
NUMERICAL EVALUATION OF THERMAL DISCOMFORT IN CONDITIONS OF SURFACE HEATING AND ASYMMETRIC RADIATION

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This paper presents the results of analytical analysis of thermal comfort and radiation asymmetry in case of wall heating depending on the room geometry and thermal properties of the external wall. The negative effects of radiation asymmetry on thermal comfort in case of summer conditions can be lowered using advanced personalized ventilation systems. In case of buildings with poor thermal properties of the envelope during the winter period low surface temperatures may occur. The aim of this research was to analyse the thermal asymmetry in the case of a room with one external wall and wall heating installed on the opposite wall. It was assumed that the radiation asymmetry will lead to discomfort and it was hypothesised that the discomfort might be reduced increasing the air velocity. The results have proven that thermal asymmetry in the middle of the room will not lead to thermal discomfort even for walls without any additional thermal insulation. However, the mean radiant temperature varies significantly depending on the position of the occupant in the room. In this case, the personalized control on the air velocity can help to improve the thermal comfort conditions.

Keywords: radiation asymmetry, thermal comfort, wall heating, thermal refurbishment

1. Introduction

Energy saving is one of the most important issues in the building sector. However, the measures aiming the reduction of energy use cannot overwrite the thermal comfort requirements, since the healthy environment and the well being of occupants are primordial for architects and HVAC engineers. By improving the thermal properties of the building envelope the energy needs are reduced considerably. Aerogel and nanotechnological insulation materials are developed and investigated to increase the efficiency of additional thermal insulation layer, [1, 2]. In the case of properly insulated buildings the thermal asymmetry may occur because of the transparent surfaces. The effects of solar radiation can be evaluated calculating an increase in MRT equivalent to shortwave gains from direct, diffuse, and indoor-reflected radiation [3]. A series of measurements involving 20 subjects was carried out under controlled environmental conditions to investigate subjective thermal comfort in the case of asymmetric radiation combined with the personal-

ized ventilation [4]. Analysis showed agreement between the subjective thermal comfort sensation without a personalized ventilation system and the calculated PMV. However, there was significant difference between the responses of female and male participants. It appears that the advanced personalized ventilation system lowers the subjective thermal comfort sensation but does it differently for men and women. The skin temperatures of the hands of the women were significantly lower than that of the men. In the case of men, radiation asymmetry led to significant differences in the facial skin temperature, while in the case of women, the differences in the facial skin temperature were not significant.

The envelope of millions of buildings is not provided with thermal insulation layer at all, thus the inner surface temperature of external building elements is low, while the surface temperature of heating equipment is high because of the substantial heat losses. So, the radiation asymmetry has to be analysed in order to avoid the thermal discomfort. Ghali et al. attempted to establish the effect of the asymmetric radiation

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field of stoves on thermal comfort, [5]. To predict the overall thermal comfort and local thermal discomfort, they developed a bioheat model [5, 6]. Their model agreed well with the experimentally reported data on local and mean skin temperatures under asymmetric radiation conditions and the corresponding heat loss from the human body, [7].

Fanger et al. established the comfort limits of radiation asymmetry, [8]. They established for cool walls, warm walls, and cool ceilings, curves showing the percentage of dissatisfied subjects as a function of the radiant temperature asymmetry. The radiant temperature asymmetry is given by the plane radiant temperature differences and the angle factors can be determined using the equations given by ISO 7726, [9].

The aim of this research was to evaluate the discomfort in a room having wall heating (warm wall) and poor thermal properties of the external wall (cold wall). The warm and cold walls are assumed to be placed on the opposite side of the room. These calculations preceded a series of measurements performed in a climate chamber involving 20 subjects (10 male and 10 female) in order to investigate the subjective evaluation of thermal asymmetry and the effect of elevated air velocity on the thermal comfort sensation. The length of this paper does not allow the presentation of the results of measurements, so these are going to be presented in another paper.

