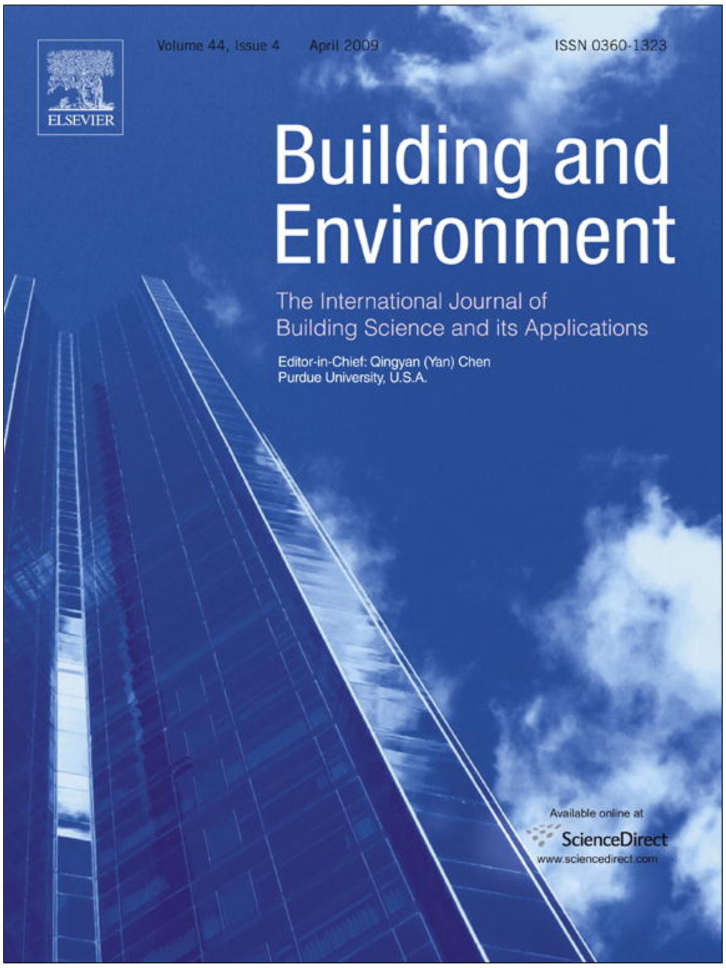
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Adaptive analysis of thermal comfort in university classrooms: Correlation between experimental data and mathematical models

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ABSTRACT

Numerous studies are in progress to support adaptive models in indoor thermal comfort evaluation and to establish quantitative indexes to allow the subject to optimize his/her comfort conditions.
A wide experimental campaign was carried out in moderate environments, such as university classrooms, and a multiple choice questionnaire was elaborated, comprehensive of information for the static and adaptive model proposed by UNI EN ISO 10551, in order to find a correlation between experimental data measured by the instruments and subjective responses given by the occupants. The questionnaire was applied in autumn, winter and spring in classrooms of the University of Perugia, Terni and Pavia. During the campaign, all data needed to calculate both Fanger and Wray comfort indices were acquired by instrumental surveys and questionnaire compilation. By means of results' analysis of both questionnaires and measurements, the following couple of parameters (derived from Fanger and Wray) were correlated: Predicted Mean Vote (PMV) versus the difference between the Equivalent Uniform Temperature and the Comfort Uniform Temperature ($T_{eu} - T_u$) and the Predicted Percentage of Dissatisfied (PPD) versus the absolute value of the same difference between temperatures ($|T_{eu} - T_u|$). For the first couple of parameters, a linear correlation was found while for the second one a second-degree polynomial relation was obtained. Better correlation was found for measurement data rather than questionnaire results. Finally values of Operative Temperature T_0 and Equivalent Uniform Temperature T_{eu}, obtained for each single experimental survey, were compared, observing a very good agreement between the two quantities, with differences that exceed 0.1 K only for a few number of values. Questionnaire and experimental PMV data were also correlated to T_0: higher values of questionnaire than instrumental PMV were obtained for the same value of T_0.

1. Introduction

Thermal-hygrometry comfort inside moderate environments is having a slow, but indispensable revision process (UNI EN ISO 7730, UNI EN ISO 10551 and ASHRAE Standard 55/2004 [1–3]). Many studies, in the recent years, dealt with the evaluation of the thermal comfort in classrooms, residential and office buildings [4–11] in different parts of the world, characterized by different climatic conditions and architectural configurations. A comparison between calculated data of the main environmental indexes, such as PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied), and the answers of the occupants is often carried out [12–16]. Results generally show that thermal sensation votes do not correspond to calculated Predicted Mean Votes, while a good agreement is found with adaptive comfort models.

Papers in the literature confirm that the adaptive approach is indispensable to correctly evaluate thermal comfort; the first studies on the adaptive models [17,18], also correlated to the International Standards [19], were applied in different conditions such as uniform and non-uniform [20], in different buildings and parts of the world, such as offices, houses, working places, and naturally conditioned buildings in Tunisia, The Netherlands, India, Japan, and Hong Kong [21–27]. Adaptive algorithms were also developed: Adaptive Control Algorithm for temperature set-point control [28]; new notions about adaptive comfort temperature to pre-set the indoor air temperature as a function of the outdoor one [29]; the thermal interaction in transient condition as a function of clothing and air velocity [30]; a theoretical comfort equation for sleeping persons modifying Fanger equation [31].

The aim of the present paper is finding the most possible general and simple correlations, for moderate environments such as university classrooms, between experimental data and surveys carried out in accordance with standards UNI EN ISO 7730, UNI EN

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Nomenclature

A	activity level (met, W/m^2)
ECDI	environmental control dissatisfaction index (%)
ET*	effective correct temperature (°C)
f_{cl}	ratio of surface area of clothed body to surface area of nude body (–)
h_c	convective heat transfer coefficient from clothing surface to air (W/m^2 K)
I_{cl}	clothing thermal insulation (clo, m^2 K/W)
L	thermal load (W/m^2)
(M)	men
PPD	predicted percentage of dissatisfied (%)
PMV	Predicted Mean Vote
PVTGI	preference vertical thermal gradient index (%)
T	temperature (°C)
TAI	thermal annoying index (%)
TDI	thermal dissatisfaction index (%)
TPI	thermal preference index (%)
TUI	thermal unacceptability index (%)
UAMI	unacceptable air movement index (%)
UVTGI	unacceptable vertical thermal gradient index (%)
v	speed (m/s)
(W)	women
ϕ	relative humidity (%)

Subscripts and superscript

a	air
av	average between T_{cl} and T_{mr}
ext	external
mr	mean radiant
*	measured temperature in the Wray model nomenclature
1	calculations in compliance with UNI EN ISO 7730/2006
2	calculations in compliance with ISO DIS 7730/2003

ISO 10551 and ASHRAE Standard 55/2004 [1–3] and with the occupants' sensations, by introducing the adaptive approach.

A research team of the Section of Applied Physics of the Department of Industrial Engineering of University of Perugia, in cooperation with the Department of Hydraulic and Environmental Engineering, University of Pavia, is carrying out a comfort analysis inside university classrooms since a few years. The research consists in wide experimental surveys, based on the acquisition of the principal comfort indexes by means of measurements of the environmental thermo-hygrometric parameters and calculation of the main thermal comfort indexes such as PMV and PPD; subjective evaluations were also considered, articulated on a statistically significant number of people present during the surveys and based on both traditional static models and more recent adaptive models [32–34].

In particular, the experimental campaign was carried out on three classrooms, different for geographical position and exposure, HVAC systems and architectural characteristics. Internal environmental measurements were correlated with external surveys in various days representative of autumn, winter and spring conditions.

In the meantime, questionnaires, specifically elaborated in compliance with standard UNI EN ISO 10551, were distributed to the occupants of the classrooms. In the post-processing phase, survey results were compared to the answers given by the occupants and interesting correlations were found.

The present work is aiming to employ the experimental results, obtained in the different above-mentioned measurement campaigns, in models from the literature. Specifically, the comparison was carried out considering the model of Wray [35] (described in Section 1.1) that, on the basis of Fanger comfort equation [36], introduces a new thermal index, called Uniform Equivalent Temperature.

Furthermore, it is interesting to evaluate the thermal comfort of an indoor environment using the index introduced by Wray, more intuitive and rapid in applications, such as the Uniform Temperature (T_u); scope of the research is also to verify if the index, found for passive solar heated buildings, could be used also for these specific types of moderate environments, with different conventional HVAC systems.

For each measurement day, in correspondence with each single instrumental acquisition, mean values of the required parameters were calculated, in relation to typical clothing of the occupants. In this way, a first series of values of PMV and PPD were obtained. For the same surveys, in accordance with Wray model, the optimal conditions of Uniform Temperature (T_u) and the real ones expressed by Equivalent Uniform Temperature (T_{eu}) were calculated. The difference between optimal and real values was correlated to the traditional indexes PMV and PPD, aiming to evaluate the model approach feasibility with traditional procedures proposed by Fanger. A linear correlation between $T_{eu} - T_u$ versus PMV, and a second-order regression polynomial between $|T_{eu} - T_u|$ versus PPD were found for questionnaire and survey data.

