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PII: S2352-7102(16)30037-7
DOI: http://dx.doi.org/10.1016/j.jobe.2016.04.003
Reference: JOBE119

To appear in: *Journal of Building Engineering*

Received date: 11 February 2016
Revised date: 6 April 2016
Accepted date: 16 April 2016

Cite this article as: Ferenc. Kalmár, Summer operative temperatures in fre running existing buildings with high glazed ratio of the facades, *Journal o Building Engineering,* http://dx.doi.org/10.1016/j.jobe.2016.04.003

Summer operative temperatures in free running existing buildings with high glazed ratio of the facades

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Abstract: Nowadays, low energy and low exergy solutions are widely used for new buildings, but existing buildings have high energy demand because of poor thermal properties of their envelope. The situation is worse in summer period in case of buildings built before 1970 with large transparent areas on the facades. The high summer outdoor temperatures and the increased number of heat waves can lead to extremely hot indoor environments or extremely high cooling energy use in these buildings. In this paper indoor operative temperatures and PMV were calculated in east and west oriented offices using measured meteorological parameters and the methodology given by EN ISO 13790. Furthermore, indoor comfort parameters were measured using TESTO 480 instrument. The operative temperature was calculated based on the measured air and globe temperatures in different locations of a room. The effect of lace curtains and drapes on the operative temperatures was analysed.

Keywords: globe temperature, operative temperature, thermal comfort, predicted mean vote

1. **Introduction**

Energy saving is one of the key priorities in the building sector. New buildings have to meet the minimum requirements related to energy performance. The same requirements have to be fulfilled in case of major renovation of existing buildings. Moreover, in European Union, Member States shall ensure that by 31 December 2020, all new buildings are nearly zero-energy buildings, [1]. Energy balance of buildings has to be analyzed for a whole year including the heating, cooling and transition periods. Glazed ratio of the facades is one of the key parameters which have to be optimised in order to obtain the minimal energy demand of a building. Solar gains in the winter, heat load in the summer, daylighting, transmission heat losses and gains should be properly balanced to obtain the optimal transparent area. The energy analysis can be done by using sophisticated simulation programs, [2-4].

However, without appropriate climatic input parameters, the results can be misleading. Unfortunately, the European climate change demonstrated by Luterbacher et al., [5] especially in summer period, has negative effects both on the energy saving efforts and on the indoor thermal comfort in buildings. According to Schär et al. the European summer climate might experience a pronounced increase in year-to-year variability in response to greenhouse-gas forcing, [6]. Coley and Kershaw analyzed the relationship between increases in external temperature due to climate change and increases in internal temperatures, [7]. They found that the relationship is linear, and differing architectures give rise to differing constants of proportionality. Kwok and Rajkovich argued that adaptation to climate change should be added to building codes and standards and the thermal comfort standards should be redefined, [8]. Jenkins et al. proposed a probability curve to estimate future overheating of a building, [9].

Smart architectural solutions leading to proper thermal comfort in buildings can be applied in case of new buildings, which are planned and constructed in an energy conscious way, [10-15]. The existing building stock is extremely various. Building structure and geometry, building materials and technology, glazed ratio of the facades and thermal characteristics of the envelope are the main factors which influence the energy performance of buildings. In case of educational buildings built between 1950 and 1970 in Hungary, reinforced concrete frame structure and large glazed areas were currently used. Even though thermal refurbishment of these buildings was started, a quite high number of buildings are operating in their original structural conditions. It is true that in summer period, the work in educational buildings is interrupted, but extremely high indoor temperatures could be registered even in May or September. In this paper the results of a series of measurements carried out in an educational building are presented and analysed from energy and thermal comfort point of view.

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2. **Equations used for calculation of the operative temperature and predicted mean vote**

The operative temperature is what humans experience thermally in a space; it is the combined effects of the mean radiant temperature and air temperature. The predicted mean vote (PMV) refers to the thermal comfort sensation scale that runs from cold (-3) to hot (+3).

The calculation method uses the RC (Resistance-Capacitance) network of the heat flows, as shown in Figure 1, [16].

Heat transfer by ventilation, H_{ve}, is directly connected both to the air temperature node, θ_{air}, and to the node representing the supply temperature, θ_{sup}. Heat transfer by transmission is split into the window segment, $H_{tr,w}$, which is assumed to have zero thermal mass, and the remainder, $H_{tr,op}$, which contains the thermal mass split into two parts, $H_{tr,em}$ and $H_{tr,ms}$. Solar and internal gains are distributed over the air node, θ_{air}, the central node θ_{s} (a mix of θ_{air} and mean radiant temperature) and the node representing the mass of the building zone, θ_{m}. The thermal mass is represented by a single thermal capacity, C_m, that is located between $H_{tr,ms}$ and $H_{tr,em}$. A coupling conductance is defined between the internal air node and the central node. The heat flow rate given by internal heat sources, Φ_{int}, and solar heat sources, Φ_{sol}, is split among the three nodes (EN ISO 13790:2008, 2008). The internal heat capacity of the