2. Mean radiant temperature and plane radiant temperature

In comfort standards the requirements are established for different building functions separately for summer and winter periods. The better the comfort category the stricter the requirement is. One of the parameters taken into account is the operative temperature. It is well known that the operative temperature is the average of the mean radiant and indoor air temperatures weighted by their respective heat transfer coefficients:

$$t_0 = \frac{h_r \bar{t}_r + h_c t_a}{h_r + h_c}, \quad (1)$$

where \bar{t}_r – is the mean radiant temperature, [°C]; t_a – is the indoor air temperature, [°C]; h_c – is the convective heat transfer coefficient, [W/m²K]; h_r – is the heat transfer coefficient by radiation, [W/m²K].

The heat transfer coefficient by convection can be determined depending on the air and clothing temperature difference (t_{cl}) or relative velocity of the air (v_{ar}), [10]:

$$h_c = \begin{cases} \tilde{t} & \text{for } \tilde{t} > \tilde{v} \\ \tilde{v} & \text{for } \tilde{t} < \tilde{v} \end{cases}, \quad (2)$$

where $\tilde{t} = 2.38(t_{cl} - t_a)^{0.25}$, $\tilde{v} = 12.1\sqrt{v_{ar}}$.

The radiative heat transfer coefficient h_r is given by Eq. (3), [11]:

$$h_r = 5.67 \cdot 10^{-8} \varepsilon \frac{A_r}{A_D} \frac{(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4}{(t_{cl} - \bar{t}_r)}, \quad (3)$$

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 mean radiant temperature can be calculated by using the well known relation (4):

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

where T_{si} – is the internal surface temperature of building element i , [K]; F_{P-A_i} – is the angle factor between the person and area A_i .

According to Fanger's theory the angle factors values depend on the position of the occupant in the room being determined for six cases, [12]. The sum of angle factors is 1. The angle factors might be determined using Eq. (5), [13]:

$$F_{P-A} = F_{\max} \left[1 - \exp \left\{ -\frac{a/c}{A + B(a/c)} \right\} \right] \times \left[1 - \exp \left\{ -\frac{b/c}{C + D(b/c) + E(a/c)} \right\} \right], \quad (5)$$

where a , b – are the dimensions of the rectangular element; c – is the distance between the person and the rectangular element.

The discomfort caused by asymmetric radiation can be determined depending on the difference between the plane radiant temperatures (t_{pr}) of the two opposite sides of the person:

$$\Delta t_{pr} = t_{pr1} - t_{pr2}. \quad (6)$$

The formula of the plane radiant temperature is similar to the equation of the mean radiant temperature:

$$t_{pr} = \sqrt[4]{\sum_{i=1}^n F_{P-A_i} T_{si}^4} - 273. \quad (7)$$

The angle factors in this case can be calculated depending on the position of the analysed building area relative to the elementary reference area, [9, 14].

For both sides of the person the sum of angle factors is 1. The predicted percentage of dissatisfied in case of cold walls can be calculated using relation (8), [10]:

$$PD = \frac{100}{1 + \exp\{6.61 - 0.345\Delta t_{pr}\}}. \quad (8)$$

3. Results

The mean radiant temperature (MRT) and radiant asymmetry was analysed in a room with one external wall and wall heating on the opposite side of the room. The basic dimensions of the room are 3.0 m × 3.0 m

