURE

The operative temperature ($t_o$) is 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 7726 [2] is:

$$t_o = t_a + (1 - A)(t_r - t_a) \quad (10)$$

There are many methods for calculating the operative temperature. For example, it can be calculated according to ČSN EN ISO 7730 [3] where:

$$A = \frac{\alpha_c}{\alpha_c + \alpha_r} \quad (11)$$

Where:

$\alpha_c$, $\alpha_r$ [W/m$^2$.K] are the coefficients of heat transfer by convection and radiation, respectively, on the body surface $t_a$,

$t_r$ [°C] is air temperature and mean radiant temperature. For low air velocity $w < 0.2$ m/s it is possible to replace operative temperature with globe temperature [7].

$$t_g = t_o, T_g = T_o \tag{12}$$

Where:

$T_g$, $t_g$ is globe temperature in unite of [K], [°C] respectively.

$T_o$, $t_o$ is operative temperature in unite of [K], [°C] respectively.

Other reference [2], considers for low air velocity $w < 0.2$ m/s and small difference of temperature $| ta - tr |$, it is possible assess the operative temperature as arithmetic mean of air and mean radiant temperature.

$$t_o = \frac{t_a + t_r}{2} \tag{13}$$

Table 1 shows value of coefficient *A* depending on the air velocity *w*.

Table.I *Dependence the coefficient A on the air velocity w*

| w [m/s] | < 0.2 | 0.2 to 0.6 | | | > 0.6 to 1 | |
|---|---|---|---|---|---|---|
| A [2] | 0.5 | 0.6 | | | 0.7 | |
| w [m/s] | < 0.2 | 0.3 | 0.4 | w [m/s] | < 0.2 | 0.3 |

It is possible to calculate the coefficient A from the following equation [2]:

$$A = 0.73 \cdot w^{0.2} \tag{14}$$

From the equations (10) and (14) can be found the operative temperature as function of air velocity, mean radiant temperature and air temperature as:

$$t_o = f(w, t_r, t_a) \tag{15}$$

Fig.3 and Fig.4 show the relation of operative temperature with air velocity, mean radiant temperature and air temperature (two viewpoints).

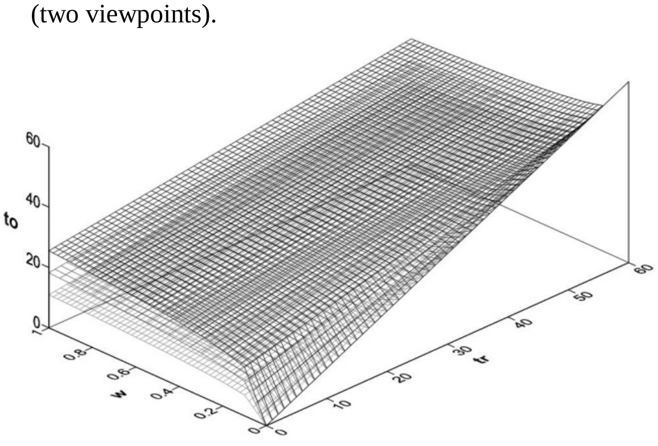


Fig. 3 Operative temperature for $t_a$=15°C, 25°C, 35° C (right side view)

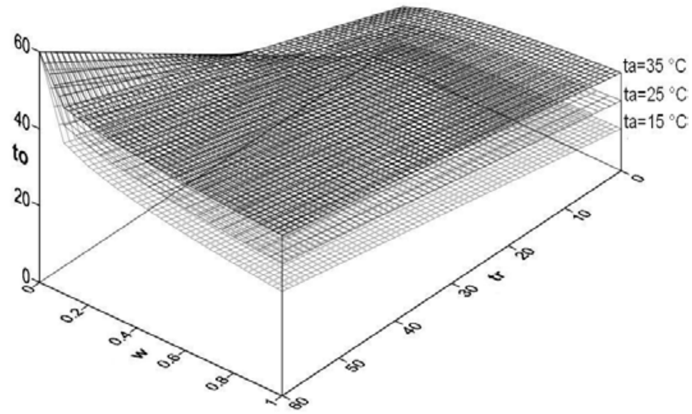


Fig. 3 Operative temperature for $t_a$=15°C, 25°C, 35° C (left side view)

These figures show three surfaces, each one represents the relation between operative temperature and air velocity for a constant air temperature.

