Equivalent parameters of thermal comfort of the room

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Abstract. Modern approaches to the substantiation of comfort parameters of the microclimate and rooms are mainly focused on the requirements of State Standard ГОСТ Р ИСО 7730 and ASHRAE Standard 55. The article describes a method for calculating the dependencies of the required air temperature on mobility, mobility and radiation temperature difference at various levels of metabolism and insulation of clothing for three classes comfort.

For each class of comfort pre-built tables of iso-comfort microclimatic parameters, which are calculated for different levels of human metabolism and clothing characteristics. The obtained values from the tables of iso-comfort microclimatic parameters are substituted into the empirically derived equation for calculating the equivalent temperature. The results in the form of the equivalent comfortable temperature are approximated as a function of the level of metabolism and the characteristics of the clothes, as a result of which generalized calculated expressions of the parameter of the equivalent comfortable temperature are obtained. The results in the form of the equivalent comfortable temperature are approximated as a function of the level of metabolism and the characteristics of the clothes, as a result of which generalized calculated expressions of the parameter of the equivalent comfortable temperature are obtained. Thus, six data arrays with thermal comfort parameters for rooms of three classes are summarized by six calculated algebraic expressions. The obtained calculated expressions of equivalent comfortable temperature can be used in the design of air conditioning systems and in programming automatic climate control systems.

1. Introduction

By nature of its impact on human heat balance, the microclimate is divided into moderate (neutral), cooling and heating [1]. For a moderate (neutral) microclimate, such a combination of its parameters is characteristic, it provides the heat balance of a person with the environment in the range of ± 2 W, with a fraction of heat transfer from evaporation of sweat not exceeding 30%. If there is negative heat balance below –2 W, the microclimate is considered to be cooling, and with a heat balance above 2 W and if the proportion of heat loss from evaporation of sweat is more than 30%, it is considered to be heating. A comfortable climate is usually defined as “a state of mind that brings satisfaction with the thermal environment” [2]. Human thermal sensations are the result of the interaction of six factors: air temperature, average radiation temperature, relative air mobility, humidity, activity level and thermal characteristics of clothes.

The human thermoregulation system allows for physiological regulation of the heat balance and ensure the thermal comfort of the body in various conditions. Heat is primarily generated by metabolism, due to digestion and muscular activity. At rest, about 56% of the total heat production occurs in the
internal organs and about 18% occurs in muscles and skin. During physical exertion, heat production by muscular work increases significantly, the percentage of heat released by muscles can increase up to 90% [3].

Under normal conditions, these processes lead to an average temperature inside the body of about 37°C [4, 5]. The human thermoregulation system tends to maintain this value when disturbances from internal or external conditions increase. The resulting effects of changing climatic conditions produce a response in the form of autonomous physiological responses, as well as activation of behavioral regulation. Autonomic regulation is controlled by hypothalamus, which controls heat flow through dermal blood flow, sweating, and aspiration. Behavioral regulation is manifested in changes in activity and clothing [6, 7]. Figure 1 shows the heat transfer components of the human body for a two-core “core-shell” model [2].

![Figure 1. Components of the human body’s heat transfer.](image)

2. Results and discussion

To estimate the thermal state of a person in the internal and external environment, multiparameter biometeorological indices are widely used.

Effective temperature (ET) is a combination of relative air humidity and temperature at which the effect of thermal sensation and heat transfer will be the same. The values of this parameter are expressed in degrees of the effective temperature, that is, in degrees of the temperature of still air saturated with water vapor. When calculating the effective temperature, the approximate dependence proposed by F.A. Missenard is used [6]:

$$ET = e - 0.4(t - 10)\left(1 - \frac{f}{100}\right),$$

where $f$ is the average daily relative air humidity, %; $t$ is the average daily air temperature, °C.

The effective temperature index is used in still air conditions. To account for the effect of air movement, B.A. Aizenshtat introduced the concept of equivalent-effective temperature [2].

Equivalent-effective temperature (EET or ET) is determined by the relation:

$$ET = 37 - \frac{37 - t}{0.68 - 0.0014f + \frac{1}{1.76 + 1.4v^{0.75}}} - 0.29t\left(1 - \frac{f}{100}\right),$$

where $t$ is the air temperature, °C; $f$ is the relative humidity, %; $v$ is the average wind speed.

