A NEW METHOD FOR EVALUATING THE JOINT EFFECT OF DRAUGHT AND THE HOT CEILING

by

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For buildings with ceiling heating and mechanical ventilation, it is extremely important to know the combined effect of the draught and the radiant thermal asymmetry caused by a warm ceiling. There is plenty of literature offering separate descriptions of the dissatisfaction caused by draught and warm ceilings, but research on the combined effect of these two local discomfort factors is incomplete.
In order to fill in this gap, human subject measurements were conducted involving 20 subjects, 10 men, and 10 women, who were asked to complete questionnaires on thermal sensation, while being exposed to a random combination of five asymmetries and two draughts. Analyzing the results obtained this way made it possible to evaluate the combined effect of the draught and radiant thermal asymmetry on thermal comfort.
The most important outcome of the research is the mathematical description of the expected dissatisfaction rate and the presentation of the differences depending on gender.

Key words*: thermal comfort, radiant thermal asymmetry, draught, joint effect, human subject measurement*

Introduction

People spend most of their time indoors [1], so it is extremely important that these spaces be comfortable. Furthermore, employees´ wages make up a vast part of the running and maintenance costs of most business organizations. At the same time, the ideal functioning of these companies also depends on their employees, making it even more important to ensure optimal working conditions, so they can work in a comfortable, undisturbed, healthy and effective way [2]. Ensuring thermal comfort and an ideal thermal environment is one of the most important prerequisites for an ideal and smooth work.

The most well-known and widely used method for describing thermal comfort is the predicted mean vote-predicted percentage of dissatisfied (PMV-PPD) model [3], which de-

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scribes thermal comfort based on six parameters: air temperature, air humidity, air velocity, mean radiant temperature, human activity and thermal insulation of clothing [3-5].

The PMV model is complemented by local discomfort factors. The effects of these factors are known separately [1], but in real life situations they appear simultaneously.

Some of the local discomfort factors have already been investigated jointly [6-9], and so has the effect of the draught at different temperature parameters [10]. However, there is little literature tackling the combined effect of warm ceilings and draughts, and this research aimed to close this gap.

The purpose of this study was to investigate the combined effect that draught and radiant thermal asymmetry between the warm ceiling and the floor, have on thermal comfort. The research was also aimed at finding answers to the two following questions:
– Which mathematical relation can describe the effect of warm ceilings on thermal comfort under the presence of draught?
– Is there a significant difference between the dissatisfaction rates of men and women related to warm ceilings if the phenomenon is accompanied by a draught effect?

Methods

Description of the methodological backgrounds

The combined effect of the local discomfort factors was investigated at the Macskasy Comfort and Air Conditioning Laboratory of the Budapest University of Technology and Economics. Its basic structure is shown in fig. 1.

During the joint measurement of the local discomfort factors, the effect of the parameter pairs of hot ceiling and draught on the thermal comfort was investigated, while keeping the thermal environment neutral according to the PMV model. In practice, this meant that the PMV value was kept in the interval (–0.2-+0.2) around the head of the human subjects. In all cases, PPD was less than 6%.

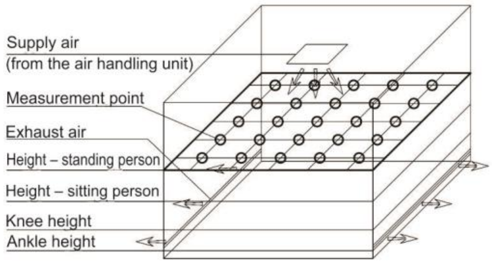

Figure1. Scheme of the comfort chamber

The following steps were performed in order to create the ideal thermal environment according to the PMV model, while maintaining the radiant thermal asymmetry and the draught at the desired rate:
– Determining the surface of the boundary structures – in this step, the desired temperature asymmetry can be set.
– Determining the supply air temperature – the supply air temperature and volume provide a thermally stationary state of the measuring chamber, but in the meantime, both parameters have an effect on the expected draught sensation.
– Fine-tuning the airflow in the measurement chamber in order to achieve and maintain the desired draught value.

Determination of the surface temperature

In the case of buildings heated by ceiling heating, the value of the ceiling surface temperature is a particularly important issue. The dissatisfaction caused by the thermal asymmetry between the warm ceiling and the floor reaches its maximum when the temperature of the warm ceiling is at its maximum value [1]. This occurs when heat loss is maximal. Thus, the room modelled during the experiment has glass sidewalls and the space below it is heated in tempering mode (10 °C).