The relation between operative temperature and globe temperature is given by similarity between the heat transfer on the surface of human body and the heat transfer on the surface of globe thermometer, and because of the globe temperature is easily obtained by reading it directly from the globe thermometer [8].

Fig.5 and Fig.6 show a comparison between the operative temperature and globe temperature, where Fig. 3b is for range of mean radiant temperature 40°[C] ≥ tr ≥ 0°[C] and air velocity in the rang 1 [m/s] ≥ w ≥ 0.2 [m/s].

The figures show two surfaces, each one represents the relation between the difference of operative and globe temperature and air velocity for a constant air temperature.

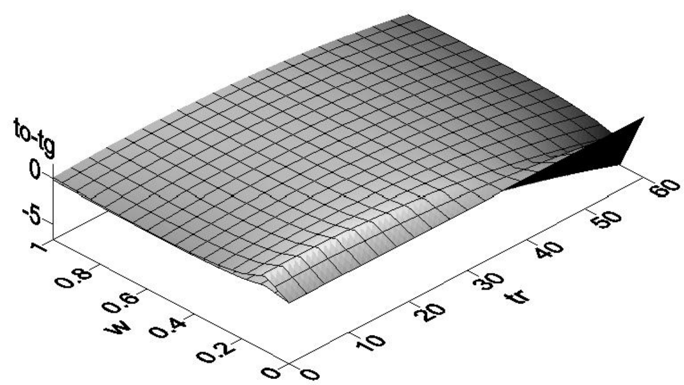


Fig.5 Difference of operative and globe temperature for $t_a$=15°,35° (sidelong view)

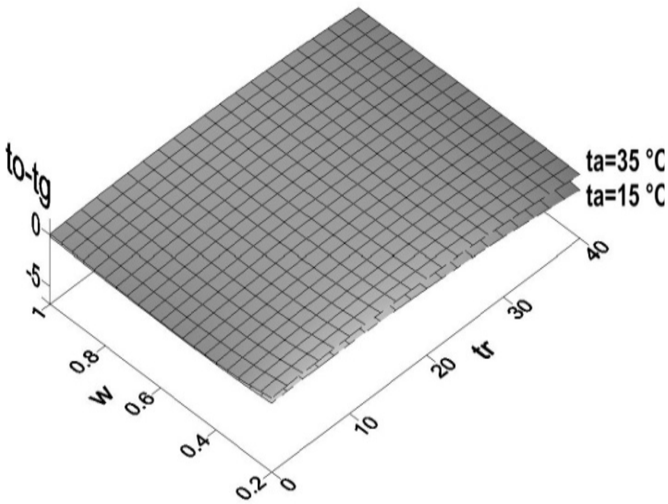


Fig.6 Difference of operative and globe temperature for $t_a$=15°C,35°C (upper view)

## V. DISCUSSION

According to obtained results the difference between the operative temperature and globe temperature depends on the air velocity and further on the difference between the mean radiant temperature and air temperature, where:

- For the difference $|t_r - t_a| \leq 10$ K and air velocity greater than 0.2 m/s, then the difference $|t_o - t_g|$ is between 0 K and 0.9K.
- For air velocity less than 0.2 m/s, then the difference between the globe and operative temperature is up to 1.35K.

The best result is for $|t_r - t_a| \leq 5$ K, and air velocity smaller than 0.2[m/s], where in this range the difference between operative temperature and globe temperature is compatible with the Czech standards [4], where the accuracy in the globe temperature measurement is ±0.5°C for air temperature between 20°C to 50°C.

Fig.7, Fig.8 and Fig.9 show the difference between operative and globe temperature for constant mean radiant and air temperature.