Finally, an additional correlation between the Operative Temperature and Uniform Equivalent Temperature was investigated, observing a very good agreement between the two quantities, with differences that exceed 0.1 K only for a few number of values.

1.1. Wray model

The model proposed by William O. Wray [35] was originally conceived for assessing thermal comfort levels in passive solar heated buildings. Nevertheless each consideration could be extended to each sort of environment presenting a quite significant non-uniform thermal distribution. As alternative to the two indexes proposed by ASHRAE Handbook [37] to characterize uniform thermal environments (Operative Temperature and Humid Operative Temperature), considered by Wray too specific and not explicitly correlated with comfort conditions, he introduces a more general single thermal index, called Equivalent Uniform Temperature (T_{eu}). T_{eu} is defined as the uniform temperature ($T_{eu} = T_{mr} = T_a$) of an imaginary enclosure in which a person will experience the same degree of thermal comfort as in the actual non-uniform environment. The Fanger thermal comfort equation [36] is the theoretical foundation of Wray model. On the hypothesis of skin surface temperature and sweat secretion rate functionally related to the metabolic activity level (by empirically determined formulae) and by linearising the fourth-degree parameters due to heat transfer for radiation, the Fanger equations turn out to be:

$$
\begin{aligned}
L = {} & A - 0.41[43 - 0.052A - 1.92\phi(T_a - 273) + 25.3\phi] + \\
& - 0.49(0.86A - 50) + 0.0023A[44 - 1.92\phi(T_a - 273) \\
& + 25.3\phi] - 0.0014A(307 - T_a) + 1.58 \times 10^{-7} \\
& f_{cl} T_{av}^3 (T_{cl} - T_{mr}) - f_{cl} h_c (T_{cl} - T_a)
\end{aligned}
\tag{1}
$$

By solving Eq. (1) under the constraints $L = 0$ and $T_{mr} = T_a = T_u$, Wray defined the Uniform Comfort Temperature T_u as the uniform temperature of an enclosure where the subject is in optimal thermal conditions (heat load set equal to zero). This is the objective to reach in order to obtain thermal comfort. As a consequence, the difference $(T_{eu} - T_u)$ measures the distance from comfort conditions in the actual considered environment. The model proposed by Wray can be represented in a graph [35] $T_a - T_{mr}$, where the line of the uniform temperature is the bisector ($T_a = T_{mr}$). From the linearised Fanger equation it is possible to find all the combinations of T_a and T_{mr} that determine the optimal comfort level ($L = 0$): all these combinations are presented in the graph by a negative slope line s, called Comfort Line. The intersection between this line and the one of the uniform temperature represents T_u. Each real non-uniform environment is represented in the graph by a point, localized by its temperatures T_a^* and T_{mr}^*. Tracing from this point the parallel to the comfort line, the intersection with the uniform temperature line identifies T_{eu}. By means of simple geometrical relations, T_{eu} can be calculated as follows:

$$T_{eu} = \left(\frac{1}{1-s}\right)T_{mr}^* + \left(\frac{s}{s-1}\right)T_a^* \tag{2}$$

where, in general, $s = s\,(A, I_{cl}, f_{cl}, h_c, \phi)$.

1.2. Standards of reference

Thermal comfort is regulated in many aspects by numerous international standards. In particular, for thermal moderate environments, an important standard is UNI EN ISO 7730/2006 [1], which defines the comfort indexes PMV and PPD. Another well-known standard is ASHRAE Standard 55/2004 [3], which defines the range of optimal thermal-hygrometric comfort conditions.

UNI EN ISO 7730/2006 introduces classes of acceptability and concepts of thermal dynamic clothing insulation and adaptation and proposes to classify thermal environments in small categories, distinguishing more acceptable limit conditions. In ASHRAE Standard 55/2004, the index ET (Effective Corrected Temperature) disappears and is substituted by PMV and PPD, representing an analytic evaluation method. It is alternative to the graphic method, already present in the 1992's version, and to the new one referred to natural ventilated environments.

UNI EN ISO 7730/2006, related to thermal-hygrometric comfort conditions in moderate thermal environments, is based on a static model where the human occupancy is considered as a passive subject of thermal exchange. The model prescribes optimal temperatures (almost constant) and values of six independent variables (temperature, relative humidity, air velocity, mean radiant temperature, clothing thermal insulation, metabolic activity level). In the latest years numerous researchers raised doubts about validity of this assumption that does not take into account climatic, cultural, social and contextual factors. They introduced the concept of adaptation, which considers the context and the thermal history of the subject and how they can modify expectations and thermal preferences of occupants [38–40].

The adaptive model introduces control and answer algorithms that allow to improve the thermal comfort level and to reduce energy consumption. In the adaptive model the subject, consciously or unconsciously, plays an active rule in reaching satisfaction about microclimate. The subject himself/herself interacts in the adaptive process, by reducing his/her individual reactions to environmental stimulus.

Three kinds of adaptation are distinguished:

- behavioral: changes that a person puts in practice, consciously or not, in order to modify parameters that regulate body thermal balance; it could be classified into personal, technological and cultural;
- physiological: the extended exposure to particular thermal conditions reduces stress. In typical conditions of moderate environments this adaptation has a little influence on comfort perception;
- psychological: previous experiences and expectations modify the sensation of sensorial stimulus and the reaction to them.

Analysis of statistical data by Dear and Brager [41] shows that the behavioral mechanism of adaptation gives to people an active rule in maintenance of the personal comfort because it is directly linked to the thermal balance of human body.

Other researchers of the adaptive model proposed relationships for environmental evaluations; in particular a model was analyzed, where an optimal variable temperature was introduced, as a function of the external meteorological conditions, the previous thermal experiences and the current occupants' expectations [37].

Nevertheless none of the proposed models has yet confirmations and agreement; therefore, UNI EN ISO 7730/2006 considers adaptation in a qualitative way. Many studies are now taking place to support adaptive models, aiming to introduce quantitative indexes for actions of people to enhance their comfort conditions.

2. Measurement campaign: methodology

2.1. Experimental surveys

The experimental data presented in this work were collected from measurement campaigns carried out in University classrooms, different for architectural characteristics, geographical locations, dimensions, capacity, HVAC systems and solar radiation exposure. In particular, the subjects of the investigation, already presented in previous studies [32,34], are three classrooms:

- Classroom F of the Faculty of Engineering of University of Perugia (Italy), Perugia (in the following named Classroom 1);
- Classroom 2 of the Faculty of Engineering of the University of Perugia (Italy), Terni (in the following named Classroom 2);
- Classroom 8 of the Faculty of Engineering of the University of Pavia (Italy), Pavia (in the following named Classroom 3).

The campaign took place during autumn, winter and spring seasons in the years 2004 and 2005.

Measurement methodology was based on the acquisition of thermal-hygrometric parameters defined by UNI EN ISO 7730/2006 [1], UNI EN ISO 10551/2002 [2] and ASHRAE Standard 55/2004 [3], useful for an evaluation of comfort through both the traditional method and the new adaptive approach. Also external climatic conditions were monitored; for a comparison with the experimental data, climatic data of the sites given by the Italian technical normative UNI 10349 are reported in Table 1.

The experimental campaign was carried out employing two microclimatic measurement sets, which matched the specifications of ISO 7726 [42]:

- Babuc set by LSI;
- HSA DGT set by TCR Tecora;

Babuc is a storage acquisition system; the program acquisition rate varies from 1 s up to 24 h; the operator can choose between many different statistic elaboration sets. Babuc is provided with 11 channels where it's possible to connect different thermo-hygrometric sensors; the characteristics of the probes are reported in Table 2.

HSA DGT is a multichannel data acquisition used to register and to work out many thermo-hygrometric parameters. It can print immediately the results, choosing from a different set of

Table 1
Classroom, location and measurement campaigns' features.

