Investigations of (local) thermal comfort as a function of radiation asymmetry and vertical air temperature difference

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Abstract. The following article describes an extract of the results of experimental investigations on the topic of thermal comfort as a function of radiation asymmetry. The investigations were carried out in the climate chamber [1, 2] of the TU Dresden with the help of subjects. The radiation asymmetry was imprinted by subdividing the climate chamber into two vertically superimposed half-rooms, one of which was heated and the other cooled. In this way, 46 experiments on the heating or cooling ceiling were carried out. The measurement results show an inseparable link between the radiation asymmetry, the vertical air temperature difference and the air velocity. The subject assessed the room climate much more negatively than the ISO 7730 [3] would predict according to the state of the art.

1 Introduction

The investigations of Fanger [4] about thermal comfort were internationally recognised and implemented in standards like ISO 7730 [3]. An important point with regard to local discomfort is the maximum surface temperature permitted for the ceiling. The resulting radiation asymmetry should be only $\Delta \vartheta_r = 4$ K for a Predicted Percentage of Dissatisfied of PPD = 5 %, which is the lowest value of the investigated systems for heating and cooling by ceiling or wall (see Fig. 1).



Fig. 1. Percentage of Dissatisfied (PD) due to radiation asymmetry according to equations in [3].

This is one of the main reasons why heating ceilings are mainly used in buildings with a low heating load (new buildings or after renovation). Otherwise, an uncomfortable high surface temperature is necessary to compensate the heat load.

At the same time, the need for summer room cooling is increasing due to general global warming and to maintain the human performance, especially in office buildings. Generally, new buildings are designed to offer a comfortable room climate throughout the year and are therefore provided with a cooling system. To reduce investment costs, space requirement and energy losses, it is wise to use one system to fulfil the HVAC-tasks (heating, ventilation and air conditioning) including cooling.

These are the reasons for new investigations with subjects in a climate room.

2 Definition of radiation asymmetry

Fanger defined in [5] the radiation asymmetry as "the difference between the plane radiant temperature of the two opposite sides of a small plane element" at a height of h = 0.6 m above the floor. This is illustrated in Fig. 2. It means that the room will be divided in an upper and a lower part. For each part, the mean radiant temperature $\vartheta_{r,m}$ can be calculated approximately using equation (1) [6] with the angle factors φ_i and the radiant temperature $\vartheta_{r,i}$ of each surface.

$$\vartheta_{\rm r,m} = \sum [\phi_{\rm i} \cdot (\vartheta_{\rm r,i} + 273 \text{ K})^4]^{0,25} - 273 \text{ K} \qquad (1)$$

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The difference between the both calculated radiant temperatures (upper and lower room part) is defined as the radiation asymmetry, see equation (2).

$$\Delta \vartheta_{\rm r} = |\vartheta_{\rm r,m,1} - \vartheta_{\rm r,m,2}| \tag{2}$$

However, especially the determination of the angle factors ϕ_i for every surface of the room is not trivial and therefore possibly not suitable for practical reasons.



Fig. 2. Illustration of the definition of radiation asymmetry: red and blue are the two room parts, purple is the plane element.

It is therefore a future goal of the studies to bring the definition into a more easily applicable form.

3 Description of the test conditions

The climate room at the TU Dresden (see Fig. 3) has dimensions of $l x w x h = (5 x 4 x 2.5) m^3$.



Fig. 3. Climate room at the TU Dresden.

The interior surfaces are divided into 73 individually tempered surface areas and the connected ventilation system can be controlled by temperature, humidity and volume flow. In order not to exert any significant influence on the measurement results, the ventilation system only serves to supply the subjects with fresh air during the test. The air speed is lower than c = 0.1 m/s shortly after the supply air opening.

The subject had to fill out a questionnaire about their thermal comfort feeling every 5 minutes. At the beginning of the test (called initialisation phase), the temperatures of the air and the surfaces are the same. For a maximum of one hour, the subject has the opportunity to change the room temperature on request by answering the survey without being aware of it. As soon as the subject feels comfortable, the initialisation is finished and the actual test begins.

For the whole test, the surface areas of the climate room are grouped as it can be seen in Fig. 4. The middle height of the side walls inclusive the door are staying on the comfort temperature of the subject, so that they have no negative influence on the comfort feeling. The remaining areas at the top and bottom are tempered opposite to each other, so that the radiation asymmetry between the half-rooms (HR) will be gradually increased. Depending on the test case, the upper surfaces are cooled (cooling ceiling, CC) or heated (heating ceiling, HC) while the lower surfaces do the opposite. The result is an approximate mirror symmetry at a height of h = 1.25 m, so that the mean radiation temperature at this height remains constant.



Fig. 4. Schematic representation of the temperature distribution of the half-rooms using the example of a cooling ceiling (green = neutral, red = heated, blue = cooled, grey = air opening).

In five steps the temperature difference between the halfrooms is increased by $\Delta \vartheta = 3$ K each and each step is maintained for $\tau = 30$ min, so that the maximum exposition time inclusive initialisation phase is 3.5 h. The subject continues to complete the questionnaire at 5min intervals throughout the entire period.

For measuring the physically values of the room climate, the following sensors are installed:

- 365 OneWire-sensors on the inside of the inner wall sheets for surface temperatures
- 26 NTC-sensors (distance of d = 10 cm) on a temperature lance for vertical air temperature
- 3 anemometers for air velocity (only at measurements with a dummy)
- 3 globe thermometers at height h = 0.1 / 0.6 / 1.1 m (only control function due to long setting time)

Fig. 5 shows the seating conditions for the subjects and the placement of the sensors.



