VARIATION IN TIME OF THE PERCEPTION OF LOCAL DISCOMFORT PARAMETERS

by

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The aim of the present research was to investigate the temporal change of the actual mean votes of subjects exposed to the joint effect of warm ceilings and draught. The paper investigates whether the value of actual mean votes remains constant or it changes over time under a constant thermal environment? To answer this question, we performed human subject studies involving 10 men and 10 women. The results were analyzed in function of time. The most important result is that, throughout the 180 minutes studies, in the 5-15 °C radiant temperature asymmetry interval between warm ceiling and floor, with a DR = 15% and DR = 25%, draught rate, the actual mean votes value was not constant but showed a decreasing trend. Furthermore, there was a significant discrepancy among the votes of females and males.

Key words: *human subject measurement, thermal comfort, actual mean vote*

Introduction

It is a given fact that people spend a high amount of their time indoors [1] – this makes it essential for these spaces to be highly comfortable [2]. From the point of view of economic organizations, the people working in offices are employees, whose salaries represent a large part of the companies´ operating and maintenance costs. Furthermore, these same employees are the ones making sure that these organizations function properly, so it is essential that they be provided with optimal working conditions, where they can work comfortably, in an undisturbed, healthy, and most efficient way [2]. One of the most important conditions for optimal and disturbance-free work is to ensure ideal thermal comfort.

Another extremely important aspect is the energy needed to maintain a suitable thermal environment and the reduction of CO_2 emissions from buildings.

However, taking into account the first thought, the primary purpose of buildings is to serve human activity impeccably [3]. Thus, people must remain at the very core of the search for the optimum between the ideal thermal comfort and minimizing the energy needed for the maintenance of the buildings.

On the other hand, most spaces of public buildings are used at the same time by many people, most of them having different preferences concerning the thermal environments

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they consider ideal. Keeping this in mind, it poses a challenge to identify and set the ideal parameters of thermal comfort for a public building in such a way as to match most people´s optimum. In order to do so, it is best to determine the ideal parameters based on statistics, with the aim of identifying the minium level of dissatisfaction.

The predicted mean vote-predicted percentage of dissatisfied (PMV-PPD) model is a highly useful tool for the description of the thermal comfort, defining thermal comfort by considering the following six parameters: air temperature, humidity, velocity, mean radiant temperature, metabolic rate, and thermal insulation of clothing [4].

In addition to the PMV model, local discomfort parameters are also widely used in the description of thermal comfort. Their separate effect is already known, having been the topic of several studies [5, 6]. Figure 1 shows the effect of the radiant thermal asymmetry, fig. 2 shows the effect of the draught.

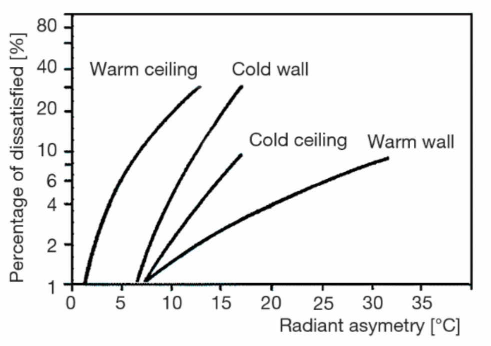

Figure 1. Percentage of dissatisfied with radiant asymmetry

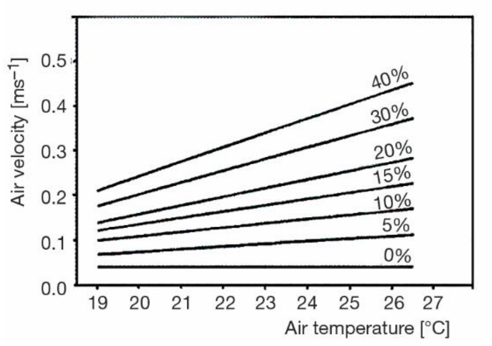

Figure 2. Relation of air velocity and air temperature for specific draught rates

As shown on fig. 1, as the radiant thermal asymmetry increases, the percentage of dissatisfied toward the warm ceiling also increases. On the other hand, fig. 2 presents the effect of the draught showing that the draught rate reaches higher levels with the increase of the air velocity and of the turbulence intensity, while it decreases with the increase of the temperature.