The index of the normal equivalent-effective temperature (NEET) is known, it is used for the analytical assessment of the thermal sensation of a dressed person. This index was proposed by I.V.
Butieva, it indicates sensitivity, taking into account the influence of wind and is determined by the formula [2].

\[ \text{NEET} = 0.8 \times \text{ET} + 7^\circ \text{C} \]

In 2005 S.S. Andreev proposed a new index — the biologically active temperature (BAT), which makes it possible to determine the complex effect the temperature, air humidity, wind speed, and total solar radiation have on humans. The values of this indicator can be calculated by the formula [2]

\[ \text{BAT} = 0.8 \times \text{NEET} + 9^\circ \text{C} \]

E.G. Golovina introduced another indicator — the radiation-equivalent-effective temperature (REET), which is calculated according to the following dependencies [2]:

\[ \text{NEET} = 12 \times \log \left[ 1 + 0.025T + 0.001(T - 8)(f - 60) - 0.45(33 - T)\sqrt{v} + 185B \right] \]

where \( T \) is the air temperature, °C; \( f \) is the relative humidity, %; \( v \) is the wind speed, m/s; \( B \) is the solar radiation absorbed by the body surface, kW/m².

In this study, the task was to generalize the iso-comfort microclimate parameters to the given level of comfort for each class of premises.

The methodology for the integrated assessment of the comfort level of a moderate microclimate according to State Standard ГОСТ Р ИСО 7730 [1] is based on the definition of PMV and PPD thermal comfort indices. The predicted average PMV rating is an index that is used to determine the average sensitivity to the microclimate parameters on a 7-point scale. PPD is an indicator that sets the predicted percentage of people dissatisfied with the microclimate who are either too warm or too cold. The functional dependence \( \text{PPD} = f(\text{PMV}) \) is obtained on the basis of the mathematical processing of the results of the subjective assessment of microclimatic conditions for a large sample of subjects. In Figure 2 this functional dependence is given in graphical interpretation for the premises of three comfort classes A, B, and C [1].

![Figure 2. Functional dependence PPD = f(PMV).](image)

This function, in fact, is a regression equation of the form:

\[ \text{PPD} = 100 - 95 \exp(-0.03353 \times \text{PMV}^4 - 0.2179 \times \text{PMV}^2) \]

The equation relates the thermal sensations of a group of people in a particular environment to the results of the calculation using the heat balance equation [6]. This semi-empirical equation is used to
predict the average rating on the ordinary rating scale of thermal comfort for a group of people. The standard provides for three classes of rooms in terms of thermal comfort.

The premises of comfort class A: \(-0.2 < \text{PMV} <+0.2\); (PPD < 6 %).
The premises of comfort class B: \(-0.5 < \text{PMV} <+0.5\); (PPD < 10 %).
The premises of comfort class C: \(-0.7 < \text{PMV} <+0.7\); (PPD < 15 %).

In [3, 4], the solution of the inverse problem with respect to the method for determining the level of comfort is described [5]. The method of successive approximations is used to calculate the totality of microclimate parameters that provide a given level of thermal comfort (iso-comfort parameters). The target functions of the calculations were to determine the required air temperature depending on mobility and relative humidity in the absence of radiation heat exposure (the first series of calculations) and to determine the required air temperature depending on mobility and radiation temperature difference at a constant (50%) relative air humidity (second series of calculations). Radiation temperature difference here means the difference between the air temperature and the average radiation temperature of the enclosing surfaces. Table 1 and figure 3 present the calculations of iso-comfortable air temperature as a function of mobility and radiation temperature difference for specific characteristics of clothing and metabolic rate for a given comfort class B.