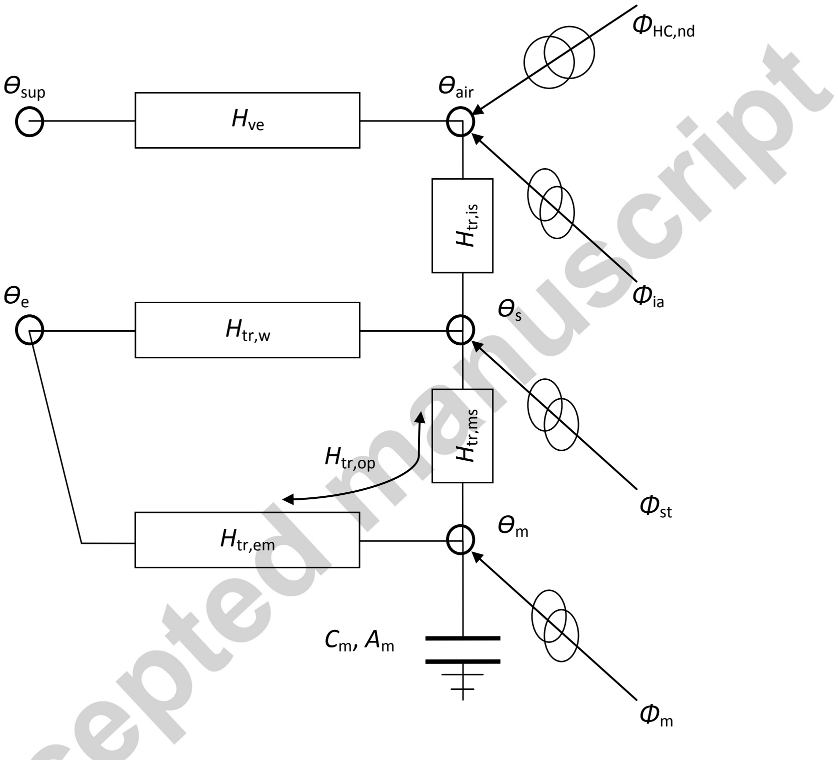
building zone, C_m, [J/K], was calculated for a maximum thickness of 10 cm. The solution model is based on a Cranck-Nicholson scheme, considering a time step of one hour, [16].
The air temperature is given by eq. (1), [16]:

$$\theta_{air} = \left(H_{tr,is}\theta_s + H_{ve}\theta_{\sup} + \Phi_{ia} + \Phi_{HC,nd}\right)/\left(H_{tr,is} + H_{ve}\right) \qquad (1)$$

where $H_{\mathrm{tr,is}}$ is the transmission heat transfer coefficient, [W/K]; H_{ve} is the ventilation heat transfer coefficient, [W/K]; and $\Phi_{\mathrm{HC,nd}}$ – is the cooling need of the building, [W].

$$\Phi_{ia} = 0.5\Phi_{\mathrm{int}} \qquad (2)$$

where Φ_{int} is the heat flow rate from internal heat sources [W].



The node temperature, θ_s, is given by eq. (3), [16]:

$$\theta_s = \left\{H_{tr,ms}\theta_m + \Phi_{st} + H_{tr,w}\theta_e + H_{tr,1}\left[\theta_{\sup} + \left(\Phi_{ia} + \Phi_{HC,nd}\right)/H_{ve}\right]\right\}/\left(H_{tr,ms} + H_{tr,w} + H_{tr,1}\right) \qquad (3)$$

where θ_e is the temperature of the external environment [°C].

$$H_{tr,1} = \frac{1}{1/H_{ve} + 1/H_{tr,is}} \qquad (4)$$

$$\Phi_{st} = \left(1 - \frac{A_m}{A_t} - \frac{H_{tr,w}}{9.1A_t}\right)\left(0.5\Phi_{\mathrm{int}} + \Phi_{sol}\right) \qquad (5)$$

where A_{t} is the area of all surfaces facing the building zone [m^2].

The coupling conductance between nodes m and s, [W/K], is given by eq. (6), [16]:

$$H_{tr,ms} = h_{ms} A_m \tag{6}$$

where h_{ms} is the heat transfer coefficient between nodes m and s [W/m^{2}K] and A_m is the effective mass area [m^2].

The operative temperature (θ_{op}) is obtained based on the air temperature and mean radiant temperature, using eq. (9), [16]:

$$\theta_{op} = 0.3\theta_{air} + 0.7\theta_s \tag{7}$$

The predicted mean vote (PMV) can be calculated with the well known equation, [17]:

$$\begin{aligned} PMV = {} & \left(0.303\exp\left(-0.036M\right) + 0.028\right)\left\{\left(M - W\right) - 3.05\times10^{-3}\times\left[5733 - 6.99\left(M - W\right) - p_a\right] - \right. \\ & - 0.42\times\left[\left(M - W\right) - 58.15\right] - 1.7\times10^{-5} M\left(5867 - p_a\right) - 0.0014M\left(34 - t_a\right) - \\ & \left. - 3.96\times10^{-8} f_{cl}\left[\left(t_{cl} + 273\right)^4 - \left(\bar{t}_r + 273\right)^4\right] - f_{cl} h_c\left(t_{cl} - t_a\right)\right\} \end{aligned} \tag{8}$$

where: t_a – is the indoor air temperature, [°C]; p_a is the water vapour partial pressure, in [Pa]; I_{cl} is the thermal resistance of clothing, [m^{2}K/W].