When determining the outside temperature, the lowest external design temperature value implemented for Hungary was used, which is –15 °C. The heat transfer coefficient values of boundary structures applied when defining the surface temperatures of the modelled room are as defined in the currently valid Hungarian energy regulation. For the aforementioned assumptions and for an indoor temperature of 22 °C, the internal surface temperature of the boundary structures is: floor 20.4 °C and walls 20.5 °C. During the experiment, the surface temperature of the floors and walls was set at 20.5 °C. Based on this, it is possible to define the surface temperature of the hot ceiling, which is set at, respectively, 5, 7, 10, 12, and 15 °C above the floor temperature.

Determination of the supply air temperature

The warm ceiling introduces heat into the chamber. Since the purpose of the experiment was to generate thermally stationary states, this heat had to be neutralized – by inflow of colder supply air.

The sustainability of the stationary state was verified through measurement and continuous monitoring during subsequent human subject measurements. In the course of the research, a total of five radiant asymmetry values and two draught sensation values were investigated, as well as their combinations, resulting in a total of 10 cases. In each case, a control and tuning test was performed focusing on a measurement point at a height of 1.1 m in the centre of the space. It was also ensured that the PPD in this point would remain below 6% over the entire duration of the measurements, while the temperature asymmetries and draught values between the ceiling and the floor were also met.

The ceiling diffuser used in the experiment had adjustable blades and a flow deflector, enabling the symmetry, orientation and character of the air jet. Instrumental measurements and visualization experiments were performed on the air jet.

Instrumental measurement

Presentation of the instrumental measurement

The spatial distribution of the factors affecting the thermal comfort was measured in the comfort chamber shown in fig. 1, having a floor surface area of 4 × 4 m and a height of 3 m. The measurements focused on examining the spatial distribution of air velocity, temperature and humidity, as well as the mean radiant temperature, PMV, PPD, turbulence intensity and draught rate (DR).

Measurements were made in four planes according to fig. 1: 0.1 m – ankle height, 0.6 m – knee height, 1.1 m – head height of a sitting person, and 1.7 m – head height of standing person.

The measurement points were recorded at the spatial locations shown in fig. 1. The point at the centre of the measuring plane represents the average of five measuring points: four of them placed the angles of a 60 cm side square in the centre of the plane, and one point placed in its centre.

The parameters influencing thermal comfort were partly measured and partly calculated. Table 1 shows the different parameters and the measurement errors associated with each of them.

Table 1. Measured and calculated parameters

Parameter	Measured/Calculated	Error of measurement
Air and mean rad. temperature	Measured	0.1 °C
Air velocity	Measured	0.03 m/s + 0.04 Measured value
Air humidity	Measured	1.8% + 0.007 Measured value
Thermal insulation of clothing	Calculated	–
Metabolic rate	Calculated	–
Intensity of turbulence	Calculated	–
PMV	Calculated	–
PPD	Calculated	–

Results of instrumental measurement

From all the instrumental measurements obtained, the present article shows the spatial distribution of PMV and DR values at 15 °C radiant thermal asymmetry and DR = 15%, as seen on figs. 2 and 3. The vertical *y*-axis of the graphs represents the magnitude of the examined variable, while the axes defining the base plane (*x* and *z*) represent the spatial dimensions.

