OBJECTIVE AND SUBJECTIVE THERMAL COMFORT EVALUATION IN HUNGARY

by

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Original scientific paper
https://doi.org/10.2298/TSCI151005095K

Thermal comfort sensation can be predicted in the most exact way based on Fanger's predicted mean vote (PMV) model. This evaluation method takes all the six influencing factors into consideration: air temperature and humidity, air velocity, mean radiant temperature of surrounding surfaces, clothing insulation, and occupants' activities. Fanger's PMV method was developed for temperate climate and European people, with the participation of university students as subjects. Many researchers had investigated its validity in different geographic locations (i. e. climatic conditions, people) and under non-laboratory circumstances. The results were summarised by van Hoof which had been published in the scientific references. The articles gave us the idea to elaborate the former measurement results. During the last decades thermal comfort was evaluated by our research team using subjective scientific questionnaires and applying the objective Fanger's model in several office buildings in Hungary. The relation between the PMV and actual mean vote values were analysed based on these results.
Investigations were carried out under steady-state conditions in winter time. We performed objective thermal comfort evaluations based on instrumental measurements using the PMV theory. Parallel to this we assessed the subjective thermal sensation using scientific questionnaires. The mathematical relationship between the actual mean vote and PMV was defined according to the evaluated thermal environment:

$$AMV = PMV + 0.275, \ (\text{arg. } -1.7 \leq PMV \leq +0.5).$$

Key words: *thermal comfort, thermal neutrality, predicted mean vote, actual mean vote, desired thermal sensation*

Introduction

Based on the predicted mean vote (PMV) model many thermal comfort assessments were conducted in office buildings by our research team. Thermal comfort measurements were completed with the use of the thermal comfort scale. The relation between the values of PMV and actual mean vote (AMV) was determined. In Hungary such research has not been carried out yet. The results relate to Hungarian office buildings and office job.

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The international practical method of the thermal comfort analysis is the PMV-PPD theory. Professor P. O. Fanger [1] developed his theory in laboratories with university students (as living subjects) in temperate climate. His results can be found in international standards, too (*e. g.* ISO 7730, ASHRAE Standard 55, CEN CR 1752). Other researchers were also investigated the evaluation of the subjective and objective thermal comfort [2-5]

Van Hoof [6] summarized the results of the application of PMV in his article. He collected the studies from international literature into groups by the following topics: validation, thermal neutrality, desired thermal sensation, and differences among building types. Further researchers investigated the thermal comfort: Yoon *et al*. [7], Araujo and Araujo [8], Mayer [9], and de Paula Xavier and Roberto [10].

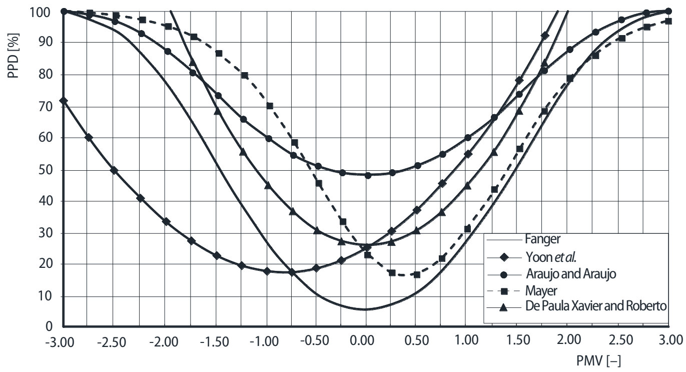

Figure 1. The relation between PMV and PPD [1]

The researchers determined the PMV-PPD function in the course of the validity analysis of the model [11]. The results of the validation of the *PMV* model can be seen in fig. 1. According to the researchers the primary reasons for the difference between the Fanger equation and their own result were the following:
– the measurements were field studies,
– there was natural ventilation in the rooms, and
– the environmental parameters differed from the European weather conditions.

The other group of researchers analysed the thermal environment in which subjects at different geographic locations sense thermal neutrality. These studies were made mainly in torrid climate zone of Asia [12, 13]. In their research they analysed, which thermal environmental condition was judged neutral by occupants in real buildings. Van Hoof [14, 15] summarized the results of ten surveys in the topic of neutral and desired temperatures.