However, in a real situation they coexist. There is ample literature tackling some local discomfort factors jointly [7-10], furthermore, there are also studies investigating the effect of draught under different temperature parameters [11, 12]. Nonetheless, there is a gap to be filled in the field of the combined effect of draught and a warm ceiling. The present research was carried out in order to eliminate this shortcoming and increase the existing quantity of knowledge. It focuses on studying the combined effect of asymmetric radiation caused by draughts and warm ceilings and is looking for answers to the questions:

– For the radiant temperature asymmetry interval of 5 °C and 15 °C between the warm ceiling and the floor, is the value of actual mean votes (AMV) constant during the 180 minutes experiments, or does it vary in function of time?
– What effect does the increase in the draught from DR = 15% to DR = 25% have on the change in the AMV value over time?
– Considering the combined effect of the draught and the warm ceiling, does gender have an effect on the temporal dynamics of AMV?

Methods

General description of the methods

Numerical, instrumental, and human subject measurement methods were used during the temporal investigation of the joint impact of the draught rate and the radiant temperature asymmetry between the floor and the ceiling, as caused by a warm ceiling.

Numerical methods

We calculated the PMV, PPD [%], *Tu*, and DR [%] values with the help of a self-developed program. To calculate the draught rate, we used [1]:

$$DR = (34 - t_a)(v_a - 0.05)^{0.62}(0.37Tuv_a + 3.14) \quad (1)$$

To calculate the PPD, we used [6]:

$$PPD = 100 - 99\exp(-0.03353PMV^4 - 0.2179PMV^2) \quad (2)$$

Presentation of the comfort chamber

The comfort chamber has two heat sources, its boundary structures can be individually heated and cooled, allowing any desired radiant temperature asymmetry to be created between any structural element. Several characteristics of the supply air (such as air temperature, humidity and volume flow) can also be regulated.

Throughout the measurements, the thermal environment was kept at a value defined as neutral by the PMV model, while we focused on examining the effect of warm ceiling and draught parameter pairs on the participants´ thermal comfort. The value of PPD at the center of the measuring chamber was constantly kept below 6%.

Figure 3. Comfort chamber

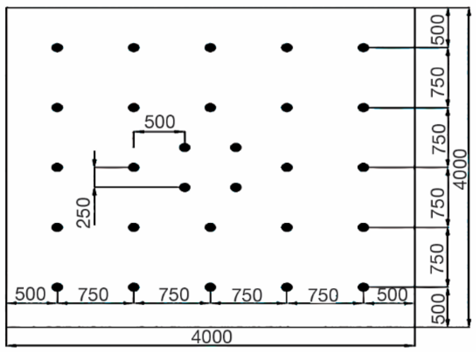

Figure 4. Measurement points, top view

The comfort chamber has specific dimensions of 4 m × 4 m × 3 m, its floor area being 16 m^2 and the height being 3 m, fig. 3. The comfort chamber is equipped with a hydronic system, the pipes run in a drywall system. Two heat pumps provide the heating and cooling energy. Furthermore, the walls, ceiling and floor have different piping systems and pumps, allowing a separate control of the temperatures of different surface. A central air handling unit provides the fresh air supply of the comfort chamber, fig. 4.

During the measurements we measured the air and mean radiant temperature (the measurement error of the sensor was 0.1 ^{o}C) the velocity of the air (the measurement error of that sensor was 0.03 m/s + 0.04 measured value) and the relative humidity (0.8% + 0.007 measured value). We also calculated the thermal insulation of the clothing, metabolic rate, turbulence intensity, DR, PMV, and PPD.

Presentation of the measurement border conditions

During the joint measurement of local discomfort factors, we examined the effect of warm ceiling and draught parameter pairs on thermal comfort. At the same time, we made sure that the thermal environment was kept at a value defined as neutral by the PMV model, meaning that the PPD value at the center of the measuring chamber remained constantly below 6%.