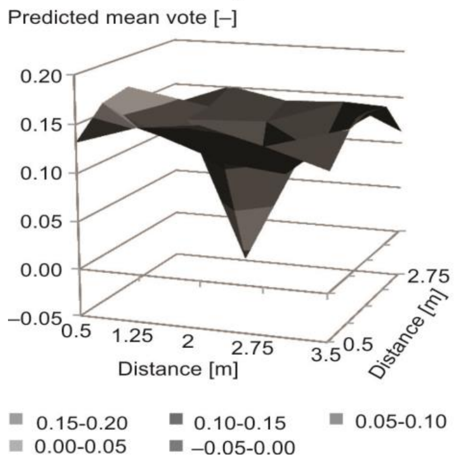

Figure 2. Distribution of PMV in space

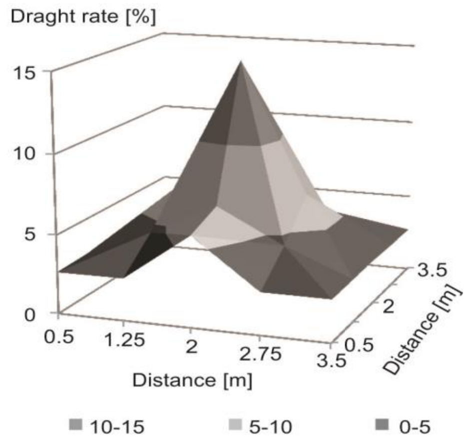

Figure 3. Distribution of DR in space

The PMV was calculated from other measured parameters. When planning the experiment, our goal was to keep the PMV at an ideal (–0.2-+0.2) interval at a height of 1.1 m in the centre of the space. It was observed that in the centre of the space, in the measurement plane, the expected value of the dissatisfied was the smallest. On the other hand, it is important to note that the expected dissatisfaction value remained within the interval (–0.2-+0.2), in spite of the inhomogeneous distribution of the PMV value.

In the case of DR, the differences due to the inhomogeneity of the space were greater because the mean draught value of the area marked as the centre of the space (approximately 15%) was significantly different from the one measured near the wall (below 5%). For each pair of asymmetry and draught parameters, the PPD value remained less than 6% and the radiant thermal asymmetry temperature difference between the floor and ceiling, as well as the DR could be maintained at the planned value.

In order to evaluate the dissatisfaction caused by the warm ceiling at a draught effect of 15% and 25%, human subject tests had to be performed.

Human subject measurement

The human subject measurements were made in the comfort chamber shown on fig. 1. During the measurement series, several experiments were performed regarding thermal comfort. The human subjects assessed their dissatisfaction rate with the hot ceiling by using a continuous scale between 0 and 1, 0 meaning a dissatisfaction of 0%, and 1 meaning a dissatisfaction of 100%.

All measurements considered the literature-based methodology used in human subject measurements [2, 7, 11-15]. Accordingly, 20 individuals were chosen, 10 healthy men and women each, who evaluated a total of 10 thermal comfort environments, determined by a total of five values of radiant thermal asymmetry between ceiling and floor (5, 7, 10, 12, 15 ^{o}C) and 2 draught effects (15%, 25%). A given thermal environment was continuously present during the measurement sessions, as the measuring chamber was thermally stationary (see section *Determination of the supply air temperature*).

Each measurement lasted for three hours during which the subjects were exposed to only one asymmetry and one ambient temperature determined by the draught. The ambient temperature settings were randomized so that no upward or downward tendencies could be inferred.

During the measurements, acoustic disturbances were excluded. Due to the high air exchange rate, the quality of the indoor air did also not cause any dissatisfaction. Furthermore, much attention was paid to eliminating any acoustic discomfort and providing appropriate visual comfort.

One measurement session consisted of a total of six repetitive measurement blocks, lasting thirty minutes each. The paper-based information collected from individuals through these methods was subsequently processed and analysed using mathematical methods.

The mathematical methodology of the evaluation

During the evaluation of the results, the relationships between the thermal comfort votes given under different conditions were examined. Throughout the study, two sets of votes using two different mathematical approaches were compared at all times. The results were evaluated using the Welch test and the Mann-Whitney exact test. Because of the difference in the nature of these two methods, the dependency or independence of two sets of votes could safely be accepted if both methods produced the same result.

The Welch test (also known as the d-test) is a parametric test from the category of statistical hypothesis tests. The significance level of the test was set at 0.05.

The Mann-Whitney test is a non-parametric test that operates with rankings of values. Its null hypothesis is that there is an equal (50%) probability that one randomly selected element from one population will be greater than a randomly selected element from a second population. The confidence interval used in the Mann-Whitney test was defined as a value of 0.95.

Result of human subject measurement

From the information obtained using the method presented in section *Methods*, the present article examines the data regarding thermal comfort and presents the results and conclusions drawn from them.

During the measurements (once every 30 minutes), the human subjects assessed their level of dissatisfaction with the radiant thermal asymmetry caused by the warm ceiling, appearing together with the draught effect.

Figure 4 shows men´s, women´s, as well as all human subjects´ dissatisfaction with the warm ceiling as a function of radiant thermal asymmetry at a draught effect of 15%. Figure 5 shows the same values at 25%. In presenting the results, the 0.95 confidence intervals are shown.