In a given comfort space the thermal sensation number quantified by comfort questionnaires was named AMV. The researchers determined the relation between PMV-AMV with the help of living subjects, considering the climatic conditions, clothing habits and working culture in their own country. The thermal comfort was analysed with measuring instrument and it was evaluated on the thermal comfort scale using comfort questionnaires as well.

In office buildings the thermal comfort and indoor air quality determine the comfort sensation and influence productivity of occupants. To be efficient at work, one needs to be provided with comfortable environment regarding thermal sensation and indoor air quality [16-18]. International literature proves that the geographical location and its climate also influences the PMV model. We processed the results of our thermal comfort field studies conducted in office buildings in winter time. As air conditioned buildings are supplied with heated and treated fresh air, draught is not a characteristic parameter. Dissatisfaction with thermal comfort can be made independent from the effect of draught. The thermal comfort is influenced by the thermal transmittance of the building envelope (walls, windows) and by the radiative heat exchange. We carried out comfort analysis in summer time as well. In this case further effects are added to the dissatisfaction with thermal comfort. To avoid the draught effect of cooled fresh supply air, it is necessary to design, construct and operate in a professional way. However, the increased personal draught sensitivity cannot be eliminated totally. The direct solar radiation has a dominant part in terms of the cooling demand and the thermal sensation, therefore the use of shading devices is advisable.

In the office building two kinds of thermal comfort analysis were conducted. On one hand, PMV was determined by measurement, on the other hand subjects judged thermal sensation using a five-stage thermal comfort scale. The results were treated and evaluated applying the scientific research methods. This paper introduces these results.

Methods

By PMV theory analysis two parallel thermal comfort evaluations were made in the office building:
- measuring PMV values and air condition parameters, and
- thermal comfort analysis using scientific questionnaires, which can be expressed in average AMV.

In order to provide a scientific study of thermal comfort the following comfort parameters were measured in the office building:
- indoor air temperature and humidity, and
- PMV and PPD values.

Thermal comfort evaluations have been carried out in several office buildings. The opportunity for an all-round objective instrumental measurement and scientific thermal comfort evaluation was given only in few cases. In many cases office work order did not make this possible. According to these requirements the measurements were made in January and February 1996. During the measurements the outdoor air temperature varied from –2.0 ºC to –1.5 ºC [19-21]. The office building is nine floors high (five of them above the ground level); ground floor area is 45 × 65 m^2; useful internal volume is about 70000 m^3. On the five office floors there are landscape offices and single offices for one or two occupants. The office spaces are completed with further building service areas: corridors, entrance halls, garage and others. The temperature and humidity measurements were carried out in all rooms on the 3rd floor. This central floor represents the whole building in an adequate way. Due to the significantly longer measurement time the direct thermal comfort measurements (PMV, PPD) were made only in selected rooms on the third office floor.

The air temperature and humidity were measured with THERM 2246 and TESTO 610 measuring instruments; PMV and PPD were quantified with thermal comfort meter (type: B&K 1212). The questionnaire survey research included all the occupants (424 people). The answering was voluntary; number of respondents was 278 people (65.6%). From them 84 employees worked on the 3rd floor where the number of the filled questionnaires was 57 (67.9%).

Evaluating the thermal comfort, the following activity and clothing were taken into account (considering the characteristics of the local enclosures):
- activity level: M/A_{Du} = 1 met (quiet sitting),
  M/A_{Du} = 1.2 met (office work, using computer),
- clothing: I_{cl} = 1.0 clo (suit, typical businessman clothing),
  I_{cl} = 0.8 clo (suit without a coat).

Evaluation of the questionnaire survey was carried out with the help of the five-stage thermal comfort scale (cool, slightly cool, neutral, slightly warm, and warm) which is also applied in international studies.

Results

Results of the instrumental measurements

The instrumental measurement delivered values of air temperature and humidity, as well as it is necessary for the determination of PMV and PPD. In chosen characteristic offices on the 3rd floor the air temperature and humidity alongside with the PMV and PPD values were measured at 32 locations.

Table 1. The measured results of the air temperature, *t*, and air humidity, φ

	t [°C]	φ [%]
m	23.1	53.9
σ	0.77	2.4
max.	24.7	58
min.	21.8	48
$\Sigma N_{\text{measurements}}$	21.8	32

Air temperature and humidity:

The measuring rate was 5 min. In the chosen time period the evaluation of measured results (3rd floor) can be seen in tab. 1.