Classroom	1	2	3
Location	Perugia	Terni	Pavia
Altitude (a.s.l.)	493 m	130 m	77 m
Monthly avg. temperature (°C) [UNI 10349]	Nov: 9.4 Dec: 5.5 May: 15.4	Feb: 7.6 Mar: 10.7 May: 17.6	Mar: 8.4 May: 17.1 June: 21.3
Capacity (seats)	300	96	160
Windows	Yes	No	Yes
Stand	No	No	Yes
HVAC systems	Air	Air and water	Air
Survey number	5	4	6
Survey period	Autumn (Nov.–Dec. '04) Spring (May '05)	Winter (Feb.–Mar. '05) Spring (May '05)	Winter (Mar. '05) Spring (May–Jun. '05)
Questionnaire number	520	66	373

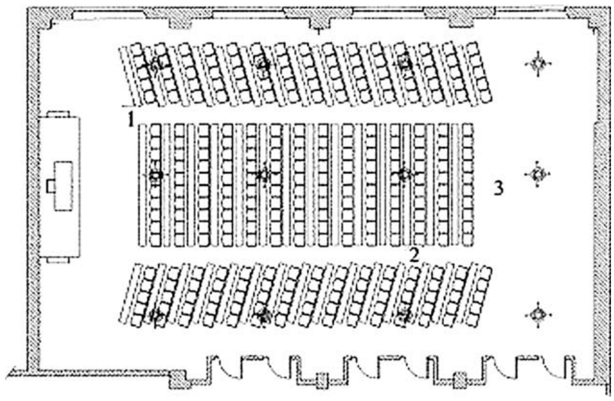


Fig. 1. Plan of Classroom 1 and measurement points (1, 2 and 3).

informations; the standard transducers' characteristics are reported in Table 2. Thermo-hygrometric conditions in the classrooms were measured in different points (at about 1.1 m height), in order to evaluate their spatial uniformity.

The following parameters were measured:

- forced airy dry bulb temperature (Babuc and HSA);
- forced airy wet bulb temperature (Babuc and HSA);
- dew point temperature (Babuc);
- globothermometer temperature (Babuc and HSA);
- mean radiation (Babuc);
- plane asymmetry radiant temperature (Babuc);
- mean air velocity (Babuc and HSA);
- floor surface temperature (Babuc);
- air temperature at neck level and ankle level (Babuc);
- CO_2 amount (Babuc).

A plan of Classroom 1 is presented in Fig. 1; the measurement points are indicated:

- points 1 and 2 for BABUC;
- point 3 for HSA DGT.

In Fig. 2 a plan of Classroom 2 is presented with measurement points:

- point 1 for BABUC;
- point 2 for HSA DGT.

Fig. 3 shows a plan of Classroom 3 with measurement points:

- points 1, 2 and 3 for BABUC;
- point 4 for HSA DGT.

Measurement points were chosen considering students' positions in the classroom and collocation of the most crowded zones, cold or warm vertical surfaces' position (i.e. windows) and possibility to place instruments.

The acquisition rate for each of the measured parameter was 20 s; therefore, about 5800 data for each of them were acquired.

Classrooms' characteristics and main measurement data are reported in Table 1, while the HVAC systems' characteristics and their operating conditions are reported in Table 3.

2.2. Questionnaire surveys

Data about subjective comfort sensation were also considered through questionnaires distributed to the occupants. A specific questionnaire was elaborated from the model presented in UNI EN ISO 10551/2002 [2] and integrated with additional questions regarding the possibility of individual microclimatic control in the environment, in order to study the behavioral aspects of human–thermal environment interaction also by the adaptive approach. A synthetic version of the questionnaire is reported in Appendix. It is subdivided into three different parts:

Table 2
Data acquisition systems – characteristics of the main probes.

Babuc		
Probe	*Operative range*	*Accuracy*
Air temperature	−50 to 80 °C	±0.17 °C
Hot wire	0–50 m/s	±0.05 m/s for $v_a = 0$–0.5 m/s ±0.1 m/s for $v_a = 0.5$–1.5 m/s ±4% for $v_a > 1.5$ m/s
Black dull copper globethermometer	−50 to 100 °C	±0.17 °C
Psychrometer	Temperature −50 to 150 °C Relative humidity from 40 to 100%	Temperature ± 0.13 °C Relative humidity ± 2%
Radiometer	−150 to 1500 W/m^2	±3%
Double air temperature	−50 to 80 °C	±0.17 °C
Carbon dioxide	0–3000 ppm	1 ppm
HSA DGT		
Probe	*Operative range*	*Response time*
Globethermometer	−40 to 95 °C	10–15 min
Psychrometer	−40 to 95 °C	10 min
Anemometer	0.1–2.5 m/s	–
Naturally airy wet bulb	−40 to 95 °C	10 min

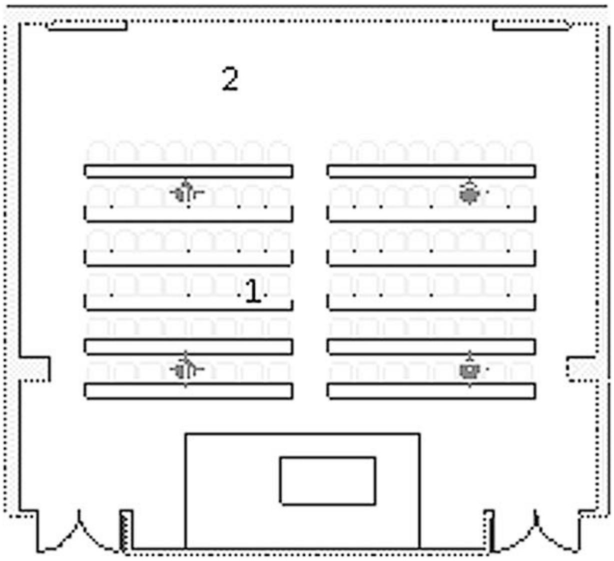


Fig. 2. Plan of Classroom 2 and measurement points (1 and 2).

- Part 1: personal data (age and sex);
- Part 2: thermal aspects (judgement about tolerability of thermal environment, air movement, temperature difference between head and ankle [36]; activity performed in the last 10, 20, 30 and 60 min; eventual preference for different conditions);
- Part 3: individual microclimatic control (interaction possibility with environmental microclimate conditions through doors and windows' opening, building services' regulations, etc. and satisfaction about possibilities of action; position inside the room, to be indicated in the classroom plan).

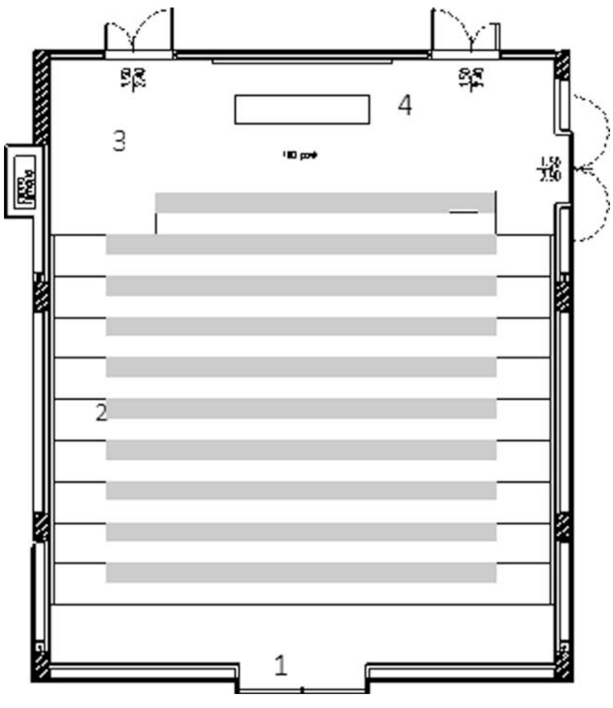


Fig. 3. Plan of Classroom 3 and measurement points (1, 2, 3, and 4).

Table 3
HVAC systems' features and operating conditions in the Classrooms 1, 2 and 3 during the surveys.

	Classrooms		
	1	2	3
	HVAC systems		
	Air	Air–water	Air
In room terminals	Round ceiling diffuser	Fan-coils	Square ceiling diffuser
Survey	Status (season)		
1	On (autumn)		On (winter)
2	On (autumn)	On (winter)	On (winter)
3	On (autumn)	On (winter)	On (spring)
4	Off (spring)	On (winter)	On (spring)
5	Off (spring)	Off (spring)	Off (spring)
6			Off (spring)

The total number of questionnaires was 959 (shared as shown in Table 1); a statistically significant number of samples was finally disposable.

Both measurements and questionnaire distribution took place 30 min after the beginning of the lesson, in order to allow the students and instruments to adjust to the environmental conditions.