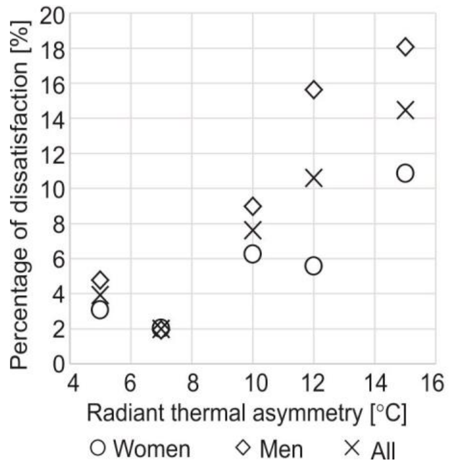

Figure 4. Percent of dissatisfied with warm ceilings: women's, men's, and votes at DR = 15%

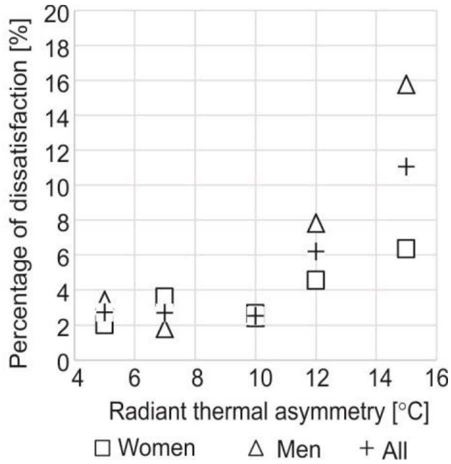

Figure 5. Percent of dissatisfied with warm ceilings: women's, men's, and votes at DR = 25%

The subjects evaluated thermal environments at a total of 5 asymmetric values: 5, 7, 10, 12, and 15 °C. The dots on the diagrams represent mean dissatisfaction rates defined as a function of asymmetry. The points on figs. 4 and 5 show the expected value of 60 measurements each in case of women and men, and 120 in case of cumulative measurements, as they include the votes of each subject at six different moments: at 30, 60, 90, 120, 150, and at 180 minutes. The maximum difference between the mean value and the extremity of the confidence interval at a DR of 15% is 1.82%, at a DR of 25% is 1.9%.

Discussion

Equations describing the dissatisfaction with warm ceiling

A curve was fitted to the expected values of the percentage of the dissatisfied shown on figs. 4 and 5, in order to mathematically describe the phenomenon. The present study intended to use a non-analytical approach in order to determine the percentage of subjects dissatisfied with the radiant thermal asymmetry in the presence of a hot ceiling and draught effect. Thus, it was not possible to determine with certainty the type of curve to fit to the measurement points.

Since the curve fitting was done for a total of five measurement points, the quadratic curve already produced a complete coverage, an R^2 of 1. For this reason, throughout the curve fitting, the accuracy of the fitting was investigated, from the straight line to the cubic curve. Thus, each case was represented by three curves and three R^2 values: a first, a second, and a third degree polynomial. With consideration of the aforementioned fitting, the equations shown in tabs. 2-7 describe the dissatisfaction rate with the warm ceiling, taking into account the votes of the evaluated women, men, and all human subjects, at a draught effect of 15% and 25%.

The following notations were used in the tables:

- The *PD* [%], percentage of dissatisfaction with the warm ceiling when appearing with draught.
- The *AS* [^{o}C], radian thermal asymmetry between the floor and the ceiling.

Table 2. Equations for dissatisfaction with warm ceilings: women´s votes at 15% draught

$PD = 0.79AS - 2.17$	R^2 = 0.82	(1)
$PD = 7.89\ 10^{-2}AS^2 - 7.8\ 10^{-2}AS + 4.64$	R^2 = 0.9	(2)
$PD = -1.4\ 10^{-3}AS^3 + 1.23\ 10^{-1}AS^2 - 1.19AS + 5.8$	R^2 = 0.9	(3)

Table 3. Equations for dissatisfaction with warm ceilings: men´s votes at 15% draught

$PD = 0.62AS - 6.02$	R^2 = 0.86	(4)
$PD = 7.13\ 10^{-2}AS^2 + 0.21AS + 0.14$	R^2 = 0.88	(5)
$PD = -8.34\ 10^{-3}AS^3 + 2.59AS^2 - 23.53AS + 67.90$	R^2 = 0.99	(6)