The PMV *and* PPD

The PMV and PPD measurements were carried out in the characteristic office rooms (12 enclosures) on the 3rd floor. The measuring locations were chosen in the occupied zone, including 3-4 measuring points in the landscape offices and 1-2 measuring points in the single office rooms. The total number of the measuring points was 21. In tab. 2 the measured results are presented, the evaluation based on the methods of mathematical statistics.

The thermal comfort evaluation was carried out for two activity levels (1 met, 1.2 met) and for two different values of clothing insulation (0.8 clo, 1.0 clo). Figure 2 shows the histograms of PMV measurements (3rd floor).

The results of scientific thermal comfort questionnaires

The results of thermal comfort questionnaires can be seen in tab. 3 according the five-stage scale. Figure 3 shows the related thermal sensation histograms (3th floor). For the mathematical evaluation the thermal sensation votes were corresponded with numbers 1-5.

The results of the responses can be evaluated with the methods of mathematical statistics and can be compared to the PMV values. Responses of questionnaires (cool = 1, warm = 5) give the AMV.

Table 2. The results of the thermal comfort measurement (3rd floor)

		Activity and clothing level		
	M/A_{du}	1.0 met	1.0 met	1.2 met
	I_{cl}	0.8 clo	1.0 clo	1.0 clo
PMV [–]	m	–1.13	–0.67	–0.17
	σ	0.38	0.31	0.25
	max.	–0.39	–0.12	0.28
	min.	–1.7	–1.2	–0.59
PPD [%]	m	38.4	17.5	6.9
	σ	19.8	9.9	2.5
	max.	72	38	12.4
	min.	9	5.8	5

Table 3. Answers of the thermal comfort questionnaires

Thermal comfort vote (AMV)	3rd floor		Whole bilding	
	N		N	
Cool (1)	3	5.3%	50	18.0%
Slightly cool (2)	24	42.1%	106	38.1%
Neutral (3)	18	31.6%	72	25.9%
Slightly warm (4)	9	15.8%	31	11.2%
Warm (5)	3	5.2%	19	6.8%
$\Sigma N_{\text{respondents}}$	57	100.0%	278	100.0%
$\Sigma N_{\text{employees}}$	84	67.9%	424	65.6%

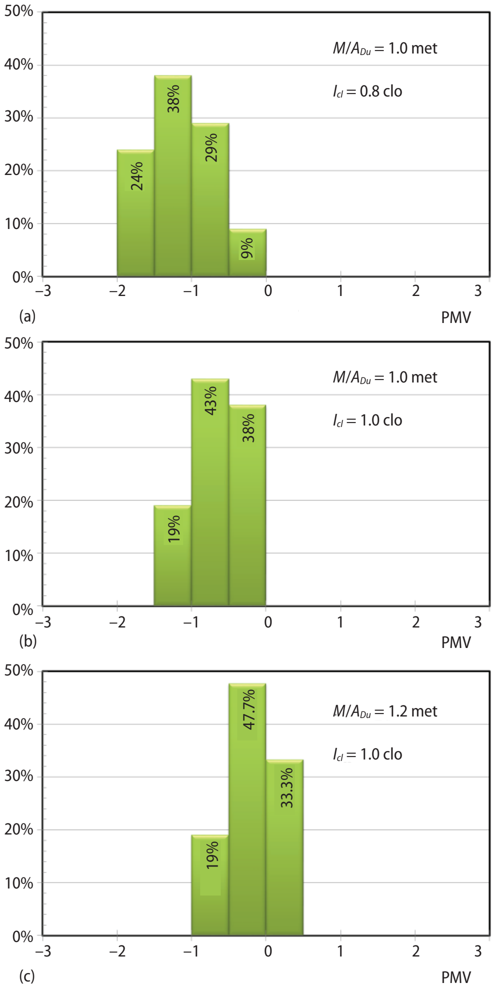

Figure 2. The histograms of PMV measurements with different activity and clothing level (3rd floor)