The clothing surface temperature can be determined using equation (9), [18].

$$t_{cl} = 35.7 - 0.028\left(M - W\right) - I_{cl}\left\{h_r f_{cl} 10^{-8}\left[\left(t_{cl} + 273\right)^4 - \left(\bar{t}_r + 273\right)^4\right] + f_{cl} h_c\left(t_{cl} - t_a\right)\right\} \tag{9}$$

where: M is the metabolic rate, [W/m^2] of body surface area; W is the external work, [W/m^2], equal to zero for most activities.

The radiative heat transfer coefficient h_r is given by equation (10), [18]:

$$h_r = 5.67\cdot10^{-8}\varepsilon\frac{A_r}{A_D}\frac{(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4}{(t_{cl} - \bar{t}_r)} \tag{10}$$

where the ratio of the body's 4π radiation area, A_r to A_D is 0,67 for crouching subject, 0.7 for the sitting and 0.73 for the standing position; ε – emittance of the clothed human body.

The clothing area factor f_{cl} can be determined using equation (11), [17]:

$$f_{cl} = \begin{cases} 1.00 + 1.290 I_{cl} & \text{for} \quad I_{cl} < 0.078\,\mathrm{m^2K/W} \\ 1.05 + 0.645 I_{cl} & \text{for} \quad I_{cl} > 0.078\,\mathrm{m^2K/W} \end{cases} \tag{11}$$

The convective heat transfer coefficient h_c, might be determined using equation (12), [17]:

$$h_c = \begin{cases} 2.38\left(t_{cl} - t_a\right)^{0.25} & \text{for} \quad 2.38\left(t_{cl} - t_a\right)^{0.25} > 12.1\sqrt{v_{ar}} \\ 12.1\sqrt{v_{ar}} & \text{for} \quad 2.38\left(t_{cl} - t_a\right)^{0.25} < 12.1\sqrt{v_{ar}} \end{cases} \tag{12}$$

where: v_{ar} is the relative air velocity (relative to the human body), in m/s.

The mean radiant temperature is given by equation (13), [17]:

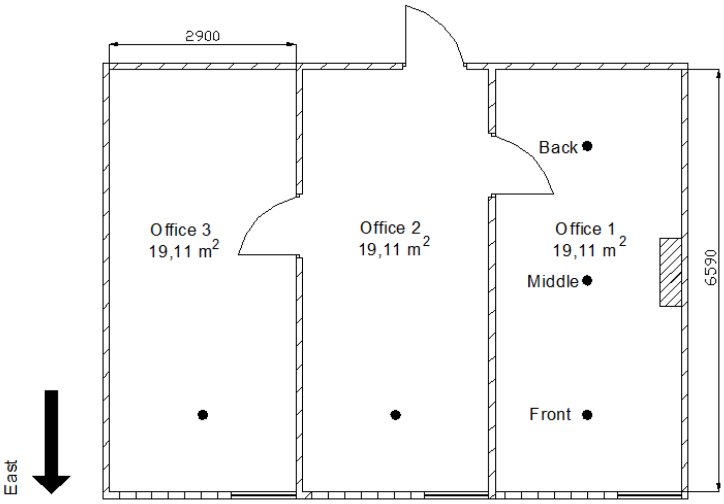
$$\bar{t}_r = \sqrt[4]{\sum_{i=1}^{n} F_{P-A_i} T_{si}^4} - 273 \tag{13}$$

3. **Case study**

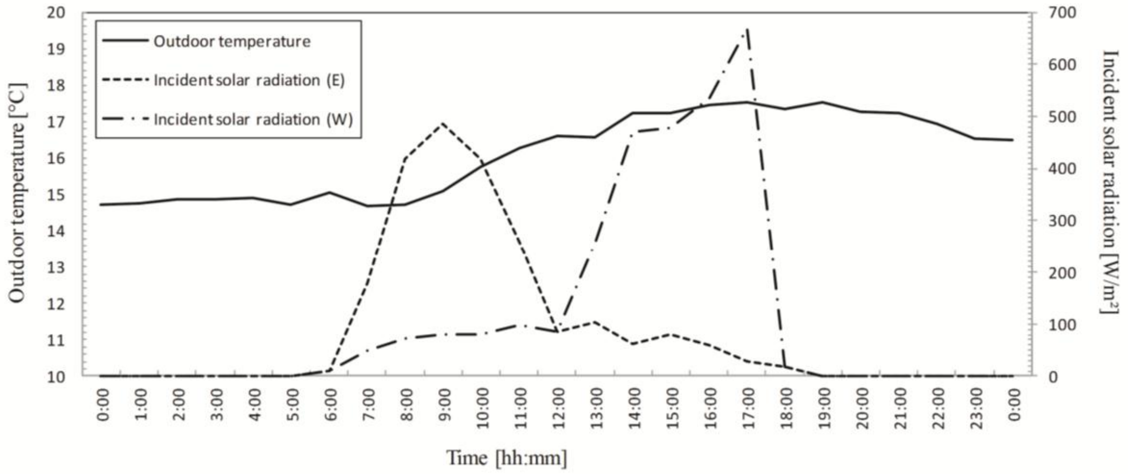
A series of measurements have been performed during the year 2015 in an educational building built between 1965 and 1970 and enlarged in 1990. The oldest building section has five levels and concrete reinforced structure. The facades were built using U profile wired glass and double glazed wood frame windows (Fig. 2, East facade). The enlargement was built on the West facade, using concrete reinforced pillars and slabs but the opaque structure of the facade is larger in comparison with the East facade and brick with vertical holes was used (30 cm thickness) covered by 5 cm thick expanded polystyrene (Fig. 2).