Table 4. Equations for the dissatisfaction with warm ceiling: votes of all human subjects, 15% draught

$PD = 1.21AS - 4.10$	R^2 = 0.90	(7)
$PD = 7.51\ 10^{-2}AS^2 + 0.29AS + 2.38$	R^2 = 0.93	(8)
$PD = -4.24\ 10^{-3}AS^3 + 1.36AS^2 - 12.36AS + 36.85$	R^2 = 0.99	(9)

Table 5. Equations for dissatisfaction with warm ceilings: women´s votes at 25% draught

$PD = 0.38AS + 0.12$	R^2 = 0.77	(10)
$PD = 3.82\ 10^{-2}AS^2 - 0.38AS + 3.43$	R^2 = 0.84	(11)
$PD = 1.18\ 10^{-2}AS^3 - 0.32AS^2 + 2.98AS - 6.17$	R^2 = 0.88	(12)

Table 6. Equations for dissatisfaction with warm ceilings: men´s votes at 25% draught

$PD = 1.25AS - 5.96$	R^2 = 0.72	(13)
$PD = 0.26\ 10^{-2}AS^2 - 3.83AS + 16.07$	R^2 = 0.97	(14)
$PD = 1.21\ 10^{-2}AS^3 + 0.62AS^2 - 7.28AS + 25.93$	R^2 = 0.99	(15)

Table 7. Equations for dissatisfaction with warm ceilings: vote of all human subjects at 25% draught

$PD = 0.81AS - 2.92$	R^2 = 0.76	(16)
$PD = 0.15AS^2 - 2.10AS + 9.73$	R^2 = 0.98	(17)
$PD = 3.0010^{-3}AS^3 + 0.16AS^2 - 2.19AS + 9.98$	R^2 = 0.98	(18)

The impact of different parameters on dissatisfaction votes

Using the results presented in section *Result of human subject measurement*, the possible relationships between the votes of dissatisfaction with the warm ceiling and the gender of the subjects involved in the research were investigated, as well as the value of the DR.

The main aspects of the study were: exploring the significant differences between men´s and women´s thermal comfort votes, uncovering a significant change in dissatisfaction votes caused by increasing the DR from 15% to 25%, tracking the changes of the dissatisfaction votes caused by modifying the radiant thermal asymmetry, and describing the nature of these changes.

When evaluating the results, two sets of data were compared in each case. Their interdependence was examined using the Welch test and the Mann-Whitney test, as shown in Chapter 2.4. The conclusion regarding the dependency of the data series was accepted only if the same result was achieved using both methods.

The impact of gender on dissatisfaction votes

Figures 6 and 7 show the average values of dissatisfaction rates for women and men at DR = 15% and DR = 25%. Table 8 shows the results of the comparison of each series (at a DR of 15% on the left side and 25% on the right side of the table).

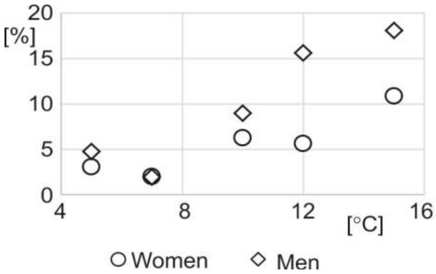

Figure 6. Women and men, DR = 15%

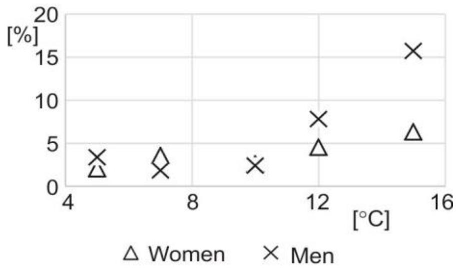

Figure 7. Women and men, DR = 25%

The following notations were used in the tables:

– t is the value of the test statistic calculated through the Welch test for the two data sets examined,
– W is the result of the Welch Test (D – dependent and I – independent),
– S is the value of two-tailed significance level, calculated through the Mann-Whitney test (above 0.05 it is considered dependent), and
– MW is the Mann-Whitney test result (D – dependent and I – independent).