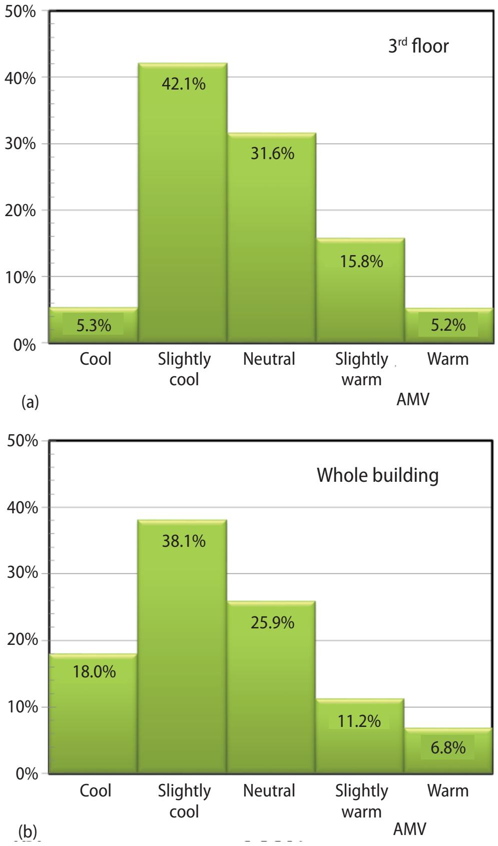

Figure 3. The results of the thermal comfort questionnaires: (a) on the 3rd floor and (b) in the whole building

Evaluation of results based on probability theory

We evaluated the data of the thermal comfort questionnaires and the instrumental measurements based on probability theory including homogeneity test. We investigated how the results of the 3rd floor represents the results of the whole building [22].

Homogeneity investigation

One of the objectives was to compare the answers of the comfort questionnaire from the 3rd floor with the whole building. The PMV measurements were only carried out on the 3rd floor. Therefore, the answers for the questionnaire from the 3rd floor and from the whole building were checked for homogeneity.

The homogeneity investigation was carried out with a χ^2-test. The calculated value of the test statistic for the 3rd floor and the complementary answers was 8.34. The critical value was determined from table for the four degrees of freedom and 0.05 significance level. The critical value was 9.49. The null hypothesis of the homogeneity of the answers was acceptable, tab. 4.

Table 4. Investigation of the homogeneity with χ^2-test between 3rd floor and rest of the building

Thermal comfort votes				Rel. freq.		χ^2
AMV	$N_{3^{rd}floor}$	$N_{whole\ build.}$	$N_{complement}$	3rd floor	Complement floors	
Cool (1)	3	50	47	0.053	0.213	6.087
Slightly cool (2)	24	106	82	0.421	0.371	0.242
Neutral (3)	18	72	54	0.316	0.244	0.714
Slightly warm (4)	9	31	22	0.158	0.100	1.072
Warm (5)	3	19	16	0.052	0.072	0.224
$\Sigma N_{respondents}$	57	278	221	Test statistic ($\Sigma\chi^2$): 8.34 Critical value: 9.49 Degrees of Freedom: 4 Significance: 0.08		

Comparison of the PMV results for temperature and relative humidity with all the other rooms

The 32 PMV measurements were carried out in certain rooms on the 3rd floor. The temperature, t, and relative humidity data, φ, of these rooms were compared to the data from the rest of the premises. In tab. 5 and tab. 6 the *non-PMV* sign corresponds to no PMV measured in the room where data were obtained. Therefore distributions of continuous data were compared and investigated by two-sample Kolmogorov-Smirnov test, Mann-Whitney test, Moses test and Wald-Wolfowitz test, tab. 6.

All tests prove the homogeneity. However, the significance level of homogeneity is lower for temperature data than for the relative humidity. According to the results, at 0.01 significance level all tests prove that the distribution is the same for the PMV measurements of temperature and humidity of the 3rd floor and the whole building.

Table 5. Statistics of the temperature and relative humidity data from the locations (PMV) and the rest of the premises (non-PMV)

Group		t [°C]	φ [%]
non-PMV	m	23,41	53,4
	$\Sigma N_{measurements}$	18	18
	σ	0,9	2,9
	max.	24,7	58
	min.	21,8	48
PMV	m	22,82	54,64
	$\Sigma N_{measurements}$	14	14
	σ	0,48	1,59
	max.	23,4	57
	min.	21,8	52
Whole building	m	23,15	53,9
	$\Sigma N_{measurements}$	32	32
	σ	0,79	2,4
	max.	24,7	58
	min.	21,8	48

Comparison of the probability variables

In research it is very common to compare data from different measurements. Considering the data points as probability variables, the problem belongs to homogeneity test investigations. The discrete variables can be compared with discrete variables or continuous variables with continuous variables tested with chi-square or single sample Kolmogorov-Smirnov test. In this case, the significance determines whether the distribution of variables can be assumed the same. The tests can be used to determine the homogeneity of independent variables. Other variation can be used to compare measured data points (connected samples) acquired simultaneously.