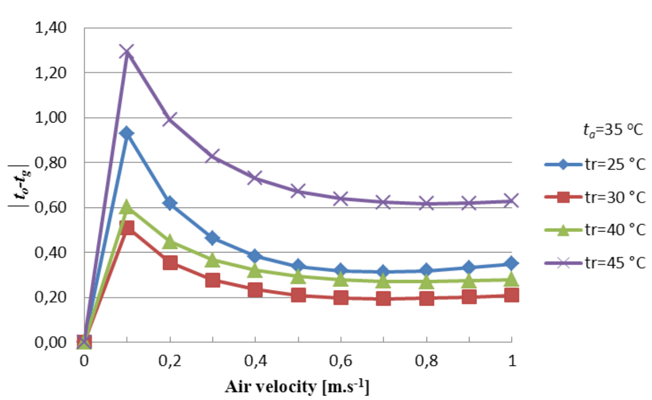


Fig.7 Difference between operative and globe temperature as function of air velocity for $t_a$=35°C

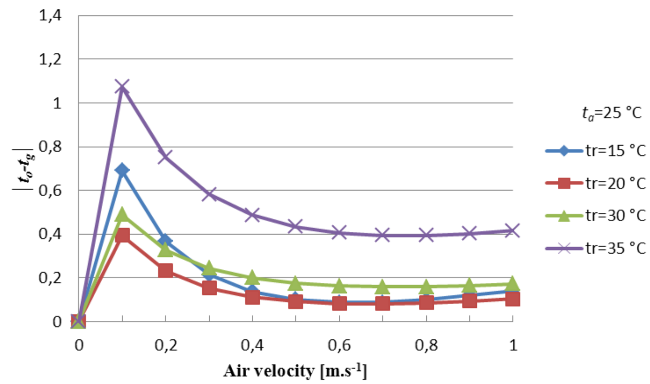


Fig.8 Difference between operative and globe temperature as function of air velocity for $t_a$=25°C

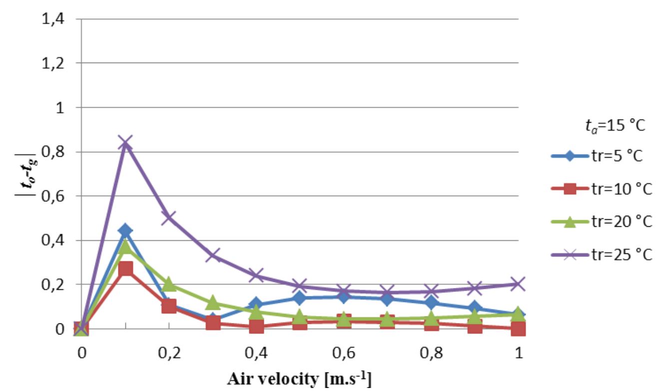


Fig.9 Difference between operative and globe temperature as function of air velocity for $t_a$=15°C

Fig.10, Fig.11 and Fig.12 show the difference between operative and globe temperature for constant mean radiant and air temperature for air velocity greater than 0.2 m/s.

The figures show two surfaces, each one represents the relation between the difference of operative and globe temperature and air velocity for a constant air temperature.

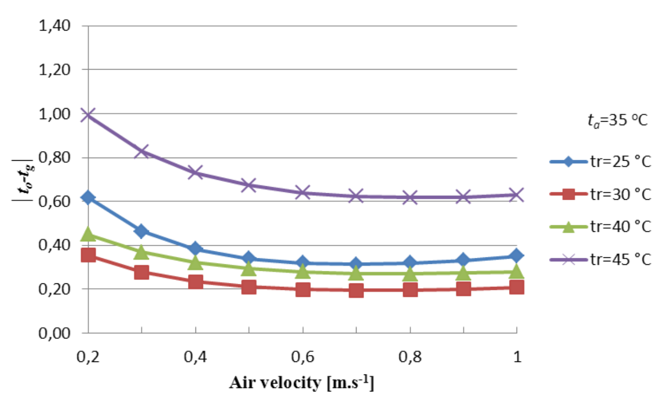


Fig.10 Difference between operative and globe temperature as function of air velocity(>0.2 m/s) for $t_a$=35°C