An important aspect is the creation and maintenance of time-stable, stationary thermal conditions. During the measurements, the asymmetric radiation and draught rate pairs between the specified warm ceiling and floor had to be provided in such a way that the temperature and PPD value would remain constant during the three hours experiment. In order to maintain thermally stationary conditions, the heat transfer of the warm ceiling, people and lighting, as well as the heat removal of walls colder than the indoor air from the space needed to be taken into account. The equilibrium equation is:

$$Q_{\text{ceiling}} + Q_{\text{human}} + Q_{\text{lighting}} - Q_{\text{walls}} - Q_{\text{floor}} - Q_{\text{air}} = 0 \tag{3}$$

In order to ensure the ideal thermal environment (according to the PMV model), while making sure that both the radiation temperature asymmetry and the draught rate were kept at the desired value, the following steps were taken:

- Defining the surface temperature of the delimiting structures – this step makes it possible to set the temperature asymmetry as desired.
- Determining the temperature of the supply air – the temperature of the supply air ensures that the measuring chamber is in a thermally stationary state. On the other hand, the aforementioned parameter also has an effect on the expected draught rate.
- Fine-tuning the air flow in the measuring chamber with the goal of to achieving and maintaining the required draught value.

While conducting the measurements, we examined the factors influencing thermal comfort in four different planes: at the ankle level, 0.1 m, at the knee level, 0.6 m, at the head height level of a sitting person, 1.1 m, and at the head height level of a standing person, 1.7 m.

During the instrumental measurements, we measured and recorded the following parameters at the aforementioned spatial points: the distribution in space of air temperature, humidity and velocity, as well as that of the mean radiation temperature, PPD, PMV, *Tu* and DR distribution. We investigated a total of 10 cases defined by five radiant thermal asymmetry values and two draught rates: radiant thermal asymmetry values: 5 °C, 7 °C, 10 °C, 12 °C, and 15 °C and draught rates: 15% and 25%.

Presentation of the human subject measurements

During the research we took into account the international literature, methods, as well as usually applied measurement times [5, 13-17]. The boundary conditions of the human subject measurements are shown in tab. 1.

The human subject measurements consisted of six measurement blocks of 30 minutes each, whereby the subjects completed general thermal comfort questionnaires, voting their AMV values. This 30 minutes block was repeated six times, so that the effect of the time can be analyzed.

Table 1. Boundary conditions of the human subject measurements

Boundary conditions	– Number of healthy human subjects participating in the research: 20 people (10 women and 10 men) – Duration of exposure: 3 hours – 180 minutes + pre-measurement tests – Number of parameter groups: 10 (5 asymmetries and 2 draught rates) – During one measurement session, we exposed the subjects to only 1 thermal comfort environment – Only one subject participated in the experiment at a time – The occurrence of parameter groups was random – The thermal comfort chamber was thermally stationary during the entire measurement – Acoustic and visual disturbances were ruled out – Due to the high volume rate, the indoor air quality was ideal – The thermal insulation capacity of the clothing was 1 clo – The met value is 1. – Breakfast was mandatory, meals adapted to the individual's daily routine – Ideally, the washroom was used before an experiment – Only water could be brought into the measuring chamber

Mathematical evaluation

In the study, we always contrasted two sets of values by applying two different mathematical approaches. First of all, we applied the the Welch test, and second of all, the Mann-Whitney exact test in order to evaluate the results.

The Welch test is one of the parametric tests among the statistical hypothesis tests. The test examines whether the means of probability variables in two separate samples differ significantly from each other.

The null hypothesis and alternative hypothesis in the case of the Welch test is the following:

– H0: The expected values of X and Y random variable are equal;
– H1: The expected values of *X* and *Y* random variable are not equal [18]

Belonging to the non-parametric tests, the Mann-Whitney test operates with rankings of values. The null hypothesis of this test is that there is an equal probability (*i.e.* of 50%) that one randomly selected element of one of two populations will be larger than any element of another population. The Mann-Whitney test´s confidence interval was defined as 95%.

The null hypothesis and alternative hypothesis in the case of the Mann-Whitney test is the following:

– H0: F1 = F2;
– H1: F1 $\neq$ F2 [18].

Considering that the two methods are different in their nature, the independence or dependence of two vote sets was accepted if and only if the same result could be reached using both of the aforementioned methods.

Results

Figures 5 and 6 show the AMV in function of time taking into account only women´s votes or only men´s votes at at draught rate of 15%.

Examining the AMV votes of women, a significant similarity was found between the votes collected at 30-60-90-120 minute measurement points, using both mathematical methods, *i.e.* the expected value of AMV does not change in the first two hours of measurements. After two hours, a significant decrease can be observed in the AMV votes, the significance level calculated by the Mann-Whitney method during the 120-150 minute comparison is $1.17 \cdot 10^{-3}$.