Table 8. Statistical evaluation for women and men: DR = 15% and DR = 25%

	DR = 15%				DR = 25%			
DATA	t	W	S	MW	t	W	S	MW
5 °C	–3.933	I	$4.6\cdot10^{-5}$	I	–4.44	I	$6\cdot10^{-6}$	I
7 °C	0.324	D	0.739	D	5.83	I	$1.6\cdot10^{-10}$	I
10 °C	–4.130	I	$3\cdot10^{-6}$	I	0.64	D	0.480	D
12 °C	–12.189	I	$3.43\cdot10^{-27}$	I	–4.90	I	$2.15\cdot10^{-7}$	I
15 °C	–5.946	I	$2.67\cdot10^{-10}$	I	–8.75	I	$2.83\cdot10^{-8}$	I

At a DR of 15% the mean values of dissatisfaction for women and for men differed significantly: in every case (except 7 °C), the dissatisfaction rate of men was higher than that of women. In addition, the mean values and the significance level both show that the difference was exacerbated above a radiant thermal asymmetry of 10 °C.

At a DR of 25%, the mean value of the dissatisfaction rate for men and women was significantly different for all data points except for 10 °C. Above an asymmetry of 10 °C there was an increasingly pronounced difference in the percentage of dissatisfied.

The impact of draught on dissatisfaction votes

Figures 8-10 show the impact of draught on the percentage of dissatisfied in the case of all human subjects, as well as separately for women and men. Tables 9 and 10 show the results of comparing the data series.

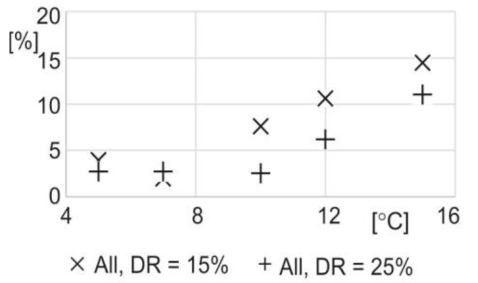

Figure 8. All votes, DR = 15% *vs.* DR = 25%

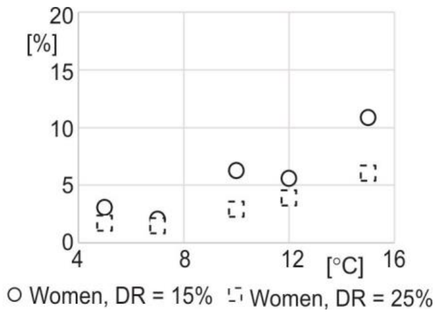

Figure 9. Women, DR = 15% *vs.* DR = 25%

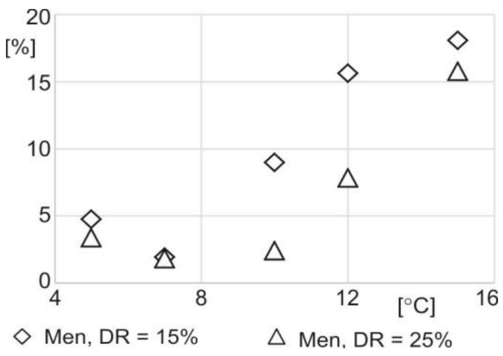

Figure 10. Men, DR = 15% *vs.* DR = 25%

Taking into account the vote of all human subjects, it can be stated that significantly different responses were obtained at each measurement point (5, 7, 10, 12, and 15 °C asymmetry), at draughts of 15% and 25%. Draught had a relevant effect on the percentage of dissatisfied with the warm ceiling.

The statistical indicators and the diagrams clearly show that truly relevant differences between votes at 15% and 25% were found above 10 °C. These values indicate a lower dissatisfaction with the asymmetry at 25% draught.

Considering women´s votes, it can be stated that there was a significant difference between the votes at each data point (except for 12 °C), so draught had a significant effect on women´s dissatisfaction with the warm ceiling.

Taking into account the votes of men, it can be stated that there was a significant difference in case of 10 °C and 12 °C. So, in case of these points, draught had a significant effect on men´s dissatisfaction due to the radiant thermal asymmetry caused by the warm ceiling.