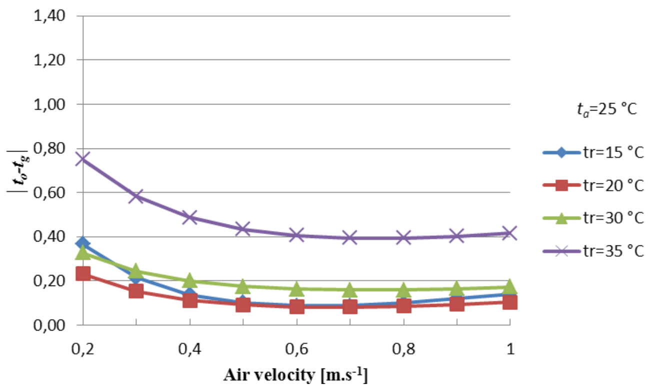


Fig.11 Difference between operative and globe temperature as function of air velocity(>0.2 m/s) for $t_a$=25°C

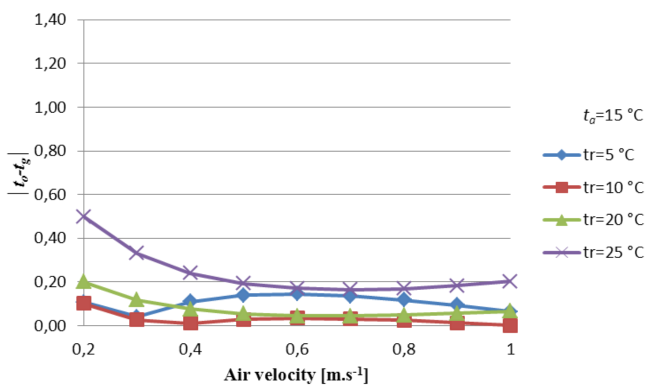


Fig.12Difference between operative and globe temperature as function of air velocity(>0.2 m/s) for $t_a$=15°C

## VI. Conclusion

Depending on the previous discussion, it is possible to use the globe temperature instead of the operative temperature for air velocity 0.2 ≥ w ≥ 1 m/s and the difference |tr–ta| ≤ 5 K to assessment the thermal state of environment. prior conclusion disagrees with the Statute-book [7], where is written that for air velocity less than 0.2 m/s, operative temperature can be replaced by the globe temperature. Another reference, the Society of Environmental Engineering [5], they had the same conclusion like in this article. By analyze the results it is possible to say that the difference between the operative temperature and globe temperature in range of velocity of 0 < w < 0.2 m/s is due to omit the effect of free convection in this range.

## Appendix

Table. II *Characteristics of measuring instruments*

| Class S (thermal load) | | | | | | Notice |
|---|---|---|---|---|---|---|
| | quantity | symbol | measurement range | accuracy | stabilization time (90 %) | |

| | | | | | | |
|---|---|---|---|---|---|---|
| Basic quantities | Air velocity | | | | | Parameter when studying the issue of comfort. It is recommended that was expressed as a standard deviation of the speed.<br>In cold environments, it is recommended that was used the device class C for any type of the analysis (comfort or extreme thermal load) |
| | absolute humidity | $p_a$ | 0.5 to 6 kPa | ±0.15 kPa<br>This value must be guaranteed for air and walls temperature equal to or greater than 30 $^o$C and for the difference ($t_r$-$t_a$)at least 10 $^o$C | Soon as possible. value is determined as a characteristic of the measuring device | |
| Derived quantities | Temperature of wet thermometer | $t_{nw}$ | 5 to 40 $^o$C | ±0.5 $^o$C | Value is determined as a characteristic of the measuring device | The sensor characteristics is prescribed |
| | Globe temperature | $t_g$ | 20 to 120 $^o$C | 20 to 50 $^o$C: ±0.5 $^o$C<br>>50 to120 $^o$C: ±0.5 $^o$C | The same | The sensor characteristic is prescribed. Temperature of the globe can be used to estimate the mean radiant temperature in cold, slight and hot zone. |
| | Wet Globe temperature | $t_{wg}$ | 0 to 80 $^o$C | ±0.5 $^o$C | The same | Accuracy of measurement for globe temperature to determine t need not be the same as the accuracy for measurement of globe temperature, as it derived values.<br>The sensor characteristic is prescribed. |


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