In the elaboration of questionnaires the following aspects were taken into account:

- average age of the subjects;
- Predicted Mean Vote (PMV);
- dispersion of PMV around its mean value;
- thermal dissatisfaction index (TDI) [%], defined as the ratio *dissatisfied persons/persons who express a judgement* (it is evaluated as the percentage of persons who have answered "light annoyance, annoyance, heavy annoyance" to the question "what is your thermal sensation?");
- thermal preference index (TPI) [%], defined as the ratio *persons who want to change/persons who express a judgement* (it is evaluated as the percentage of persons who have answered "much too cool, too cool, a little bit cool, a little bit warm, too warm, much too warm", to the question " how would you like to feel?");
- thermal unacceptability index (TUI) [%], defined as the ratio *persons who consider unacceptable/persons who express a judgement* (it is evaluated as the percentage of persons who have answered "no, it is not acceptable" to the question "On the basis of your personal preferences, how would you consider the room temperature acceptable or unacceptable?");
- thermal annoying index (TAI) [%], defined as the ratio *persons who cannot tolerate it/persons who express a judgement* (it is evaluated as the percentage of persons who have answered "slightly hard to tolerate, hard to tolerate, very hard to tolerate, intolerable" to the question "how do you consider this room?");
- unacceptable air movement index (UAMI) [%], defined as the ratio *persons who express a negative judgement/persons who express a judgement* (it is evaluated as the percentage of persons who have answered "completely not acceptable, not acceptable, slightly not acceptable, slightly acceptable" to the question "how do you feel about the air flow in this moment?");
- unacceptable vertical thermal gradient index (UVTGI) [%], defined as the ratio *persons who express a negative judgement/persons who express a judgement* (it is evaluated as the percentage of persons who have answered "completely not acceptable, not acceptable, slightly not acceptable, slightly acceptable" to the question "how you consider the temperature difference between head and ankle?");

Table 4
Synthesis of measured data in Classrooms 1, 2 and 3.

Classrooms	S	1	Std dev	Avg	2	Std dev	Avg	3	Std dev	Avg
T_{ext} [°C]	1	12.4	0.09	15.0	5.2	0.20	9.6	6.1	0.18	18.3
	2	11.1	0.17		4.8	0.38		11.7	0.60	
	3	12.3	0.15		8.8	0.24		20.6	1.77	
	4	17.7	0.32		19.7	0.11		22.4	0.08	
	5	21.5	0.19		–	–		22.6	0.33	
	6	–	–		–	–		26.6	0.24	
RH_{ext} [%]	1	70.5	2.54	72.9	62.1	2.26	65.2	48.0	2.87	48.5
	2	96.3	1.46		98.3	1.46		28.4	3.63	
	3	89.8	2.45		51.2	3.48		60.9	6.92	
	4	55.3	4.21		49.0	3.00		53.2	1.59	
	5	52.8	2.05		–	–		62.2	1.46	
	6	–	–		–	–		38.3	2.55	
T [°C]	1	22.5	0.11	24.2	21.2	0.62	22.1	22.6	0.81	24.2
	2	24.1	0.50		24.8	0.82		21.7	0.79	
	3	24.2	0.98		20.9	0.10		24.0	0.25	
	4	24.4	0.46		21.3	0.14		24.8	0.29	
	5	25.8	0.30		–	–		26.4	0.35	
	6	–			–	–		25.9	0.99	
RH [%]	1	50.9	3.98	47.7	63.7	2.05	56.8	30.5	2.49	41.0
	2	45.3	2.17		53.4	2.67		25.0	3.39	
	3	49.7	3.06		60.1	1.62		52.9	1.91	
	4	45.6	2.49		50.0	0.00		50.8	2.02	
	5	47.0	1.71		–	–		49.0	1.35	
	6	–	–		–	–		37.5	1.80	
T_{mr} [°C]	1	23.2	0.32	22.3	21.0	0.65	21.7	23.6	0.77	21.5
	2	24.0	0.40		23.5	0.89		20.4	1.65	
	3	24.9	1.01		20.4	0.06		20.1	4.49	
	4	18.0	1.73		21.9	0.16		25.1	0.28	
	5	21.5	4.68		–	–		15.7	1.13	
	6	–	–		–	–		24.1	2.12	
v_a [m/s]	1	0.079	0.046	0.032	0.004	0.004	0.006	0.065	0.056	0.075
	2	0.010	0.020		0.006	0.012		0.085	0.059	
	3	0.036	0.041		0.011	0.020		0.067	0.043	
	4	0.015	0.022		0.004	0.014		0.022	0.029	
	5	0.020	0.036		–			0.061	0.072	
	6	–	–		–			0.150	0.116	
M [W/m^2] (M)	1	72.0		72.0	72.0		72.0	72.0		72.0
	2	72.0			72.0			72.0		
	3	72.0			72.0			72.0		
	4	72.0			72.0			72.0		
	5	72.0			–			72.0		
	6	–			–			72.0		
I_{cl} [clo] (M)	1	1.5		1.0	1.1		0.8	0.8		0.6
	2	1.3			0.7			0.8		
	3	1.2			0.7			0.6		
	4	0.6			0.6			0.6		
	5	0.5			–			0.4		
	6	–			–			0.4		
M [W/m^2] (W)	1	69.0		69.0	69.0		69.0	69.0		69.0
	2	69.0			69.0			69.0		
	3	69.0			69.0			69.0		
	4	69.0			69.0			69.0		
	5	69.0			–			69.0		
	6	–			–			69.0		
I_{cl} [clo] (W)	1	1.5		1.1	0.3		0.7	0.9		0.6
	2	1.4			0.7			0.7		
	3	1.3			0.8			–		
	4	0.7			0.8			0.6		
	5	0.5			–			0.5		
	6	–			–			0.4		
PMV (M)	1	0.1		0.4	0.0		0.0	0.0		0.2
	2	0.4			0.3			−0.7		
	3	0.5			−0.5			0.3		
	4	0.5			0.1			0.9		
	5	0.6			–			0.7		
	6	–			–			0.3		
PMV (W)	1	0.0		0.3	−0.4		−0.4	0.0		0.0
	2	0.4			0.2			−0.9		
	3	0.4			−0.5					
	4	0.2			−1.0			0.6		
	5	0.6			–			0.5		
	6	–			–			−0.4		
PPD [%] (M)	1	5.4		9.5	6.2		7.6	6.1		12.2
	2	8.5			7.8			16.3		
	3	11.0			11.2			6.5		
	4	10.7			5.1			22.1		
	5	12.0			–			15.3		
	6	–			–			6.9		
PPD [%] (W)	1	5.3		8.9	5.4		12.1	6.1		11.9
	2	8.4			7.0			21.9		
	3	10.1			9.8			–		
	4	8.5			26.1			13.3		
	5	12.3			–			10.2		
	6	–			–			8.0		

S: survey number; Std dev: standard deviation; Avg: Average of surveys; PPD: UNIEN ISO 7730/2008; (M): men; (W): women.

- preference vertical thermal gradient index (PVTGI) [%], defined as the ratio *persons who wants to change/persons who express a judgement* (it is evaluated as the percentage of persons who have answered "lower than now, higher than now" to the question "would you prefer a temperature difference of temperature between head and ankle");
- environmental control dissatisfaction index (ECDI) [%], defined as the ratio *persons who express a negative judgement/persons who express a judgement* (it is evaluated as the percentage of persons who have answered "very unsatisfied, not satisfied, slightly not satisfied, slightly satisfied", to the question "How do you feel about the possibility of controlling thermal comfort?").

3. Measurement campaign: results

A synthesis of measured data is reported in Table 4. Very good comfort conditions inside university classrooms during experimental surveys were found for the autumn season, in reference with average thermal resistance of occupants calculated by responses of questionnaires. In fact PMV values result to be within the interval −0.5 to +0.5, recommended in Appendix D of UNI EN ISO 7730, except for two surveys of 2/12/2004, where it reaches values a bit above the superior limit (PMV = 0.6 and PMV = 0.78). A similar situation was found during the winter season, where PMV is contained by the predicted limits, resulting a bit outside in correspondence with two surveys, in the days 4/3/2005 and 8/3/2005 (respectively, PMV = 0.64 and PMV = −0.65). Comfort conditions relative to spring season have instead a more variable trend, which is strongly dependent on meteorological conditions. Values are maintained within the recommended interval or a bit outside for the main part of the surveys. All these results have a more interesting interpretation reading the measured average external temperature and standard values reported on UNI 10349 (see Table 1). HVAC systems seem to assure the respect of design comfort values during the cold season. On the other hand, during the spring season, this condition isn't obtained when the systems are switched off and natural ventilation is not enough to maintain acceptable comfort levels for the students in the classrooms.

Further on a questionnaire analysis is reported in Table 5, showing that:

- occupants feel a thermal sensation of slightly hot;
- the elevated values of thermal indexes of dissatisfaction, preference and annoyance put in evidence the difficulties of putting up with existing thermal conditions;

Table 5
Questionnaires analysis: synthesis of main results.