Table 9. All votes, DR = 15% *vs.* DR = 25%

DATA	*t*	W	*S*	MW
5 °C	4.17	I	$9\cdot10^{-6}$	I
7 °C	–3.26	I	$1\cdot10^{-2}$	I
10 °C	13.67	I	$1.54\cdot10^{-4}$	I
12 °C	5.68	I	$2.59\cdot10^{-8}$	I
15 °C	3.32	I	$3.1\cdot10^{-5}$	I

Table 10. Statistical evaluation: men and women: DR = 15% *vs.* DR = 25%

	DR=15%				DR=25%			
DATA	*t*	W	*S*	MW	*t*	W	*S*	MW
5 °C	3.815	I	$2.2\cdot10^{-5}$	I	3.010	I	$2\cdot10^{-2}$	I
7 °C	–5.108	I	$1.22\cdot10^{-8}$	I	0.438	D	0.44	D
10 °C	8.253	I	$2.48\cdot10^{-16}$	I	11.281	I	$1.44\cdot10^{-28}$	I
12 °C	1.569	D	0.11	D	9.404	I	$5.39\cdot10^{-19}$	I
15 °C	4.978	I	$1.4\cdot10^{-7}$	I	1.729	D	0.42	D

The impact of increasing radiant thermal asymmetry

At a draught rate of 15%

This chapter examines whether there was significant difference in the data pairs measured at different radiant asymmetry values.

In the case of the evaluated women, at a DR of 15%, it can be stated that there were significant differences between the data points, except for the data pair 10-12 ^oC. Considering the mean values, it is clear that as the value of asymmetry increased, the percentage of dissatisfaction also increased with it. In the case of the evaluated men, at a DR of 15%, each pair of data was significantly different and an increasing tendency was shown also in this case. Taking into account the votes of all human subjects, at a draught effect of 15%, each data pair was significantly different, and the increasing nature could be observed in this case, as well.

It can be stated that increasing the amount of asymmetric radiation resulted in an increase of dissatisfaction at a draught effect of 15%.

At a draught rate of 25%

In the case of the evaluated women, at a DR of 25% the dissatisfaction rate increased with the increase of the radiant thermal asymmetry. However, the maximal dissatisfaction rate at a radiant thermal asymmetry of 15 ^oC was of 6%, which is almost negligible.

In the case of the evaluated men, all data points were significantly different, although the mean value of the points 5-7-10 ^oC stayed below 5%, and the statistical values showed that the difference was not pronounced. Significant difference was found at radiant thermal asymmetry values above 10 ^oC. This means that, with a draught effect of 25%, the dissatisfaction caused by the warm ceiling occurred at a radiant thermal asymmetry of more than 10 ^oC.

Taking into account all human subjects´ votes, it can be shown that the data points between 5 ^oC, 7 ^oC, and 10 ^oC were significantly the same. In other words, at a temperature of up to 10 ^oC, a higher draught of 25% had the following impact: increasing the temperature of the hot ceiling, and thus also increasing radiant thermal asymmetry had no significant effect on dissatisfaction with warm ceilings.

The data pairs 10-12-15 ^oC were significantly different from each other and their mean values showed a tendency of increasing. Thus, it can be stated that raising the radiant thermal asymmetry above 10 ^oC had a significant effect on the percentage of dissatisfaction with the warm ceiling.

Conclusion

The current paper has presented equations describing the dissatisfaction with the hot ceiling in the presence of draught. These equations have been described in function of radiant thermal asymmetry and time, taking into account the votes of women, men, and all human subjects. The equations showed first, second, and third degree fittings, also describing improvements in the fitting.

On the other hand, the relationship between data sets measured for different parameter groups have been investigated. The conclusions drawn examined the effect of gender and draught among the evaluated human subjects, as well as the effect of increasing radiant thermal asymmetry on the dissatisfaction with the warm ceiling. The results have been presented as follows.

- At an asymmetry of 5-15 ^oC, and 15% and 25% draught, women and men had significantly different votes of dissatisfaction with hot ceilings (with very few exceptions), with men having a higher rate of dissatisfaction with hot ceilings than women.
- At an asymmetry of 5-15 ^oC, increasing the draught effect from 15% to 25% significantly reduced the percentage of dissatisfied with the warm ceiling.

- In almost all cases, if asymmetry was increased, the percentage of dissatisfied with warm ceilings also increased; an exception was found at an asymmetry of 5-10 ^{o}C, and DR=25%, where increasing the radiant thermal asymmetry had no significant effect on dissatisfaction with warm ceiling.

Acknowledgment

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