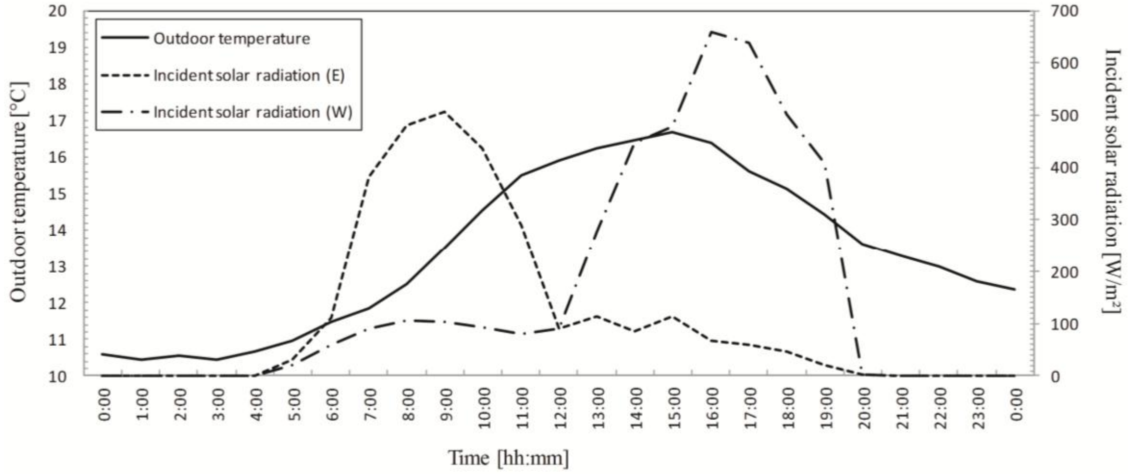
Because of the reinforced concrete frame structure room modules were obtained. Offices can have one, two or three modules. On the west facades there are some windows provided with rolling shutters (especially on 3rd-5th level) but on the ground floor and 1st floor no shading is provided. The situation is worse on the east facade, because there is no shading or protection against the solar radiation neither for windows nor for transparent walls. Of course, during the hottest months of the year (July and August) the educational activity in the building is not intensive, however there are employees working in the building. Furthermore, in May and September the educational activities are running in the building. The net floor area of the whole building is about 12,000 m^2. The laboratories were already refurbished, but the oldest part of the building is still in its original state.

Four offices with similar geometry were chosen in order to investigate the operative temperature. Three offices are situated on the 3rd floor and have east orientation of the windows (Fig. 3), and one office is on the 1st floor, having west orientation.



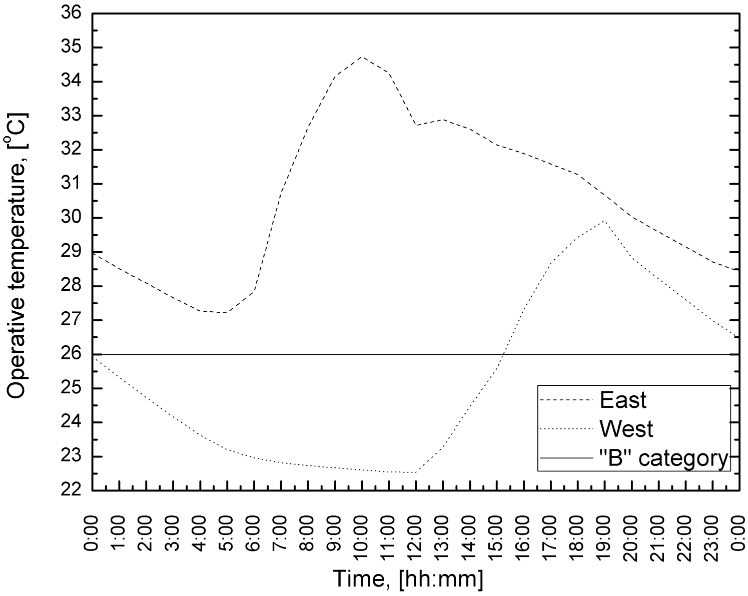
In the following the operative temperature will be analysed in the aforementioned offices. The meteorological data of the chosen days are shown in Figure 4 and 5.