Classrooms		1		2		3	
	S		Avg		Avg		Avg
Questionnaires	1	137	–	17	–	108	–
	2	89		24		61	
	3	123		11		49	
	4	85		14		71	
	5	86		–		32	
	6	–		–		52	
Age of subjects	1	20.8	21.0	22.1	22.9	20.6	21.0
	2	20.6		22.0		20.8	
	3	20.6		23.0		19.5	
	4	21.5		24.6		21.0	
	5	21.6		–		22.2	
	6	–		–		21.9	
PMV	1	0.34	0.53	−0.06	0.42	0.69	0.46
	2	0.32		1.63		0.02	
	3	1.02		0.09		0.27	
	4	0.39		0.00		0.87	
	5	0.58		–		0.69	
	6	–		–		0.20	
PMV dispersion	1	0.95		0.76	0.89	0.95	0.85
	2	1.00		1.32		0.87	
	3	2.17		1.17		0.63	
	4	0.75		0.29		0.87	
	5	0.64		–		0.74	
	6	–		–		1.03	
TDI [%]	1	33.8		82.4	60.9	61.1	47.3
	2	34.3		70.8		41.0	
	3	60.6		54.5		24.5	
	4	41.2		35.7		62.0	
	5	46.5		–		50.0	
	6	–		–		45.1	
TPI [%]	1	47.3		76.5	63.3	67.6	57.0
	2	43.6		79.2		42.6	
	3	68.2		54.5		44.9	
	4	43.5		42.9		73.2	
	5	54.7		–		62.5	
	6	–		–		51.0	
TUI [%]	1	11.4		41.2	45.1	27.8	18.3
	2	8.7		70.8		11.5	
	3	16.0		18.2		6.1	
	4	5.9		50.0		29.6	
	5	3.5		–		18.8	
	6	–		–		15.7	
TAI [%]	1	39.2		82.4	79.1	54.6	42.3
	2	35.8		91.7		32.8	
	3	47.7		63.6		34.7	
	4	35.3		78.6		53.5	
	5	30.2		–		40.6	
	6	–		–		37.3	
UAMI [%]	1	32.4		76.5	80.2	56.5	43.2
	2	29.1		100.0		27.9	
	3	48.5		72.7		42.9	
	4	38.8		71.4		59.2	
	5	38.4		–		31.3	
	6	–		–		41.2	
UVTHI [%]	1	28.4		64.7	55.7	32.4	30.4
	2	22.1		75.0		27.9	
	3	22.6		54.5		24.5	
	4	10.6		28.6		31.0	
	5	12.8		–		31.3	
	6	–		–		35.3	
PVTGI [%]	1	40.4		88.2	64.9	39.8	37.4
	2	38.8		79.2		31.1	
	3	27.6		63.6		30.6	
	4	22.4		28.6		39.4	
	5	22.1		–		40.6	
	6	–		–		43.1	
ECDI [%]	1	41.6		94.1	81.7	69.4	68.3
	2	48.4		95.8		82.0	
	3	46.9		72.7		59.2	
	4	57.6		64.3		80.3	
	5	52.3		–		56.3	
	6	–		–		62.7	

- the low air movement makes worse the discomfort of occupants, especially in Classroom 2;
- except for Classroom 2, vertical thermal gradient does not present too high percentage of dissatisfied;
- considering the environment control, most of people, especially in Classrooms 2 and 3, present an elevated dissatisfaction.

It may be concluded that Classroom 2 globally presents a higher percentage of dissatisfied. This is probably because of the psychological sensation due to the absence of windows.

The relationship between experimental data and questionnaire results is reported in Fig. 4, where also the bisector line ($PMV_{instrumental} = PMV_{questionnaire}$) is reported; the bisector line (dotted line in Fig. 4) represents the ideal fitting condition between instrumental and questionnaire data, while the continuous line represents the correlation between instrumental and questionnaire data found in this experimental campaign. The regression equation is related to data of the experimental campaign. It is evident that questionnaire data accentuate discomfort conditions: with reference to the bisector line, when instrumental PMV is lower than 0.36, questionnaires provide more negative values (an higher sensation of cold); when instrumental PMV is more than 0.36, questionnaires supply more positive values (an higher sensation of hot).

4. Theoretical analysis

4.1. Application of Wray model to experimental data

The application of Wray model begins with the determination of T_u, temperature to be reached in order to obtain optimal comfort conditions. To solve Eq. (1) with the above-mentioned hypothesis, it is necessary to attribute a value to the parameters (A, I_{cl}, f_{cl}, h_c, ϕ). By analyzing personal data, collected in questionnaires, it is possible to find out the number of men and women present during the surveys. By fixing metabolic values for both the sexes, the mean weighted value for the activity level (A) was found. Considering the sedentary activity of students attending university lessons, a fixed values of 72 and 69 W/m^2 was attributed, respectively, for men and women. By evaluating instead the questionnaires' thermal section, the clothing composition could be derived for each student. By attributing to clothing values of thermal resistance reported in Appendix E in Ref. [1], the mean value of thermal insulation of the occupants' clothing was calculated ($I_{cl,med}$), in addition to maximum and minimum values ($I_{cl,max}$, $I_{cl,min}$), representative, respectively, of most and least dressed person, independently from sex. The value of clothing thermal insulation is not explicit in Eq. (1), but it is necessary to determine the other parameters T_{cl}, f_{cl}, and h_c correlated to it. The informatic program proposed in Appendix B of Ref. [1] was applied to calculate indexes PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied), implemented through Visual Basic language, from which the above-mentioned coefficient was extrapolated, always gained in correspondence with $I_{cl,med}$, $I_{cl,max}$, $I_{cl,min}$. The values of air temperature T_a and air velocity relative to human body v_{ar} were acquired by experimental surveys, such as the value of relative humidity ϕ. The mean radiant temperature was calculated by measuring globe temperature, air temperature and air velocity [37].

By implementing the above-obtained parameters, T_u was calculated always in correspondence with the minimum, mean and maximum values of thermal clothing resistance.

By using the same parameters, T_{eu} was calculated, associated to the considered classroom, by means of Eq. (2). Values of s were determined from graphs of reference [35], traced by Wray for prefixed mean values of f_{cl}, h_c, v_{ar} ($f_{cl} = 1.15$, $h_c = 2.83$ W/m^2 K,

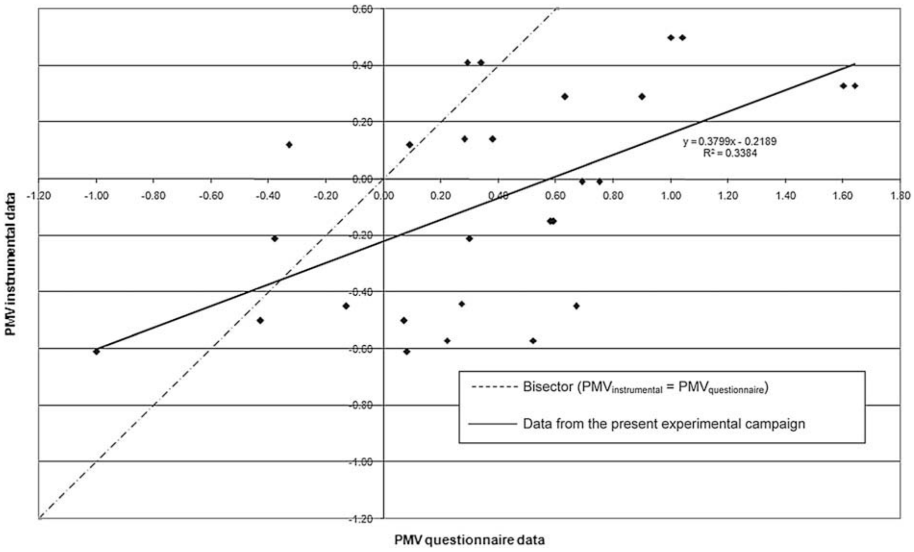


Fig. 4. PMV of instrumental data versus PMV of questionnaire data.

$v_{ar} = 0.1$ m/s) and by interpolating on the basis of the considered A, ϕ and I_{cl}. The accuracy of the result obtained by such graphic method is guaranteed by the poor sensibility of T_{eu} in comparison with s. By varying such parameter of a quantity bigger than the introduced approximation, a corresponding T_{eu} oscillation of about 0.1–0.2 °C is obtained, therefore the uncertainty of the final result can largely be contained within these limits. Consequently, it is not justified the use of the analytical method for the determination of s, that means a significant time consuming for data processing.

Computational analysis was consecutively repeated for each single survey during the measurement days. In the same measurement day, since the sample of students in the classroom was invariable, mean values of metabolism and clothing thermal insulation remain constant while all the other parameters of interest are variable. Taking into account Classroom 3, surveys were carried out both in the morning and afternoon, suspended during lunch break that separates the two lessons. Therefore the sample of students is not the same for the whole day of measurement, consequently morning and afternoon were considered as two distinctive days of measurement, each of them associated with different values of metabolic activity and clothing thermal insulation.

In parallel with T_u and T_{eu}, traditional Fanger indexes PMV and PPD were calculated, by means of the software program reported in Ref. [1].