Table 1. The dependence of air temperature on mobility and radiation temperature difference for PPD conditions = 10%, thermal resistance of clothing is 1.0 clo. \(t_r = t_a\), °C, work category 1a (68 W/m²; 1.1 met).

| \(\Delta t_r, ^\circ\text{C}\) | \(v = 0.1, \text{ m/c}\) | \(v = 0.3, \text{ m/c}\) | \(v = 0.5, \text{ m/c}\) | \(v = 0.7, \text{ m/c}\) |
|-----------------|-------------------|-------------------|-------------------|-------------------|
| -8              | 27.60             | 27.63             | 29.27             | 27.65             |
| -4              | 25.81             | 26.29             | 28.10             | 26.63             |
| 0               | 23.98             | 24.92             | 26.90             | 25.59             |
| 4               | 22.12             | 23.52             | 25.67             | 24.51             |
| 8               | 20.356            | 22.08             | 22.901            | 23.41             |

| \(\Delta t_r, ^\circ\text{C}\) | \(v = 0.1, \text{ m/c}\) | \(v = 0.3, \text{ m/c}\) | \(v = 0.5, \text{ m/c}\) | \(v = 0.7, \text{ m/c}\) |
|-----------------|-------------------|-------------------|-------------------|-------------------|
| -8              | 23.23             | 23.72             | 23.94             | 24.066            |
| -4              | 21.45             | 22.40             | 22.81             | 23.06             |
| 0               | 19.63             | 21.04             | 21.65             | 22.03             |
| 4               | 17.89             | 19.65             | 20.46             | 20.97             |
| 8               | 16.252            | 18.227            | 19.248            | 19.877            |

Figure 3. Surfaces of iso-comfort temperatures in coordinates “mobility – radiative temperature difference”. 
Thus, for each class of premises a database was obtained for a wide range of clothing characteristics (clo) and metabolic rate (met), consisting of tables of iso-comfortable parameters.

A fragment of the database of iso-comfort parameters for premises of class B is shown in figure 4.

![Figure 4. Fragment of the database of iso-comfort parameters.](image)

Based on the described database, we obtained a generalizing criterion of thermal comfort, the use of which greatly simplifies the calculation of iso-comfort parameters. The derivation of this criterion is based on the empirically derived equation for the equivalent temperature proposed in [3] (a parameter corresponding to the same thermal sensations). This equation is a function of air temperature, average radiation temperature, mobility, and clothing characteristics:

\[
t_{eq} = 0.55t_a + 0.45\bar{t}_r + \frac{0.24 - 0.75\sqrt{v_d}}{1 + l_{cl}} (36.5 - t_a),
\]

where \(t_{eq}\) is the equivalent temperature, °C; \(t_a\) is the air temperature, °C; \(\bar{t}_r\) is the average radiation temperature, °C, \(v_d\) is the air velocity, m/s; \(l_{cl}\) is the thermal resistance of clothing, clo.

When substituting into this equation the values of the parameters corresponding to a given level of thermal comfort from the database of iso-comfort parameters, the equivalent comfort temperature is calculated. This parameter corresponds not only to the same (equivalent) thermal sensations, but also satisfies the required level of thermal comfort.

Let us consider an example of calculating the equivalent comfortable temperature. Table 2 shows iso-comfort parameters for premises of class B for a given metabolism value of 1.1 met and thermal resistance of clothing 1 clo.

| \(\Delta t_r, °C\) | \(v = 0.05, m/c\) | \(v = 0.1, m/c\) | \(v = 0.15, m/c\) | \(v = 0.2, m/c\) |
|------------------|------------------|------------------|------------------|------------------|
| –4               | 26.03            | 26.26            | 26.43            | 26.54            |
| –2               | 25.12            | 25.35            | 25.60            | 25.78            |
| 0                | 24.22            | 24.43            | 24.76            | 25.00            |
| 2                | 23.35            | 23.49            | 23.92            | 24.22            |
| 4                | 22.48            | 22.55            | 23.06            | 23.42            |
PMV = – 0.49

| Δt_r, °C | $v = 0.05$, m/c | $v = 0.1$, m/c | $v = 0.15$, m/c | $v = 0.2$, m/c |
|---------|-----------------|-----------------|-----------------|-----------------|
| –4      | 21.98           | 22.20           | 22.53           | 22.76           |
| –2      | 21.12           | 21.29           | 21.71           | 22.00           |
| 0       | 20.27           | 20.37           | 20.87           | 21.23           |
| 2       | 19.44           | 19.44           | 20.03           | 20.45           |
| 4       | 18.60           | 18.60           | 19.19           | 19.66           |