Analyzing the votes of the men, it can be concluded that at each measurement point (30, 60, 90, 120, 150, and 180 minutes), the AMV values are significantly interdependent. This means that with a DR = 15% draught effect, the AMV votes of men do not change significantly during the three hours measurements.

The significance levels calculated by the Mann-Whitney method exceed 0.053 for each data point.

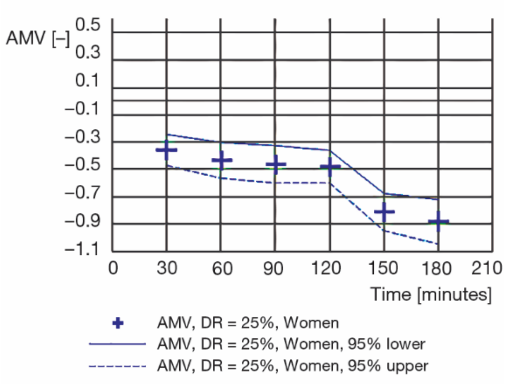

Figure 5. The AMV in function of time, women, DR = 15%

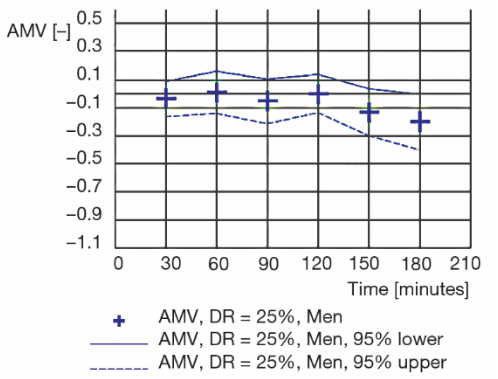

Figure 6. The AMV in function of time, men, DR = 15%

Figures 7 and 8 show the AMV in function of time taking all votes into account at a draught rate of 15%, respectively the AMV in function of time taking into account only women´s votes at draught rate of 25%.

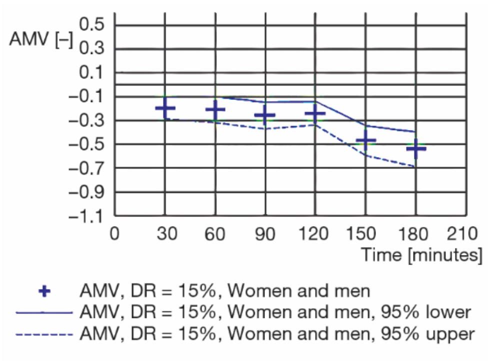

Figure 7. The AMV in function of time, women and men, DR = 15%

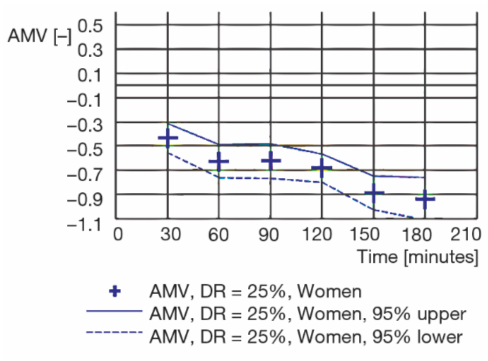

Figure 8. The AMV in function of time, women, DR = 25%

At DR = 15%, when all votes are taken into account, the same correlations can be discovered as in the case of women's votes. It can be stated that with a draught effect of 15%, taking into account all the votes, the value of AMV does not change in the first two hours of the measurement, and which it decreases significantly.

At a draught of 25%, the AMV votes of women differ significantly at the 30-60 minutes and the 120-150 minutes measurement points. In these cases, the significance levels calculated using the Mann-Whitney method are 0.045 and 0.035, respectively. At the 60-90-120 minute and 150-180 minute measurement points, the AMV values are significantly the same.

Figures 9 and 10 show the AMV in function of time taking into account only men´s votes, respectively taking all votes into account at draught rate of 25%.