4.2. Comparison between the approach of Wray and Fanger

From values of T_u and T_{eu} of each single survey the differences $T_{eu} - T_u$ and $|T_{eu} - T_u|$ were calculated, in order to make a comparison with Fanger indexes PMV and PPD. For both the differences, a null value determines a coincidence between the comfort Uniform Temperature and Equivalent Uniform Temperature ($T_u = T_{eu}$) and it corresponds to thermal-hygrometric comfort conditions. The difference $|T_{eu} - T_u|$ expresses by means of a single value the distance to comfort conditions: higher values correspond to more distant comfort conditions. The difference $T_{eu} - T_u$, even though it maintains the sensation proportionality, adds to the value the sign, which can be positive if the considered environment is associated to a warm sensation and negative if associated to a cold sensation. As a consequence, the value of $T_{eu} - T_u$ is directly comparable to PMV, while $|T_{eu} - T_u|$ can be compared to PPD.

On the basis of these considerations, on one hand values of PMV and $T_{eu} - T_u$ and on the other hand PPD and $|T_{eu} - T_u|$ were correlated, verifying the existence of simple relationships to link the two couples of parameters. The analysis was carried out by plotting on two graphs the differences $|T_{eu} - T_u|$ and $T_{eu} - T_u$ on the x values, while on the y values were, respectively, indicated PMV and PPD, calculated from experimental data. Further on the trend of representative points of each experimental survey was traced on the graphs (Figs. 5 and 6) in correspondence with minimum, average and maximum values of thermal clothing insulation. On the same graphs the tendency lines, that better fit the trend of the considered points, were plotted. As it is shown in Figs. 5 and 6, a clear correlation exists among the couples of calculated indexes: in detail PMV and the difference $T_{eu} - T_u$ are linked by a linear dependency, while PPD is closer to a second-order function rather than $|T_{eu} - T_u|$. The equations of both the curves are reported, respectively, in Figs. 5 and 6. The fitting quality is guaranteed by the determination index R^2, for which values of $R^2 = 0.983$ and $R^2 = 0.987$ were, respectively, determined.

The values of PMV and PPD, calculated by means of the above-mentioned equations, definitely agrees with Fanger definition of thermal neutrality expressed by the condition $T_u = T_{eu}$. From the first equation a value approximate to zero, and therefore perfectly in accordance with Fanger approach, is obtained. From the second equation a value of PPD = 4.1% is determined, not far from the reference value of PPD = 5%.

Another correlation was investigated between PMV versus $T_{eu} - T_u$ (Fig. 7) and PPD versus $|T_{eu} - T_u|$ (Fig. 8) of both questionnaire and instrumental data for each experimental survey in correspondence with average values of thermal clothing insulation. As for Figs. 5 and 6, a linear dependency is proposed for PMV and $T_{eu} - T_u$ ($R^2 = 0.29$ for questionnaire data and $R^2 = 0.70$ for instrumental data), while a second-order correlation was found for PPD and $|T_{eu} - T_u|$ ($R^2 = 0.72$ for questionnaire data and $R^2 = 0.87$ for instrumental data). As evident, in both correlations, a good fitting quality is reached by instrumental data while the correlation is not very significant for questionnaire data of PMV versus ($T_{eu} - T_u$). However, a similar tendency for both instrumental and questionnaire data was found: the two straight lines have in fact a similar slope, even if values of questionnaire PMV higher than instrumental ones were found, for the same value of

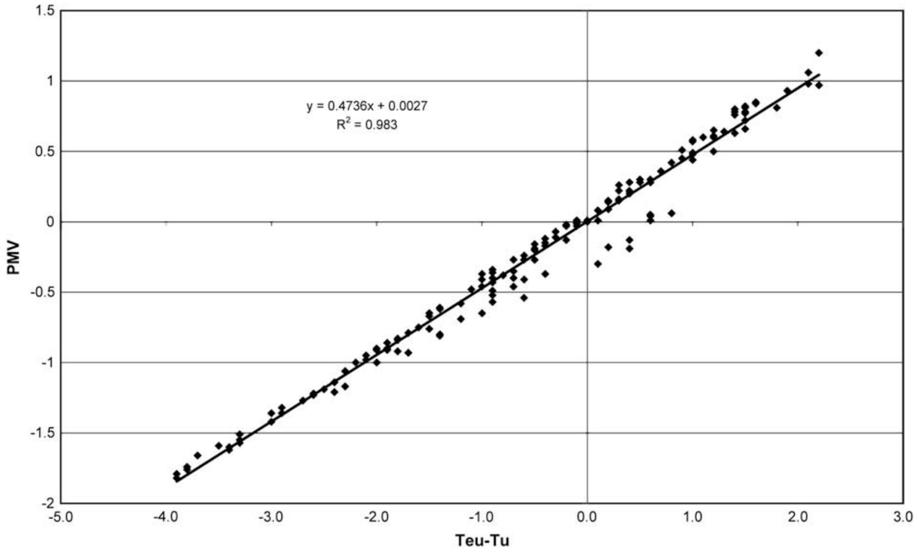


Fig. 5. PMV as a function of $T_{eu} - T_u$.

$T_{eu} - T_u$; it confirms a warmer sensation of the occupants with respect to data of PMV calculated from the survey of environmental parameters. The less significant correlation of questionnaire data is due to the subjective response, such as found also in the literature [29].

Therefore the derived equations and correlations allow the computation of $T_{eu} - T_u$ and $|T_{eu} - T_u|$ from the comfort traditional indexes for a wide interval of values of thermal insulation clothing (0.29–1.64 clo), typical of all seasons. This consents to be the concepts of thermal-hygrometric comfort more intuitive, by quantifying a sensation of warm and cold felt by the occupants in a defined enclosure by means of a temperature difference. The temperature is in fact a parameter of common and daily use. Each person has a direct experience with temperature and it is a parameter always easy to deal with. As a consequence, expressing through temperature what so far was reserved only to experts is a substantial innovation and can be a useful tool for the diffusion to the wide public of concepts regarding thermal-hygrometric comfort and the management within internal environments.

4.3. Correlation between the Operative Temperature and the Uniform Equivalent Temperature

During the post-processing of experimental data, in parallel with the determination of traditional comfort indexes and characterizing Wray theory's temperatures, the Operative Temperature T_0 (defined as the uniform temperature of an imaginary enclosure with which man will exchange the same dry heat by radiation and convection as in the actual environment) was calculated. The value obtained for each single survey was from time to time compared to the corresponding T_{eu}, in order to verify if the definition analogies of these two parameters led to similar experimental values. By analyzing experimental data, a substantial coincidence of the two parameters was put in evidence, with differences that only in few

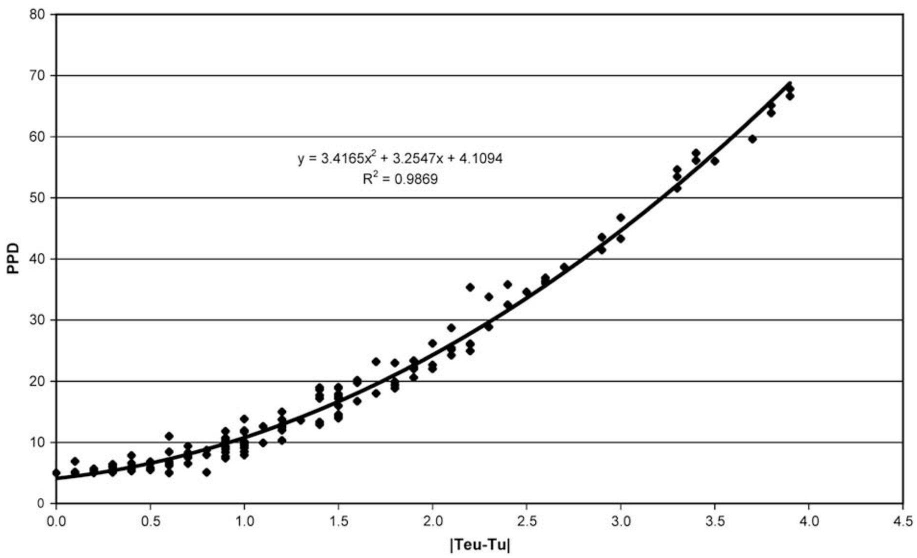


Fig. 6. PPD as a function of $|T_{eu} - T_u|$.