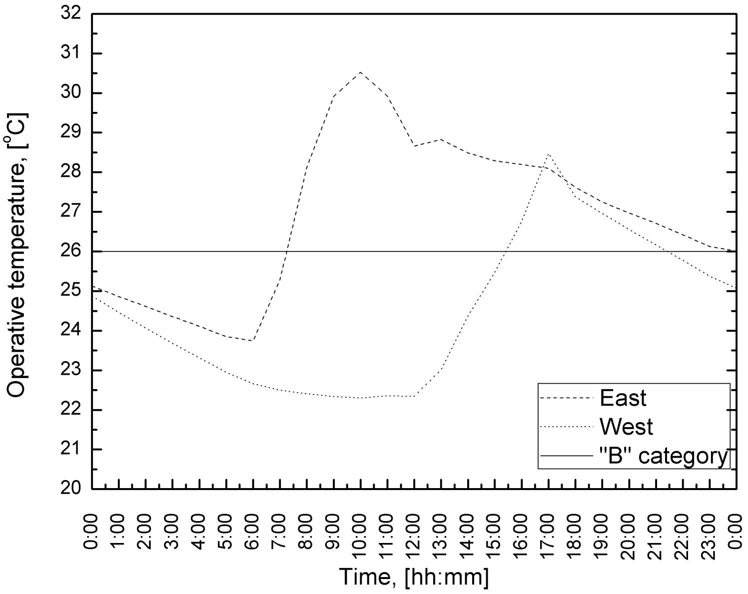




3.1 **Predicted operative temperatures**

In order to determine the operative temperatures in the analysed rooms, the methodology given by standard EN ISO 13790:2008 was used. The heat capacity of the east oriented offices are similar (C_{east}= 6.7 MJ/K) and the heat capacity of the west oriented office is a little bit lower (C_{west}= 5.8 MJ/K). Using Eq. 1-7 and the meteorological data given in Figures 4-5 the expected operative temperatures were calculated. The obtained results are shown in Figures 6-7. The predicted operative temperatures are correlated to 26 °C which is the highest operative temperature value required in a "*B*" comfort category office [19]. This value is valid for a *II*. category office specified by standard EN 15251, [20]. It can be observed that the differences between the required and calculated values are significant; consequently proper thermal comfort could be obtained only installing air conditioning devices. Assuming the clothing thermal insulation of 0.5 clo (ISO 9920:2007, Men: underpants, shirt with short sleeves, light trousers, light socks, shoes; Women: bra, panties, shirt with short sleeves, skirt, sandals) [21], and the activity level of 70 W/m^2 (sedentary activity; ISO 8996:2004) [22], the calculated PMV values were higher than 3.0 (hot environment), which means practically 100% dissatisfied.





3.2 **Instruments and measured temperatures**

In order to analyze the thermal environment in the building, measurements were performed during the year 2015. The indoor comfort parameters have been measured with calibrated TESTO 480 instruments.

The air temperature, globe temperature, air velocity, relative humidity is measured simultaneously and the PMV value is calculated and displayed. The accuracy of the probes is the following:

- globe temperature: globe probe Ø150 mm, TC Type K, accuracy: ±(0.3 °C + 0.1 % of measured value);
- air temperature: probe accuracy: ±0.4 °C;
- relative humidity: probe accuracy: ±2% RH (+2 to +98% RH);

- air velocity probe accuracy: ±(0.03 m/s +5% of measured value).

Using the measured globe temperature (t_g) the mean radiant temperature can be determined using the following relations, [23]:

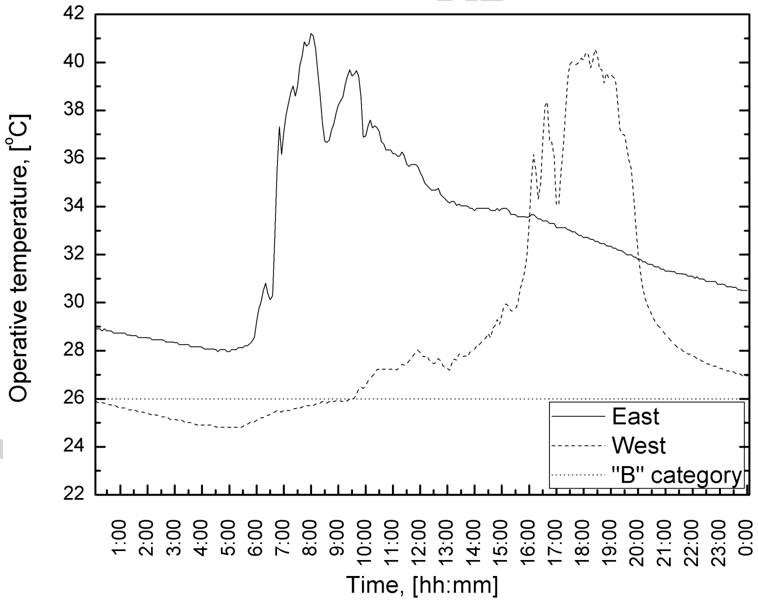
- natural convection

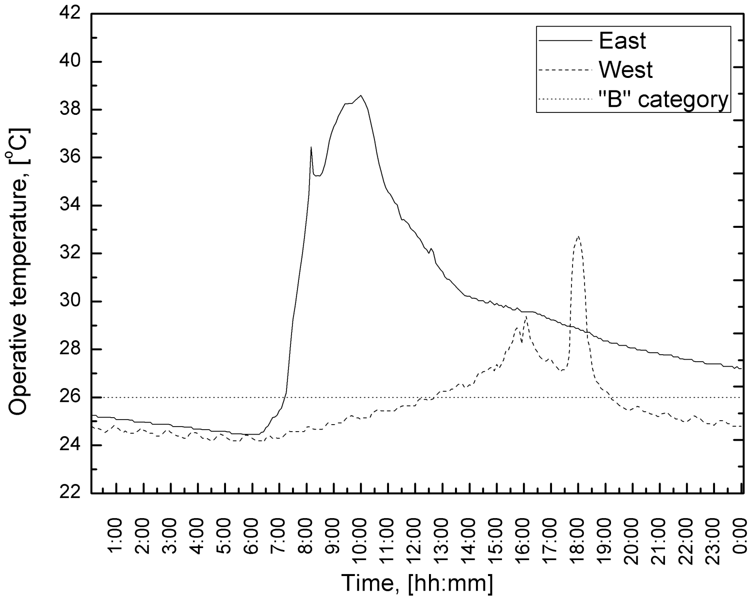
$$\bar{t}_r = \left[\left(t_g + 273\right)^4 + 0.4 \times 10^8 \left|t_g - t_a\right|^{0,25} \times \left(t_g - t_a\right) \right]^{0,25} - 273 \tag{14}$$

- forced convection:

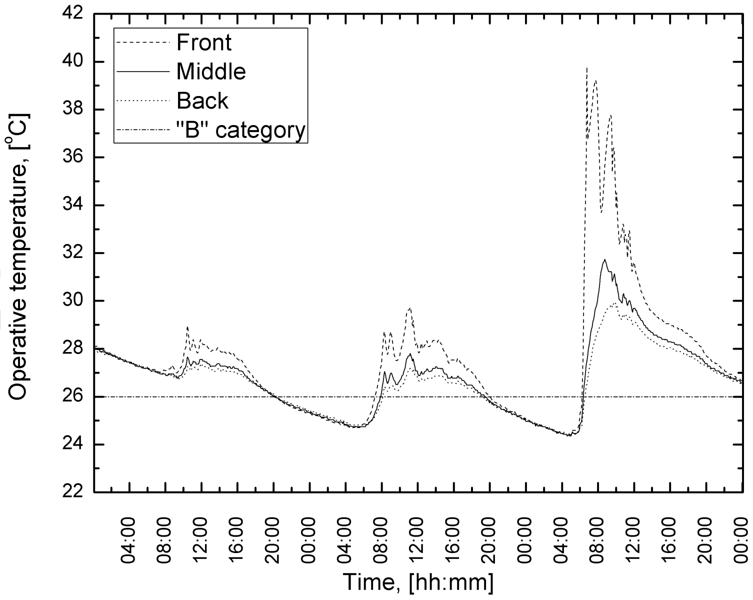
$$\bar{t}_r = \left[\left(t_g + 273\right)^4 + 2.5 \times 10^8 \times v_{ar}^{\,0,6} \left(t_g - t_a\right) \right]^{0,25} - 273 \tag{15}$$

The instruments were placed in the location of the workplaces in the analysed offices. The probes were fixed at 1.1 m height. In all cases the desk is settled near the window, so the chair of the employee is at 1.5 m distance from the external building element (Fig. 3). The external transparent element is on the left side of the sitting person in all cases. In the Office no. 1 there is a 3.6 kW split air conditioning system installed under the ceiling (Fig. 3). In Figures 9 and 10 the operative temperature values are shown in office no 1 (east orientation) and the office having west orientation of the external transparent element. During these days no air conditioning system was in operation, no shading element was used, the windows and doors were closed. These operative temperatures were registered on the days with meteorological data shown in Figures 4 and 5.