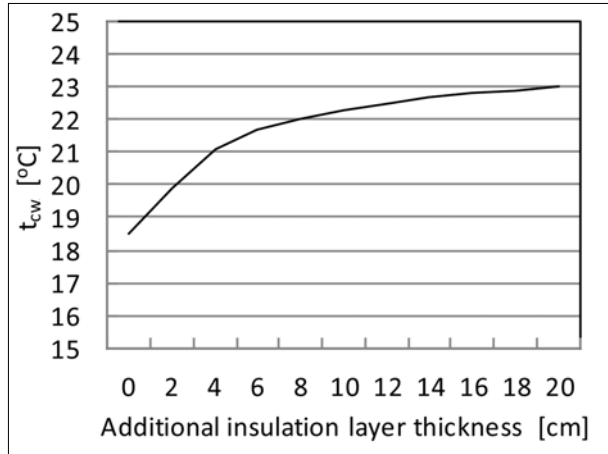


Fig. 1. Internal surface temperature of the cold wall

× 2.8 m. The MRT was analysed in different positions on the line between the cold and warm walls (the line is at equal distance between the two other walls). First the height and distance between the cold and warm wall was kept constant and the other dimension of the room was increased. Thereafter the distance between the cold and warm wall was increased and the other dimension of the room and the height were kept constant. The external wall of the room is assumed to be built from brick with vertical holes (type B30, used on large scale in Hungary especially between 1970–1990 years). The overall heat transfer coefficient of the wall is: $U_{wall} = 1.3 \text{ W/m}^2\text{K}$. The effect of additional external thermal insulation (EPS) was analysed too. Practice has shown that in Hungary in winter period most people prefer 24 °C indoor air temperatures. In these conditions, for $t_e = -10 \text{ °C}$, the internal surface temperature of the cold wall is presented in Fig. 1.

The warm wall temperature depends on the heat demand of the room. Assuming one person sitting in the room with activity level of 1.2 met, the heat demand and the warm wall temperature were determined (Fig. 2).

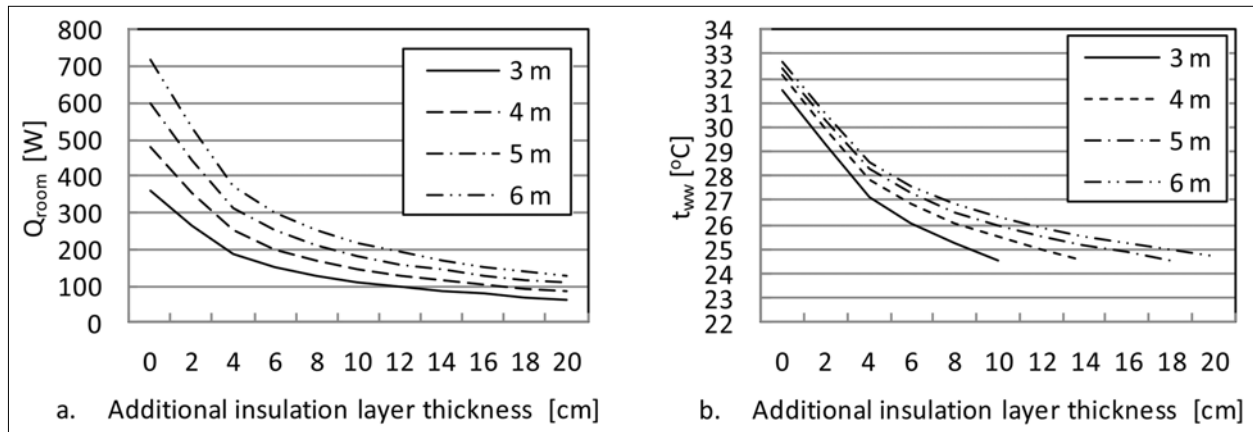


Fig. 2. Heat demand of the room (a) and warm wall temperature (b)