The values of iso-comfort parameters (air temperature, air mobility, average radiation temperature) and thermal resistance of clothes are substituted into the formula of equivalent temperature and then the equivalent comfortable temperature is calculated.

$$t_{eqc} = 0.55t_{ac} + 0.45\overline{t_{rc}} + \frac{0.24 - 0.75v_{ac}}{1 + t_{cl}} (36.5 - t_{ac}),$$

where $t_{ac}$ is the comfortable air temperature, °C; $\overline{t_{rc}}$ is the comfortable average radiation temperature, °C; $v_{ac}$ is the comfortable air velocity, m/s; $t_{cl}$ is the thermal resistance of clothing, clo.

As a result, based on the data of Table 2, we determine the values of the equivalent comfortable temperature if the thermal resistance of clothes is 1.0 clo and the metabolic rate is 1.1 met (table 3).

Table 3. Equivalent comfortable temperature for the following conditions: thermal resistance of clothing is 1.0 clo, metabolic rate is 1.1 met.

| PMV = +0.49 |
|-------------|
| Δt_r, °C    | $v = 0.05$, m/c | $v = 0.1$, m/c | $v = 0.15$, m/c | $v = 0.2$, m/c |
|-------------|-----------------|-----------------|-----------------|-----------------|
| –4          | 24.61           | 24.47           | 24.38           | 24.26           |
| –2          | 24.63           | 24.47           | 24.42           | 24.37           |
| 0           | 24.66           | 24.45           | 24.46           | 24.45           |
| 2           | 24.73           | 24.41           | 24.50           | 24.53           |
| 4           | 24.79           | 24.37           | 24.52           | 24.60           |

Equivalent comfortable temperature is 24.61 °C

| PMV = –0.49 |
|-------------|
| Δt_r, °C    | $v = 0.05$, m/c | $v = 0.1$, m/c | $v = 0.15$, m/c | $v = 0.2$, m/c |
|-------------|-----------------|-----------------|-----------------|-----------------|
| –4          | 20.70           | 20.42           | 20.38           | 20.30           |
| –2          | 20.78           | 20.41           | 20.44           | 20.41           |
| 0           | 20.86           | 20.39           | 20.48           | 20.50           |
| 2           | 20.96           | 20.36           | 20.51           | 20.58           |
| 4           | 21.05           | 20.43           | 20.55           | 20.66           |

Equivalent comfortable temperature is 20.65 °C

Consequently, the values of the equivalent comfortable temperature for the conditions of thermal resistance of clothing of 1.0 clo and metabolic rate of 1.1 met for premises of comfort class B are:

- $t_{eqc} = 24.64$ °C if PMV = +0.49;
- $t_{eqc} = 20.65$ °C if PMV = –0.49.

Thus, the iso-comfort parameters given in Table 2 are summarized by a single value equivalent to a comfortable temperature.

Table 4 shows the results of calculations of the equivalent comfortable temperature for premises of comfort class B.
Table 4. Equivalent comfortable temperatures for premises of comfort class B.

| PMV = + 0.49 | 0.7 clo | 1.0 clo | 1.3 clo |
|--------------|--------|--------|--------|
| 1.1 met      | 26.66  | 25.28  | 23.93  |
| 1.2 met      | 26.07  | 24.61  | 23.19  |
| 1.3 met      | 25.69  | 24.18  | 22.71  |
| 1.4 met      | 24.92  | 23.31  | 21.75  |
| PMV = –0.49  | 0.7 clo | 1.0 clo | 1.3 clo |
| 1.1 met      | 23.73  | 21.77  | 19.85  |
| 1.2 met      | 22.76  | 20.65  | 18.58  |
| 1.3 met      | 22.13  | 19.91  | 17.75  |
| 1.4 met      | 20.86  | 18.45  | 16.09  |

For convenience of practical application, the calculation results are approximated using the built-in subroutines of the Excel spreadsheet editor in the form of exponential functions:

- for PMV = +0.49, \( t_{eqc} = 40.23 \times 0.77 \times met \times 0.82 \times clo; \)
- for PMV = –0.49, \( t_{eqc} = 53.60 \times 0.77 \times met \times 0.70 \times clo. \)

The data generalizing the calculated expressions of the parameter of equivalent comfort temperature correspond to the required level of thermal comfort in the premises of comfort class B. Thus, a single generalizing criterion for determining the parameters of thermal comfort is obtained.