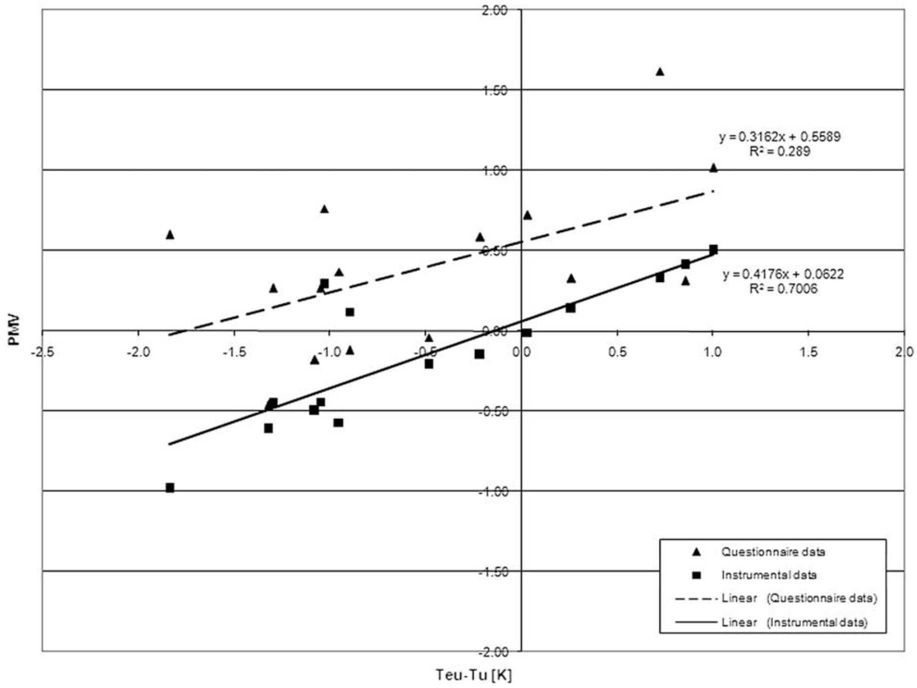


Fig. 7. PMV of instrumental and questionnaire data as a function of $T_{eu} - T_u$.

cases overcame the order of 10th of K, variation to be almost always negligible. In fact, as described in UNI EN ISO 7730, in most of practical cases, when air velocity is low (<0.2 m/s) or when the difference between T_a and T_{mr} is small (<4 K), T_0 can be calculated with sufficient approximation as the arithmetic average between T_a and T_{mr} that is very little kept off the T_{eu}. Therefore an additional simplification in the computation of the differences $T_{eu} - T_u$ and $|T_{eu} - T_u|$ is obtained. The T_0 can be calculated by means of the only three parameters T_a, T_{mr}, and v_{ar} (always determined during the experimental surveys) and it can directly replace T_{eu}, avoiding the implementation of Eq. (2) that requires a heavy determination of the parameter *s*.

Further on a correlation between PMV and T_0 data was carried out in Fig. 9 for both instrumental and questionnaire results. Questionnaire answers are nearly a 0.5 grade above measurement data, with approximately the same slope, even if a not very

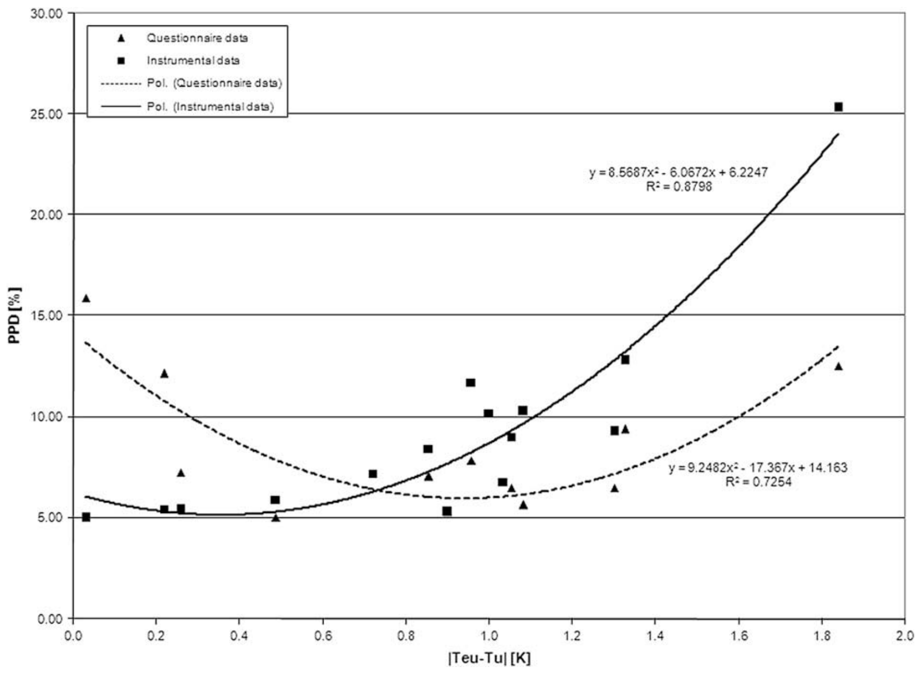


Fig. 8. PPD of instrumental and questionnaire data as a function of $|T_{eu} - T_u|$.

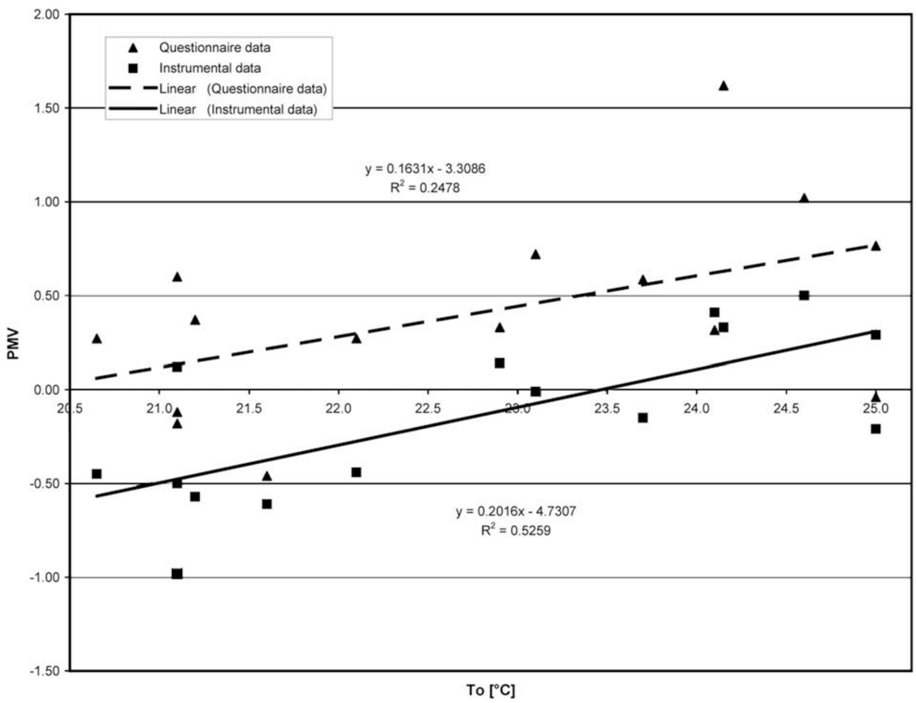


Fig. 9. PMV of instrumental and questionnaire data as a function of T_0.

significant correlation was found for the questionnaire data ($R^2 = 0.25$), such as in Fig. 7, due to the subjective response [43,44]. This is a confirmation of the above-mentioned relationship between instrumental PMV and PMV of questionnaires and of PMV with $T_{eu} - T_u$ (Figs. 4 and 5).

5. Conclusions

The subject of the present work is the analysis of thermal-hygrometry comfort inside university classrooms, carried out by the Section of Applied Physics of the Department of Industrial Engineering of University of Perugia, in cooperation with the Department of Hydraulic and Environmental Engineering University of Pavia. The scope is analyzing possible simple correlations between experimental data and experimental surveys for moderate environments, such as university classrooms. The investigation is based on a wide experimental campaign extended in three university classrooms different for geographical location, HVAC systems, architectonical and exposure features. During the measurements data useful for the determination of the traditional comfort indexes in compliance with UNI EN ISO 7730 and the parameters in agreement with Wray model [35] were acquired. Experimental measurements were carried out by means of special microclimatic acquisition systems and by the distribution of a specific questionnaire to occupants. PMV values referred to measurement data and PMV of questionnaire were compared, showing that questionnaire data tend to accentuate discomfort conditions. The collected data, for both instrumental and questionnaire results, were then processed putting into relation PMV with the difference of temperatures $T_{eu} - T_u$ and PPD with the modulus $|T_{eu} - T_u|$, verifying the existence of a correlation among the parameters. In particular, from the analysis of the obtained data, the linear relationship, represented by a straight line passing by the origin, between the couple of parameters PMV versus $T_{eu} - T_u$ was put in evidence. This is in total agreement with Fanger theory [36], which forecasts the null value of PMV in neutral comfort conditions ($T_{eu} = T_u$, $T_{eu} - T_u = 0$). Regarding the couple PPD versus $|T_{eu} - T_u|$, a second-order relation was obtained, with a curve that in neutral thermal conditions intersects the axis of PPD in correspondence with the value 4.11%, not far from the 5% previewed by Fanger theory [36]. As evident, in both instrumental and questionnaire correlation a better fitting quality is reached by instrumental data rather than questionnaire data.