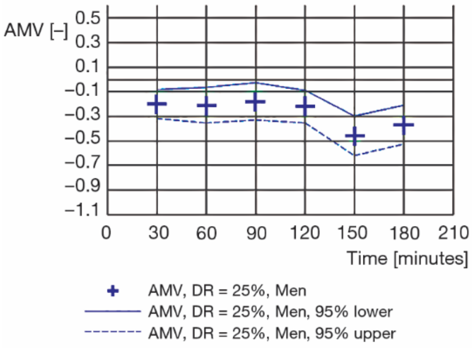

Figure 9. The AMV in function of time, men, DR = 25%

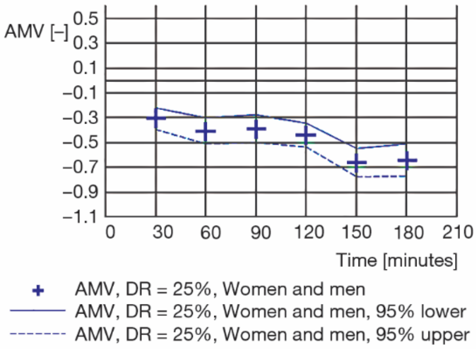

Figure 10. The AMV in function of time, women and men, DR = 25%

In the case of a draught effect of 25%, examining the AMV vote of men, it can be stated that the expected value at the 30-60-90-120 minute measurement points does not significantly depend on the passing of time. A similar trend can be detected for the 150-180 minutes value pairs. Significantly independent AMV values are obtained in a 120-150 minutes comparison, where the Mann-Whitney significance level is 0.042.

With a draught effect of 25%, taking into account all votes, the relationship between time and AMV votes is similar to the relationships found at 15%. It can be stated that with a draught effect of 25%, taking into account all votes, the value of AMV does not change during the first two hours of the measurement, after which it decreases significantly.

Discussion

When comparing the results, the following aspects were examined:

– the effect of raising the draught rate from DR = 15% to DR = 25%, taking into account all votes or only female or male votes, and
– the effect of the gender, with a draught rate of DR = 15% and DR = 25%.

In the study, we used the Mann-Whitney and the Welch method. The 95% confidence interval was determined with both methods and a statement was considered admissible if both of the aforementioned methods yielded the same end result.

Figure 11 shows the effect of draught on the change in AMV over time taking all votes into account.

In the asymmetry interval of 5-15 ^{o}C between the warm ceiling and the floor, taking all votes into account, the AMV measured at 25% draught rate is significantly lower after 120 minutes than the AMV measured at 15% draught rate. In addition, at 60 minutes, the difference between the AMV votes given for DR = 15% and DR = 25% was significant.

With a draught rate of DR = 15% and DR = 25%, the AMV value decreases significantly after 120 minutes. In addition, it can be concluded that the mean AMV value and the upper limit of the 95% confidence interval are negative in all cases.

Figure 12 shows the effect of draught on the change in AMV over time taking into account women´s votes.

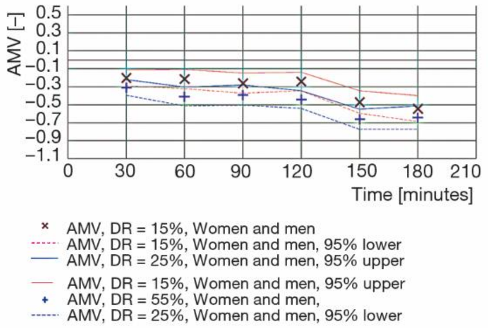

Figure 11. The AMV in function of time, men and women DR = 15% *vs.* DR = 25%

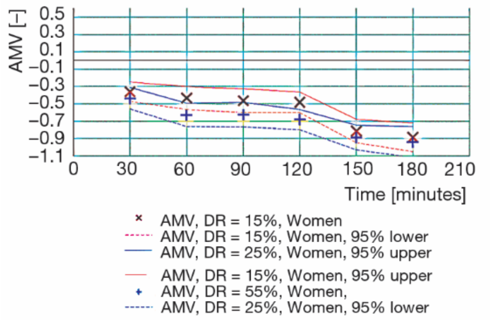

Figure 12. The AMV in function of time, women, DR = 15% *vs.* DR = 25%

If examining only women´s votes, the significant difference between DR = 15% and DR = 25% can be seen only for the AMV recorded at 60 minutes. The AMV value belonging to the DR = 25% draught effect is lower also here. Furthermore, it is clear that, regardless of the draught rate, after 120 minutes there is a definite decrease in the value of AMV votes. When examining only the votes of women, it can also be stated that the mean AMV value and the upper limit of the 95% confidence interval are negative in all cases.

Figure 13 shows the effect of draught on the change in AMV over time taking into account only men´s votes.

