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# Study of human response in conditions of surface heating, asymmetric radiation and variable air jet direction

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ABSTRACT

Low temperature radiant heating systems are widely used in buildings being advantageous both from energy use and thermal comfort point of views. However, attention should be paid to asymmetric radiation especially in the case of wall heating. The aim of our research was to analyse the perception of thermal asymmetry in combination with different air velocities. A series of measurements were carried out in controlled environment involving 20 subjects (10 female, 10 male). It was shown that the thermal asymmetry is perceived at low air velocities, but increasing the air velocity to 0.1 m/s, 0.15 m/s or 0.2 m/s the perception of air movement overwrite the perception of thermal asymmetry. The heat removed by convection by the same air flow and air jet velocity was different for women and men group. The higher decrease of the skin temperature in case of women (around 2 K) leads to thermal sensation votes under −0.5 (even though the air and mean radiant temperature were 24 °C). The responses of women and men group regarding draught perception were different as well.



## 1. Introduction

Occupants' well being is the most important goal of building designers and operators. Proper operation of heating, ventilation and air conditioning systems (HVAC) and fine tuning of indoor parameters is essential to avoid the sick building syndrome, [1–6]. The relation between indoor environment quality (especially the effects of thermal comfort parameters and indoor air quality) and workers' productivity was investigated and presented by several authors and it was proven that there is a strong correlation between the perceived indoor air quality, thermal comfort sensation and work productivity, [7–17]. Measurements were performed usually in existing office or education buildings under real work conditions. Draught and asymmetric thermal radiation may lead to the increase of the percent of dissatisfied persons (PPD), so these discomfort parameters have to be avoided in order to obtain high work productivity and comfortable, healthy indoor environments, [18–21]. However, practice has shown that it is extremely hard to provide homogenous environments in closed spaces and locally the combination of environmental parameters can lead to discomfort. Thus, thermal comfort has to be evaluated properly, to obtain correct information about the local resultant of indoor parameters. Currently, there are two different approaches for thermal comfort evaluation: the heat balance (PMV-PPD model) and the adaptive approach. The heat-balance approach is based on Fanger's steady state experiments in controlled climate chamber and theory of heat balance, [22]. Humphreys and Nicol were between the first researchers working on the development of the adaptive model [23]. Based on the work of de Dear and Brager the first adaptive comfort standard was elaborated, [24]. Local discomfort caused by draught or radiation asymmetry may affect the satisfaction with thermal environment [25,26]. The effect of these parameters on thermal sensation can be investigated properly in climate chambers with controlled indoor parameters. There are numerous papers and reports published on the evaluation of draught perception. It was proven that there is a relation between overall thermal comfort sensation and sensitivity to draught [27]. The advantages and disadvantages of radiant heating were thoroughly analysed, [28,29]. It is still ambiguous, what the resultant effect on thermal sensation of two simultaneous discomfort parameters is? Is it possible that two discomfort parameters neutralize each other, or the discomfort sensation is accentuated? The common effect of asymmetric radiation and elevated air velocity in hot environments was investigated, [30]. It was found that the effect of asymmetric radiation can be removed by an air flow jet with variable direction and elevated velocity. Moreover, some subjects reported cold and complained by draught sensation. Obviously, turbulence intensity should be taken into account when the draught sensation is discussed, [31,32]. In most of cases asymmetric radiation is caused by solar radiation entering the closed spaces by transpar-

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ent building elements (mainly short wave radiation). It was shown, that there is a difference between the perception of long and short wave radiation, [33]. The increase of the mean radiant temperature caused by the solar radiation is variable in the closed space. To neutralize the discomfort by increased asymmetric radiation, traditional ventilation or air conditioning systems cannot be used efficiently. Advanced personal ventilation systems, can give better results [34–38]. The appropriate thermal comfort sensation can be provided by creating a personal comfort bulb around the occupant, [39–43].

In case of wall heating systems heterogeneous indoor environments are obtained. It was proven, that mean radiant temperature varies significantly, especially in the case of a wall heating installed opposite to the cold wall. Obviously, in this case long wave radiation has to be taken into account.

The main goal of this research was to investigate the human response in the case of asymmetric radiation caused by cold and warm walls, and to analyse the common effect of elevated air velocity and asymmetric radiation on thermal comfort sensation. A series of measurements were carried out involving 20 subjects in controlled environment.