It is not that straightforward when discrete and continuous probability variables are compared. In this case, the distribution can not be the same. However, the comparison is valid, as both variables measure the same physical characteristic, only on a different scale. The problem can be analysed for connected variables with a regression method. There are limited mathematical tools when the samples are independent, as in this case. The thermal comfort data can be collected by five-point scale questionnaire (AMV) and measurement (PMV). The AMV data was five value discreet variable while the PMV was a continuous variable on [–3, +3] range. Therefore the momentum of the variables can be compared.

Table 6. Comparison of the temperature, *t*, and relative humidity, *φ*, of the PMV measurement points and the rest of the premises (with input values at the top and test statistic results at the bottom of the table)

Group		N	Mean rank	Sum of ranks
t [°C]	non-PMV	18	19.61	353
	PMV	14	12.50	175
	Whole building	32	–	–
φ [%]	non-PMV	18	14.75	265.5
	PMV	14	18.75	262.5
	Whole building	32	–	–
Test statistics*			t	φ
Mann-Whitney U			70	94.5
Wilcoxon W			175	265.5
Z			–2.13	–1.21
Asymp. Sig. [2 – tailed]			0.03	0.22
Exact Sig. [2·(1 – tailed Sig.)]			0.03**	0.23**

* Grouping variable: group
** Not corrected for ties

The actual thermal comfort of the employees X (AMV) was acquired by questionnaire in all premises on every floor. The workers can express the thermal comfort on a five-point scale considering office work (1 met) and office wear (1 clo) (Values of scale: 1 = cool, 2 = slightly cool, 3 = neutral, 4 = slightly warm, and 5 = warm.). The X was a discrete probability variable with value set, $R_x = \{1,2,3,4,5\}$, and distribution $p_i = \mathbf{P}(X = i)$ (values from tab. 3).

This variable Y was compared with the expected thermal comfort value (PMV). The Y was a continuous probability variable (likely to be approximated by normal distribution), with values between –3 and +3. Data for Y was acquired on the 3rd floor simultaneously with X measurements with the same external conditions. The two samples have to be considered independent because the number of elements and the location of measurement were different.

In the first step, X was linearly transformed to [–3, +3] range, the range of Y continuous probability variable:

$$\tilde{X} = 1.5\left(X - 3\right) \tag{1}$$

Expected value of transform:

$$\mathbf{E}(\tilde{X}) = 1.5\left[\mathbf{E}(X) - 3\right] \tag{2}$$

Deviation:

$$d = \boldsymbol{\sigma}(\tilde{X}) = 1.5\boldsymbol{\sigma}(X) \tag{3}$$

Then constants α and β were calculated when:

$$\mathbf{E}\left(\alpha\tilde{X} + \beta\right) = \mathbf{E}(Y), \quad \boldsymbol{\sigma}\left(\alpha\tilde{X} + \beta\right) = \boldsymbol{\sigma}(Y) \tag{4}$$

The comparison of expected values and deviations shows the tab. 7.

The measurement showed lower values compared to the questionnaire. However, the deviation was smaller than by the questionnaire as it was also expected.

Table 7. The comparison of mean values and deviations

	Mean value	Deviation	α	β
X (PMV)	2.51	1.117	–	–
$\tilde{X}$ (PMV)	–0.735	1.68	–	–
Y (PMV) /1 met, 1	–0.67	0.31	0.185	–0.534

Conversion of probability variables

The next step was to determine how the two variables can be transformed to each other, so to express X (AMV) as a function of Y (PMV) or vice versa. The linear transformation formula is based on the expected value and the deviation is:

$$\alpha \tilde{X} + \beta = 1.5\alpha X + \beta - 4.5\alpha \approx Y \qquad (5)$$

Using the data from tab. 7 in case of M/A_{Du} = 1 met, I_{cl} = 1 clo:

$$Y \approx 0.185X - 0.534 \qquad (6)$$

*The X (*AMV*) expressed as a function of Y (*PMV*)*

Assuming that Y follows normal distribution with parameters m and σ. The variable Y takes its values with 90% confidence in the interval:

$$\left(m - 1.5\sigma,\ \ m + 1.5\sigma\right) \qquad (7)$$

So the variable X takes its values with 90% confidence in the interval:

$$\left(\frac{m + 4.5\alpha - \beta - 1.65\sigma}{1.5\alpha},\ \ \frac{m + 4.5\alpha - \beta + 1.65\sigma}{1.5\alpha}\right) \qquad (8)$$