In the case of men's votes, with the exception of 90 and 180 minutes, raising the DR value from 15% to 25% has a significant effect on the AMV. It is true also in this case, that the AMV values belonging to the 25% draught effect are lower.

Figure 14 shows the effect of gender on the change in AMV over time in case of draught of 15%.

With a 15% draught rate, women's and men's AMV votes differ significantly across the entire interval, men's votes being higher than women´s votes. The difference increases af-

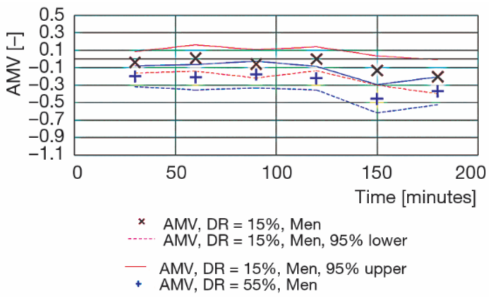

Figure 13. The AMV in function of time, men, DR = 15% *vs.* DR = 25%

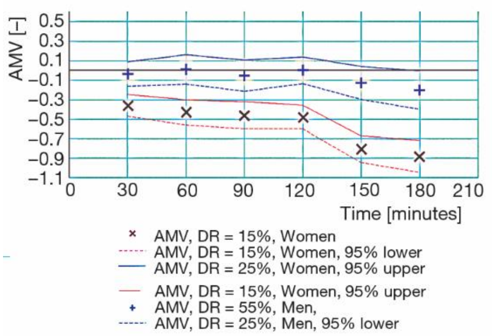

Figure 14. The AMV in function of time, women *vs.* men, DR = 15%

ter 120 minutes, at which point the vote of women decreases significantly, while that of men remains almost constant. Over the entire time interval, the mean value of the women's AMV vote and the 95% confidence interval are in the negative range.

Figure 15 shows the effect of gender on the change in AMV over time at a draught of 25%.

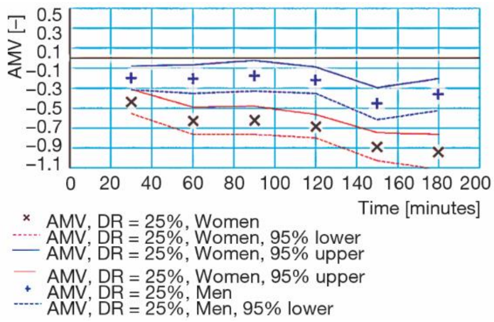

Figure 15. The AMV in function of time, men *vs.* women DR = 25%

With a draught rate of 25%, the AMV votes of women and those of men differ significantly across the entire interval, with the votes of men being higher. Over the entire time interval, both the mean value of AMV votes for women and men and also the 95% confidence interval are in the negative range.

Conclusios

The contribution of the current paper to the literature is that it shows how the AMV value changes over time in comfort environments where the PMV is close to neutral, and the combined effect of the radiant thermal asymmetry and draught appers. Moreover, the paper also presents the effect of the draught and genders on the AMV. The most relevant results are the following:

- In the radiant temperature asymmetry interval of 5-15 oC between the warm ceiling and the floor, with a draught rate of DR = 15% and DR = 25%, the AMV value was not constant during the 180 minutes studies, but showed a decreasing trend.
- The significant effect of draught can be detected after 120 min, when it results in a significantly lower AMV at DR = 25% than in the case of DR = 15%;
- The sensitivity to draught is much more pronounced in the case of women.
- Even at DR = 15% and 25%, there is a significant difference between the AMV perception of women and men: in men it is higher, in women it is lower.

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Nomenclature

AMV – actual mean vote, [–]
DR – draught rate, [%]
PMV – predicted mean vote
PPD – predicted percentage of dissatisfied, [%]
Q_{air} – heat transfer from the chamber to the air, [W]
$Q_{ceiling}$ – heat transfer from the ceiling to the chamber, [W]
Q_{floor} – heat transfer from the chamber to the floor, [W]
Q_{human} – heat transfer from the human to the chamber, [W]
$Q_{lighting}$ – heat transfer from the lighting to the chamber, [W]
Q_{walls} – heat transfer from the chamber to the walls, [W]
t_a – average air temperature, [°C]
Tu – turbulence intensity, [%]
v_a – average air velocity, [ms^{-1}]

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