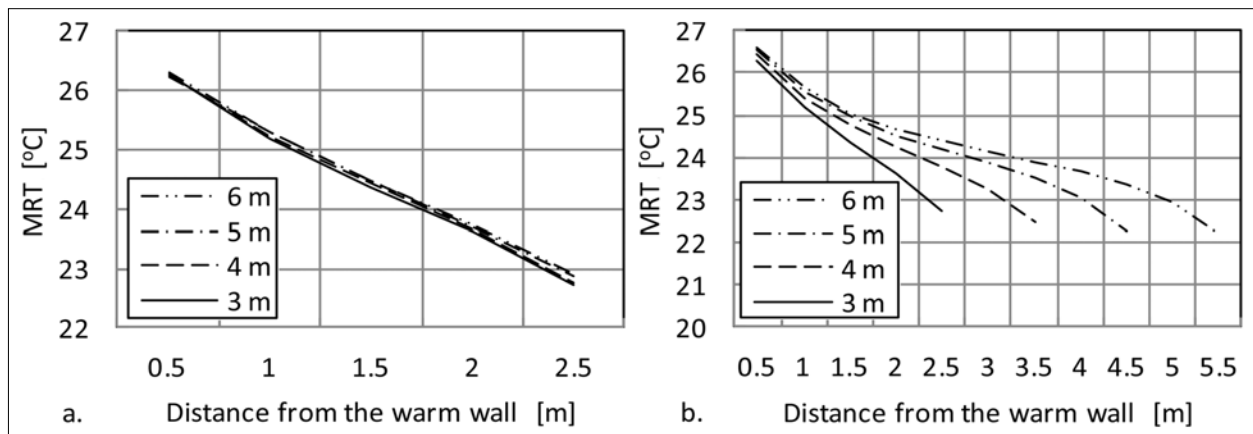


Fig. 3. MRT in the analysed room

Assuming the person sitting on the line between the cold wall and warm wall at equal distance from the other two walls, MRT was determined for different room geometries (Fig. 3). In Fig. 3a the MRT values are shown keeping the distance between cold and warm wall constant (3.0 m), while in Fig. 3b the MRT is presented for different distances between the cold and warm walls keeping the other dimensions of the room constant. These values were determined for cold wall without any additional thermal insulation.

The radiant asymmetry was determined only in the middle of the room with 3.0 m × 3.0 m × 2.8 m dimensions, without any additional thermal insulation on the external wall. In this case the temperature asymmetry was: $\Delta t_{pr} = 27.49 - 20.96 = 6.53$ K. According to ISO 7730, this plane temperature asymmetry will not lead to discomfort

4. Discussion

The mean radiant temperature varies about 4 K between the warm wall and cold wall. However, having the air temperature 24 °C even in the worst cases the operative temperature will be acceptable for occupants: closest to the cold wall, the operative temperature will be 23.11 °C, closest to the warm wall the operative temperature will be 25.3 °C (in the winter season the recommended value by ISO 7730 is 22 ± 1 °C in the “A” comfort category, respectively 22 ± 3 °C in the “C” comfort category). So, even in such cases the occupants probably will not complain by discomfort. Obviously, this can be assured by using high amount of energy.

In case of an old U profile wired glass external wall ($U = 3.0$ W/m²K) neglecting the solar radiation the internal surface temperature of the cold wall $t_{cw} = 11.25$ °C, the heat loss is 826.2 W (reference room), while the warm wall temperature should be 41.2 °C. These temperatures will lead to a mean radiant temperature variation between 21.5 °C (closest to the cold wall) and 29.1 °C (closest to the warm wall). The temperature asymmetry is: $\Delta t_{pr} = 32.04 - 17.98 = 14.06$ K, which leads to $PD = 14.7\%$. According to ISO 7730 the temperature asymmetry in case of cool wall should be lower than 13 K (“C” comfort category). Thus, in this case the occupants will complain because of the discomfort caused by radiation asymmetry.

The mean radiant temperature was calculated both by using the Eq. (5) and identifying one by one the angle factors from Fanger’s diagrams [12]. It can be stated that the Eq. (5) led to a sum of angle factors higher than 1.0 in the analysed cases. Calculating the mean radiant temperatures with these F_p values mean radiant temperature was higher than the value calculated with Fanger’s diagram. Furthermore, the well-

known relations used for the calculation of the angle factors in the case of plane radiant temperatures gave the sum equal to 1.0 only in the middle of the reference room. Modifying the position of the occupant or the length of one of the walls, the sum of the angle factors differs from 1.0.

Based on this numerical analysis of the mean radiant temperature and radiant asymmetry, a series of measurements were performed in the Indoor Environment Quality Laboratory (University of Debrecen), involving 20 college age subjects (10 female, 10 male). The results of the experiments will be presented in another paper, but it was stated that the subjective responses confirm the results of the numerical analysis. Moreover, by increasing the air velocity subjects complain by discomfort caused by draught.

5. Conclusion

In the case of rooms with one external building element, mean radiant temperature and the radiant asymmetry will not lead to discomfort in the case wall heating, if the air temperature is chosen properly. The poor thermo-physical properties of the external building elements are compensated by higher energy use for heating. In the case of old glazed structures, neglecting the effect of the solar radiation, the radiant asymmetry will lead to discomfort even at high indoor air set-point temperatures. The available equations used for the calculation of the angle factors should be used with precaution.

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