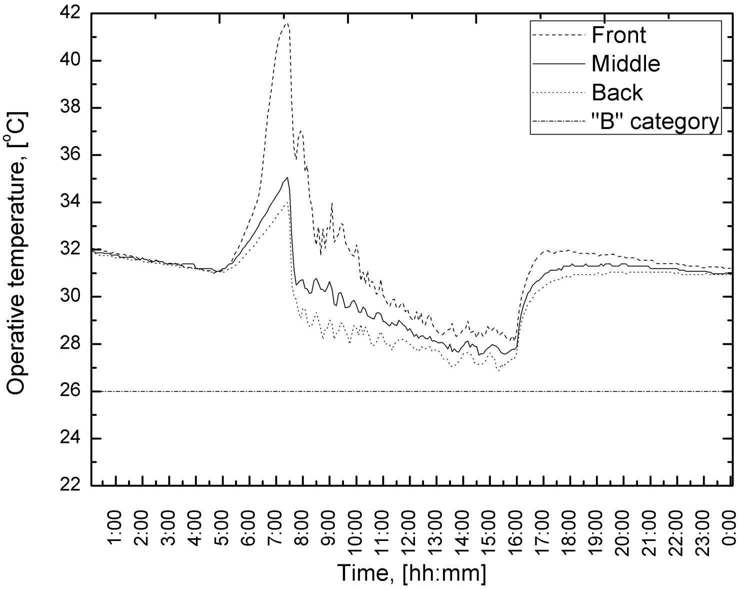




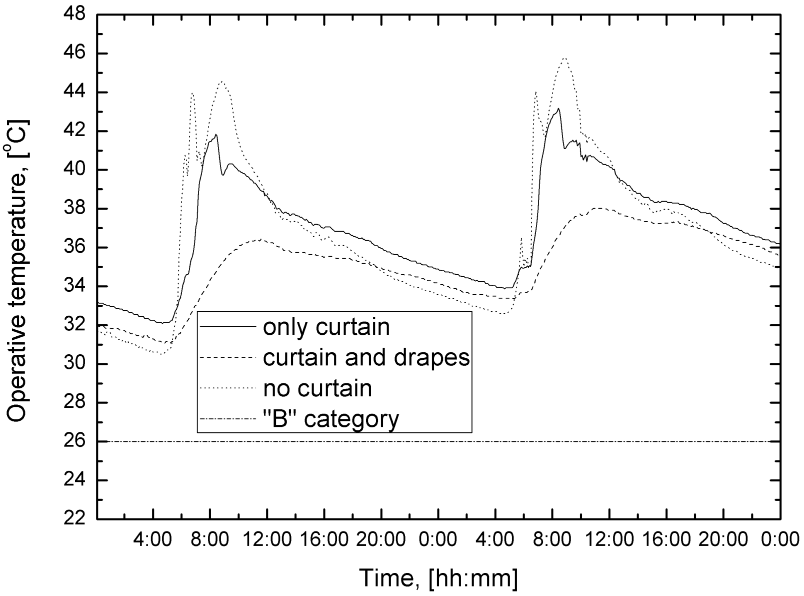
It can be observed that there are huge differences between the calculated and measured operative temperature values, especially in the period of the day with high direct solar radiation. The situation is worse in case of east orientation. In order to investigate the differences between the operative temperatures in different locations of a room, in office no. 1 using three TESTO 480 instruments the operative temperature was measured at a distance of 1.5 m from the external building element, in the middle of the room and at a distance of 1.5 m from the internal wall, opposite to the external building element, according to Figure 3. The measured operative temperature values, for three consecutive days, are shown in Figure 11 (no air conditioning, no shading, windows and doors were closed).



Analysing the operative temperature values, it can be stated that these days were part of a heat wave. The influence of the location on the operative temperature increased at higher external temperatures and solar radiations. In the office no. 1 measurements were carried out in order to see the influence of the air conditioning system on the operative temperatures in the three measuring points. The air conditioning system was switched on at 7:00 a.m. and switched off at 4:00 p.m. The air temperature was set to 26 °C. The windows and doors were closed, no shading device was used. The operative temperatures are presented in Figure 12.



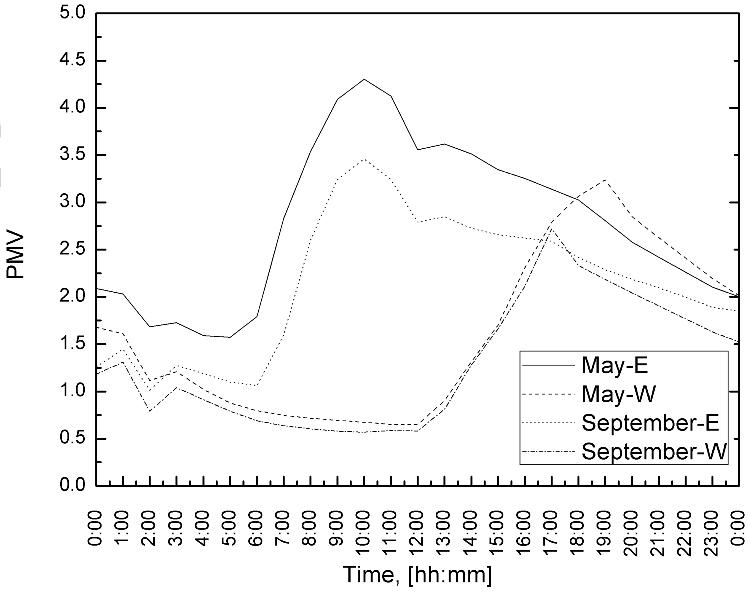
It can be observed that there are quite important differences between the operative temperatures in different locations of the room. Naturally, the highest values were registered on the workplace of the employee, since this point is the closest to the external transparent element. Setting the air temperature to 26 °C, the operative temperature prescribed for “B” comfort category couldn’t be met because of extremely high mean radiant temperature values. Since there are no external shading devices installed, in the following, in the east oriented offices located next to each other (Fig. 3) simultaneous measurements were carried out in order to see the effects of lace curtains and drapes on the operative temperatures. In office no. 1 a simple lace (translucent) curtain was hung, on the office no. 2 an opaque drape and a simple lace (translucent) curtain were hung and in office no. 3 no curtain and no drape was hung on the internal side of the external transparent wall and window. The operative temperature values, measured on the location of the workplace, are shown in Figure 13 (no air conditioning, windows and doors were closed).