*The Y (*PMV*) expressed as a function of X (*AMV*)*

Continuous probability value is more difficult to fit with a discreet probability variable. However, if there are sufficient data points for X, then the average follows normal distribution based on the central limit theorem. Therefore Y can be estimated. If there are N samples for X, then the transformed $\tilde{X} = 1.5(X - 3)$ average follows distribution of $N[\mu;d/(n)^{1/2}]$. So the values are in the range ($\mu - 1.65d/(n)^{1/2}$, $\mu + 1.65d/(n)^{1/2}$) with 90% confidence. The estimated values $Y = \alpha\tilde{X} + \beta$ can be found in the range ($\alpha\mu - 1.65d/(n)^{1/2} + \beta$, $\alpha\mu + 1.65d/(n)^{1/2} + \beta$).

The results of the PMV measurements considering 1 met activity level and 1 clo clothing insulation: average –0.67. The AMV-PMV relation equation is defined in the range of thermal neutrality. The AMV value is slightly lower:

$$AMV = PMV + 0.275 \qquad (9)$$

Based on the evaluated thermal environment parameters the mathematical relationships between AMV and PMV are valid in the range of $-1.7 \leq PMV \leq +0.5$.

Conclusions

In the office building complex thermal comfort measurements were carried out under steady-state conditions in winter time. Results were analysed and the theoretical quantifications and evaluations were also performed. The results can be summarised with the following general conclusions:

- The results of the thermal comfort questionnaires approach with high accuracy the results of PMV measurements considering clothing insulation and the activity level that represents the office work. The results of the PMV measurement considering 1 met activity level and 1 clo clothing insulation: average –0.67. The AMV-PMV relation equation is defined in the range of thermal neutrality. The AMV value is slightly lower.

$$AMV = PMV + 0.275 \tag{10}$$

- Based on the evaluated thermal environment parameter the mathematical relationships between AMV and PMV are valid in the range of $-1.7 \leq PMV \leq +0.5$.
- In respect of the deviation of results it can be ascertained that the deviation is higher in case of the questionnaires. It is 4.67-fold higher (by stetting 1 clo, 1 met) than in the case of the instrumental measurement. This could be expected considering the general difference between measurements carried out with instruments or with living subjects, which was quantified as well.
- Under Hungarian circumstances based on measurement results of conditioned office studies it can be ascertained, that the Fanger's PMV-PPD method for thermal sensation evaluation is applicable adequately. The difference between PMV and AMV values is minimal. In Hungary such a complex thermal sensation research and field study had not been conducted before. The presented results clearly certified the applicability of the PMV model.

Acknowledgment

This work is connected to the scientific program of the *Development of quality-oriented and harmonized R+D+I strategy and functional model at BME* project. This project is supported by the Szechenyi Development Plan (Project ID: TAMOP-4.2.1/B-09/1/KMR-2010-0002). Sustainable energetic. Increasing the efficiency of air conditioning systems. Project leader: Dr. Laszlo Kajtar.

Nomenclature

AMV – actual mean vote, [–]
clo – clothing, thermal insulation of clothing, [1 clo = 0.155 m^{2}KW^{-1}]
d – deviation of probability variable, [–]
E – expected value of probability variable, [–]
I_{cl} – thermal insulation of clothing, [clo]
m – mean value of probability variable, [–]
met – metabolic rate of humen body, [1 met = 58.2 Wm^{-2}]
M/A_{Du} – activity level, [met]
N – number of data values (*e. g.* persons, measurements), [–]
P – probability function, [–]
PMV – predicted mean vote, [–]
PPD – predicted percentage of dissatisfied, [%]
p_i – p-value, probability value, [–]
R_x – codomain of variable *X*, [–]
t – air temperature, [°C]
X – discrete probability variable, [–]
$\tilde{X}$ – transformed discreet probability variable, [–]
Y – continuous probability variable, [–]

Greek symbols

α, β – constant, [–]
μ – expected value of standard deviation, [–]
φ – relative air humidity, [%]
σ – standard deviation of probability variable, [–]

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Paper submitted: October 5, 2015
Paper revised: March 12, 2016
Paper accepted: April 28, 2016