## 2. Objectives and hypothesis

Previous experiments show that in warm environments the discomfort caused by asymmetric radiation can be mitigated by variable air jet direction and elevated air velocity, [30]. In the case of large transparent areas solar radiation may lead to high plane temperature differences especially in summer, but even in transition periods (spring, autumn). According to ISO7730, at a certain plane radiant temperature difference the highest percentage of dissatisfied is obtained at warm ceiling. The mentioned Standard indicates that cold wall gives the second highest percentage of dissatisfied. As next step of our research related to the analysis of the interrelation between asymmetric radiation and variable air jet direction the It was assumed that having a cold wall in the test room and warm wall on the opposite side of the room, occupants will claim discomfort because of asymmetric radiation. The hypothesis was that using the variable air jet direction the thermal discomfort will be attenuated. The air velocities were chosen around the maximum admissible values recommended by ISO 7730 in A, B and C building categories. It was presumed that thermal sensation will be evaluated significantly different by female and male subjects.

## 3. Practical implications

Old buildings are characterized by poor thermal properties of the envelope. During the winter period the internal surface temperatures of external building elements (both opaque and transparent) are quite low. If the heating surface is placed opposite to the cold wall, the risk of discomfort caused by thermal asymmetry is high. In the case of properly insulated new buildings glazed areas are expected to have the lowest surface temperatures in winter. These elements may cause thermal asymmetry as well. It was proven that in warm environments the thermal discomfort caused by thermal asymmetry can be mitigated using variable air jet direction and elevated air velocity. Once installed in a room to create the "optimal thermal comfort bulb" around the occupants according to individual needs in summer, the advanced personalized ventilation system can be efficiently used to improve the thermal environment during the heating season as well.

## 4. Methods

### 4.1. Experimental procedure

Measurements were performed in the Indoor Environment Quality Laboratory of the University of Debrecen. The simplified schema of the lab is presented in Fig. 1.

The test room ($2.50 \times 3.65 \times 2.55$ m) is placed in a "box" built from 15 cm thick PUR panels. The walls of the test room are realized from solid brick. In the space between the PUR panels and test room the temperatures can be set between −15 °C and +34 °C. Installing two doors (used in refrigeration rooms) three different temperatures can be set around the test room. In order to obtain asymmetric radiation in the test room, the temperature in one of the "outdoor" spaces was set to −10 °C. In the test room and in other spaces around the test room the temperature was set to +24 °C. Because of the hysteresis of control elements installed at the air handling unit, small variations of the air temperature were registered (Fig. 2).

The small increase of the mean indoor temperature during the 2 h measurements in our opinion was caused by the heat loss of occupants.

Because of the poor thermo-physical quality of the test room wall, the average surface temperature on the inner side was around +17.5 °C (Fig. 3).

In the test room radiator, wall, ceiling and floor heating is possible. During the experiments only the wall heating was in operation on the opposite side of the cold wall. The average surface temperature of the warm wall was +31.1 °C (Fig. 3). Consequently, a temperature difference of 13.6 °C was obtained between the surface temperatures of two opposite walls (the distance between these walls is 2.5 m). In the middle of the room at 0.6 m height the difference between the plane radiant temperatures was 6.53 K. The duration of the experiments was planned for 2.0 h. Because of the high thermal inertia of the wall heating system and brickwork the variation of the surface temperatures is negligible (Fig. 4).

In the middle of the test room one person was planned to sit facing to the window (cold wall on the left side, warm wall on the right side). The fresh air (100% outdoor air, 50 $m^3 \cdot h^{-1}$) was provided continuously during the experiments at 24 °C through displacement ventilation mode (the terminal device was placed in the room corner (cold wall-wall with window) above the floor. The average air velocity in the middle of the room at 1.1 m height was 0.02 m/s. The 2.0 h experiment was split into 4 sub-periods (30 min each). In the first 30 min of the experiment the air velocity around the head of the subjects was 0.02 m/s. Thereafter, using an advanced personalized ventilation system (ALTAIR, [40]) the air velocity was increased successively from 30 to 30 min, to 0.1 m/s (Tu = 54%; DR = 5%), 0.15 m/s (Tu = 48%; DR = 7.6%) and 0.2 m/s (Tu = 33%; DR = 9.8%). The air jet reached the head, neck, arms and chest. The direction of the air jet was changed every 10 s rotating it successively in the following order: left-front-right-front-left and so on. Before starting the measurements with subjects, the indoor parameters (air temperature, globe temperature, relative humidity, air velocity) in the test room were measured using a TESTO 480 instrument. According to registered data, the PMV values are presented in Fig. 5.

### 4.2. Instruments

The air temperature and the $CO_2$ concentration were measured by a TESTO 435 instrument. Attaching the comfort probe to the TESTO 435 instrument, the indoor air turbulence intensity was measured in accordance with EN 13,779. When setting the experiment, the globe temperature, the relative humidity, the air temperature and velocity were measured with TESTO 480 instrument.