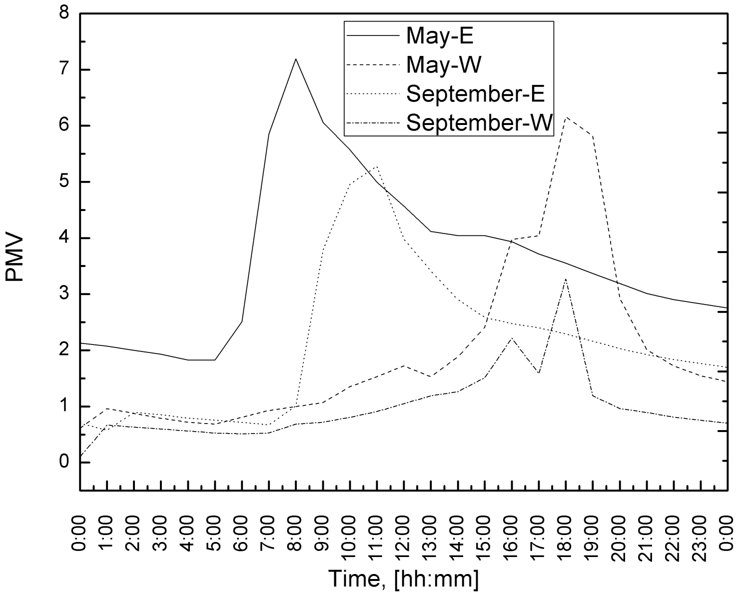


It can be observed that, in the period from 8:00 to 12:00, there are significant differences between the operative temperature values. Unfortunately, even the lowest values are much higher than the required 26 °C ("B" comfort category).

4. **Discussion**

According to ISO 7730 the PMV values should be between −0.5 and +0.5 in case of a "B" comfort category building. Similarly, EN 15251 prescribe for II building category PMV between −0.5 and +0.5. Taking into consideration the expected indoor comfort parameters and those measured with TESTO 480 instrument, PMV was calculated. For offices having east and west orientation of the glazed areas the PMV values are shown in Figure 14 and 15. Subjective thermal comfort sensation can be evaluated on the seven point scale. On this scale the +3 value corresponds to "hot" environment. However, introducing the calculated indoor comfort parameters in eq. 8, in some periods of the day, the PMV values obtained, especially for east orientation of the transparent elements, were higher than 3.





The PMV calculated based on the measured indoor parameters exceeds considerably the PMV based on the predicted indoor parameters. This is caused especially by the direct solar radiation which is high behind the transparent elements. Furthermore, in case of east oriented facade, the U profiled transparent wall absorbed important heat quantity and its temperature increase above 40 °C. This element “operates” similar to a radiant surface during the day.

Analysing the operative temperatures measured under different conditions it can be stated that, in old buildings with large transparent surfaces the operative temperature values prescribed by CR 1752 and EN 15251 standards hardly can be meet without air conditioning systems. The obtained results harmonize well with the outcomes of previous research reports related to the summer indoor environment assessment in free running buildings, [24, 25].

Nevertheless, there are simple solutions which can help in improving the thermal sensation of occupants. In educational or office buildings, where the working hours are from 8:00 to 16:00, the west orientation of glazed elements is advantageous both from thermal comfort and energy point of view. In offices with east orientation, location of workplaces near the external transparent surfaces has to be avoided. Of course, in this case daylighting cannot be the sole source of light, but daylighting glare is anyway disadvantageous. If external shading is not possible, because there is no financial possibility for such investment, internal shading should be used. Installing drapes and curtains, the PMV can be ameliorated. As it was proved by Csáky, the thermal comfort sensation can be further improved by night ventilation and natural ventilation, [26].

5. **Conclusions**

In case of existing buildings with large transparent surfaces on the facades, extreme hot indoor environments may occur even in May or September. In such environments the occupants cannot perform the daily activities. In order to predict the thermal comfort in buildings, different calculation methods can be used. However, in rooms with large transparent surfaces, important differences may appear between the predicted and measured indoor temperatures. It was shown that even though the heat gains are calculated using the real incident solar radiations and outdoor temperatures, the measured operative temperature exceeds significantly the predicted value. Nevertheless, the differences between calculated and measured operative temperature values in a room depend on the location of the measurements. In case of buildings with large transparent surfaces on the facades, calculating the operative temperature and PMV in the middle of a room is misleading. In such buildings, choosing properly the location of the workplace in a room (avoiding the effects of direct solar radiation), important cooling energy savings can be obtained. Where possible west oriented rooms should be used for offices, if the working hours are between 8:00 and 16:00.

Acknowledgments

The author would like to express his gratitude for Agro-Meteorological Observatory Debrecen for providing indispensable meteorological data.

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Figure 1. RC network heat flows

Figure 2. East (left) and west (right) facades of the analysed building

Highlights

- operative temperatures were calculated in offices with large transparent areas
- indoor thermal comfort parameters were measured using TESTO 480 calibrated instrument
- calculated and measured operative temperatures were compared
- the operative temperature was determined in three different points of a room
- the effect of curtains on the operative temperature was analyzed