Fig. 5. View on the measuring sensors: air temperature lance (left), anemometers (on the dummy), globe thermometers (right).

In the present paper the results of 46 tests are presented, half with heating ceiling and cooling floor and half with cooling ceiling and heating floor.

4 Results

Fig. 6 - 9 show the core statements of the investigations described. Fig. 7 shows the vertical air temperature distribution depending on the surface temperature difference between the two half-rooms. In the case of the heating ceiling (with cooling floor), the air temperature is distributed stably according to the physical air stratification because of temperature-related density differences. The average air velocity during the entire investigation is only c = 0.02 m/s with low turbulence. However, the air temperature gradient increases steadily.

The maximum air temperature differences amount to $\Delta \vartheta_a \approx 8 \text{ K}$ at the largest investigated half-room temperature difference of $\Delta \vartheta = 15 \text{ K}$. Accordingly, there is a noticeable cooling in the subject's occupied zone.

In contrast, in the case of the cooling ceiling (with heating floor) a temperature distribution takes place against the physical air stratification. The air is heated in the lower half-room, rises and then sinks again as a result of cooling through the upper half-room. This mixing results in a lower air temperature gradient with a maximum of $\Delta \vartheta_a = 3.5$ K and a slight warming in the occupied zone. A further consequence, however, is an average air velocity increasing with the temperature difference, as shown in Fig. 6. The air movement is also much more turbulent, which becomes apparent in the standard deviation of the air velocity.



Fig. 6. Mean air velocity and its standard deviation (as a measure of turbulence) for cooling ceiling.

Fig. 8 and 9 show the subjects' assessment of their global sensation of comfort when exposed to the described physical room air parameters as a result of the





temperature difference between the half-rooms. In a total of 46 tests (equally divided between the two test cases), one third of the subjects were females. A further evaluation of the influence of gender is planned. It has been established so far that gender has no discernible influence on the determination of the individual comfort temperature during the initialisation phase.

In both cases, the proportion of subjects who assess the indoor climate as cool increases – in the case of heating ceiling slightly higher.



■-3 ■-2 ■-1 ■0 ■1 ■2 ■3

Fig. 8. Distribution of global comfort for heating ceiling (-3 means to cool, 0 means neutral, +3 means to warm).



■-3 ■-2 ■-1 ■0 ■1 ■2 ■3

Fig. 9. Distribution of global comfort for cooling ceiling.

The most important findings are briefly summarised:

• local sensations were mostly due to cool feelings (especially at the feet in case of HC and at the uncovered arms and hands in both test cases) • no significant proportion of simultaneous local warm and cool sensation was assessed by the subjects

The results of the surveys and the measurements permit further detailed analyses, which, however, would go beyond the scope at this point.

5 Discussion

In the case of heating ceiling (HC), the results are simply due to the decreasing operative temperature in the occupied zone, which cannot be sufficiently compensated by the thermal radiation ceiling. A second reason is the contact between the feet and the cold floor. This can be seen above all in the increasing proportion of arms, hands and feet that are felt cool.

In case of cooling ceiling (CC), the cool arms are the most common reason for discomfort. Due to the constant warming of the room air in the occupied zone with increasing radiation asymmetry (see Fig. 7, right), only the increasing air velocity can be the cause (see Fig. 6). This provokes latent drafts and a stronger cooling effect of the skin in the area of the arms.

Fig. 10 shows the percentage of dissatisfied due to local temperature sensation. In both test cases, a relevant higher PD was detected in this investigation than it would have been assumed according to the calculation equations of [3]. Particularly in the case of cooling ceilings, there is a large gap between the results and the standard. When the draft risk or the PD due to vertical air temperature difference is calculated, in all cases it results in PD ≤ 6 %.



● HC, TUD ▲ HC, ISO ● CC, TUD ▲ CC, ISO

Fig. 10. Comparison of PD due to radiation asymmetry between calculation according to ISO 7730 [3] and the presented results for the different half-room cases.

When comparing the results obtained from the heating ceiling with the cooling ceiling, great similarities are noticeable. However, the causes of discomfort are different as shown in the results of the physical measurement data. With regard to the curves from the ISO 7730 [3], no similarities are discernible.

The regression lines for the results shown in Fig. 10 are for the half-room view with heating ceiling HC (and cooling floor):

$$PD_{\rm HC} = -0.27 \cdot \Delta \vartheta_{\rm r}^2 + 7.74 \cdot \Delta \vartheta_{\rm r} \tag{3}$$

and for the cooling ceiling CC (and heating floor):

$$PD_{\rm CC} = -0.076 \cdot \Delta \vartheta_{\rm r}^2 + 4.35 \cdot \Delta \vartheta_{\rm r} \tag{4}$$

6 Summary and outlook

In summary, the investigations have shown inseparable physical relationships between the local comfort criteria:

- radiation asymmetry,
- vertical air temperature difference and
- air velocity.

However, the state of the art is based on separate studies of the individual criteria. In view of the available results, this does not appear to make much sense since an individual evaluation would have led to a significantly lower PD in each case.

The further investigations will focus on the ceiling as the only system surface, while all other walls represent the room load. This corresponds to a more practical application example. Furthermore, the thermal comfort during heating or cooling via side walls is to be investigated. In addition, the aim is to make the physical dependencies between the local comfort criteria calculable in order to transfer them to any application.

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