Table 5 shows the calculated expressions for the equivalent comfortable temperature for premises of all comfort classes according to the standard [1].

Table 5. Parameter of equivalent comfort temperature.

| Class of premises according to State Standard ГОСТ Р ИСО 7730 | Predicted average PMV score, points | Equivalent comfortable temperature, °C |
|-------------------------------------------------------------|------------------------------------|----------------------------------------|
| A               | +0.19                              | \( t_{eqc} = 43.04 \times 0.72 \times met \times 0.79 \times clo; \) |
|                 | –0.19                              | \( t_{eqc} = 48.32 \times 0.64 \times met \times 0.73 \times clo; \) |
|                 | +0.49                              | \( t_{eqc} = 40.23 \times 0.77 \times met \times 0.82 \times clo; \) |
| B               | –0.49                              | \( t_{eqc} = 53.60 \times 0.58 \times met \times 0.70 \times clo; \) |
| C               | +0.69                              | \( t_{eqc} = 38.63 \times 0.80 \times met \times 0.84 \times clo; \) |
|                 | –0.69                              | \( t_{eqc} = 44.25 \times 0.65 \times met \times 0.72 \times clo; \) |

The calculated expressions of the comfort parameters of the microclimate using the equivalent comfort temperature, obtained from formula (1), have the form:

- comfortable air temperature

\[
 t_{ac} = \frac{t_{eq} - 0.45\Delta T_{rc} - \frac{0.24 - 0.75\sqrt{v_{ac}}}{1 + I_{cl}}}{1 - \frac{0.24 - 0.75\sqrt{v_{ac}}}{1 + I_{cl}}};
\]

(2)

- comfortable average radiation temperature

For PMV = +0.49, \( t_{eqc} = 40.23 \times 0.77 \times met \times 0.82 \times clo; \)

For PMV = –0.49, \( t_{eqc} = 53.60 \times 0.77 \times met \times 0.70 \times clo. \)
\[ \Delta T_{rc} = \frac{t_{eqc} - t_{ac} - 0,24 - 0,75 \sqrt{v_{ac}} (36,5 - t_{ac})}{1 + I_{clo}} \];

- comfortable air velocity

\[ v_{ac} = \left[ \frac{0,24 - t_{eqc} - 0,45 \Delta T_{rc} (1 + I_{clo})}{36,5 - t_{ac}} \right] \frac{2}{0,75} \].

As the approbation, the parameter of equivalent comfort temperature proposed in this work, we will determine the necessary average radiation temperature in the premise of comfort class B.

The life support system maintains an air temperature of 25 °C in the room, the air mobility is 0.3 m/s, staff’s clothing has a characteristic of 1.1 clo, the level of metabolism during work is 1.15 met.

From the expressions for the equivalent comfortable temperature for the premises comfort class B (table 5), we calculate the equivalent comfortable temperature:

- for PMV = +0.49, \( t_{eqc} = 23.83 \) °C;
- for PMV = –0.49, \( t_{eqc} = 19.39 \) °C.

As a result of the calculation using formula (3), the following values were obtained for the desired average radiation temperature:

- for PMV = +0.49, \( t_{rc} = 24.49 \) °C;
- for PMV = –0.49, \( t_{rc} = 14.60 \) °C.

Thus, to ensure the state of comfort of the corresponding premise of class comfort B, given the initial data, the average radiation temperature should be in the range of 14.6 °C to 24.5 °C.

3. Conclusion

The method of determining the necessary combinations of microclimate parameters and personal parameters that provide the required level of thermal comfort in accordance with the State Standard ГОСТ Р ИСО 7730 is considered. It is proposed to use an empirically derived calculation expression for the equivalent temperature, on the basis of which a generalizing parameter of the equivalent comfort temperature is obtained, which corresponds to the required level of thermal comfort in the room. Six calculated data arrays with thermal comfort parameters for premises of comfort classes A, B and C are summarized by six algebraic expressions. These calculated expressions of equivalent comfortable temperature can be used in the design of air conditioning systems and in programming of automatic climate control systems.

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