Further on, in correspondence with each single experimental survey carried out during the measurement sessions, values of the Operative Temperature T_0 were calculated and compared to the corresponding values of the Equivalent Uniform Temperature T_{eu}. The obtained results show a substantial coincidence of these two parameters, having detected only in few cases differences above the 10th of K. Consequently, it outlined the possibility of simplifying the procedure for the determination of the above-mentioned differences $T_{eu} - T_u$ and $|T_{eu} - T_u|$. Without a significant error, it is possible to substitute the T_0, obtainable by simple microclimatic surveys, to the T_{eu}, avoiding the implementation of Eq. (2) and consequently the determination of the complex parameter s.

Finally, by comparing instrumental and questionnaire PMV to the Operative Temperature T_0, questionnaire answers are found to be always 0.5 grade above measurement data, having approximately the same slope. This is a confirmation of the above-mentioned relationship between instrumental PMV and PMV of questionnaires and the application of Wray model for moderate environments.

Acknowledgements

Authors wish to thank Prof. Francesco Fantozzi for measurements in Classroom 2 during his lessons.

Appendix. Synthesis of the questionnaire

PART 1: PERSONAL DATA

- Age________years( )
- Sex

M	F
▫	▫

PART 2: THERMAL QUESTIONNAIRES

- How do you feel about the temperature in this moment?

Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
▫	▫	▫	▫	▫	▫	▫

- What is your thermal sensation?

Comfort	Light annoyance	Annoyance	Heavy annoyance
▫	▫	▫	▫

- How would you like to feel?

Much too cool	Too cool	A little bit cool	No change	A little bit warm	Too warm	Much too warm
▫	▫	▫	▫	▫	▫	▫

- On the basis of your personal preferences, how would you consider the room temperature

Acceptable	Not acceptable
▫	▫

- How do you consider this room?

Perfectly tolerable	Slightly hard to tolerate	Hard to tolerate	Very hard to tolerate	intolerable
▫	▫	▫	▫	▫

- How do you feel about the air flow in this moment?

Completely not acceptable	Not acceptable	Slightly not acceptable	Slightly acceptable	Acceptable	Perfectly acceptable
▫	▫	▫	▫	▫	▫

- Would you like to have an air flow

Smaller than now	Exactly how it's now	Greater than now
▫	▫	▫

- Provide us indication regarding your clothing (ex. Underwear, woman clothing, trousers, accessories, shirt, pullover etc.)

- Which was your occupation in the last hour?

Occupation	Last 10 minutes	Between 10 and 20 minutes ago	Between 20 and 30 minutes ago	Between 30 and 60 minutes ago
Office job	▫	▫	▫	▫
Walk in flat land	▫	▫	▫	▫
Walk in ascent	▫	▫	▫	▫
Walk in slope	▫	▫	▫	▫
To run	▫	▫	▫	▫
To rest	▫	▫	▫	▫
To be seated	▫	▫	▫	▫
To read	▫	▫	▫	▫
To drive	▫	▫	▫	▫
To wash and dress-up himself	▫	▫	▫	▫
To clean	▫	▫	▫	▫
To cook	▫	▫	▫	▫
To wash dishes	▫	▫	▫	▫
To eat	▫	▫	▫	▫
Something else				

- How do you consider the temperature difference between head and ankle?

Completely not acceptable	Not acceptable	Slightly not acceptable	Slightly acceptable	Acceptable	Perfectly acceptable
▫	▫	▫	▫	▫	▫

- Would you prefer a temperature difference between head and ankle

Lower than now	Exactly how it is now	Higher than now
☐	☐	☐

(continued on next page)

Appendix (Continued)

PART 3: PERSONAL MICROCLIMATIC CONTROL

- How can you define the level of control of microclimatic conditions?

No control	Light control	Medium control	High control	Total control
☐	☐	☐	☐	☐

- How do you feel about the possibility of controlling thermal comfort?

Very unsatisfied	Not satisfied	Slightly not satisfied	Slightly satisfied	Satisfied	Very satisfied
☐	☐	☐	☐	☐	☐

- Can you open/close the windows?

No	Yes	There aren't any windows
☐	☐	☐

- How often do you do this?

Never	Rarely	Sometimes	Frequent	Always
☐	☐	☐	☐	☐

- Can you open/close the external doors?

No	Yes	There aren't any doors
☐	☐	☐

- How often do you do this?

Never	Rarely	Sometimes	Frequent	Always
☐	☐	☐	☐	☐

- Can you open/close the inner doors?

No	Yes	There aren't any doors
☐	☐	☐

- How often do you do this?

Never	Rarely	Sometimes	Frequent	Always
☐	☐	☐	☐	☐

- Can you regulate the thermostat?

No	Yes	There aren't any thermostat
☐	☐	☐

- How often do you do this?

Never	Rarely	Sometimes	Frequent	Always
☐	☐	☐	☐	☐

- Can you regulate curtains/rolling shutters?

No	Yes	There aren't any of them
☐	☐	☐

- How often do you do this?

Never	Rarely	Sometimes	Frequent	Always
☐	☐	☐	☐	☐

- Can you regulate radiators?

No	Yes	There aren't any radiators
☐	☐	☐

- How often do you do this?

Never	Rarely	Sometimes	Frequent	Always
☐	☐	☐	☐	☐

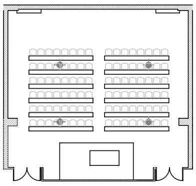
- Can you regulatefan coils?

No	Yes	There aren't any fan coils
☐	☐	☐

- How often do you do this?

Never	Rarely	Sometimes	Frequent	Always
☐	☐	☐	☐	☐

- Indicate your positions in the classroom map below



References

[1] UNI EN ISO 7730. Ergonomics of the thermal environment – analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria; 2006.
[2] UNI EN ISO 10551. Ergonomia degli ambienti termici – valutazione dell'influenza dell'ambiente termico mediante scale di giudizio soggettivo; Gennaio 2002.
[3] ASHRAE Standard 55/2004. Thermal environment conditions for human occupancy. Atlanta, GA, USA: ASHRAE; 2004.
[4] Kwok AG, Chun C. Thermal comfort in Japanese schools. Solar Energy 2003;74: 245–52.
[5] Wong NH, Khoo SS. Thermal comfort in classrooms in the tropics. Energy and Buildings 2003;35:337–51.
[6] Atthajariyakul S, Leephakpreeda T. Real-time determination of optimal indoor-air condition for thermal comfort, air quality and efficient energy usage. Energy and Buildings 2004;36:720–33.
[7] Wang Z. A field study of the thermal comfort in residential buildings in Harbin. Building and Environment 2006;41:1034–9.
[8] Nicol F, Humphreys M. Maximum temperatures in European office buildings to avoid heat discomfort. Solar Energy 2007;81:295–304.
[9] Corgnati SP, Ansaldi R, Filippi M. Ipotesi per un modello di valutazione del comfort termico, per la classificazione della qualità dell'ambiente interno, 61° Congresso Nazionale ATI – Perugia, Settembre 2006.
[10] D'Ambrosio Alfano FR, Ianniello E, Ziviello C. A protocol for objective and subjective assessment of global comfort in school environments. Proceedings of Roomvent Conference, Helsinki; June 2007.
[11] d'Ambrosio Alfano FR, Ianniello E, Palella BI. Alcune considerazioni sui risultati di una campagna di misure per la valutazione del comfort globale in edifici per l'istruzione. 62° Congresso Nazionale ATI - Salerno, Settembre; 2007.
[12] Feriadi H, Wong NH. Thermal comfort for naturally ventilated houses in Indonesia. Energy and Buildings 2004;36:614–26.
[13] Hwang R-L, Lin T-P, Kuo N-J. Field experiments on thermal comfort in campus classrooms in Taiwan. Energy and Buildings 2006;38:53–62.
[14] Wagner A, Gossauer E, Moosmann C, Gropp Th, Leonhart R. Thermal comfort and workplace occupant satisfaction – results of field studies in German low energy office buildings. Energy and Buildings 2007;39:758–69.
[15] Ansaldi R, Corgnati SP, Filippi M. Comparison between thermal comfort predictive models and subjective responses in Italian university classrooms. Proceedings of Clima, WellBeing Indoors; 2007.
[16] Corgnati SP, Filippi M, Viazzo S. Perception of the thermal environment in high school and university classrooms: subjective preferences and thermal comfort. Building and Environment 2007;42:951–9.
[17] Raja IA, Nicol JF, McCartney KJ, Humphreys MA. Thermal comfort: use of controls in naturally ventilated buildings. Energy and Buildings 2001;33:235–44.
[18] Nicol JF, Humphreys MA. Adaptive thermal comfort and sustainable thermal standard for buildings. Energy and Buildings 2002;34:563–72.
[19] De Dear RJ, Brager GS. Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55. Energy and Buildings 2002;34:549–61.
[20] Zhang Y, Zhao R. Overall thermal sensation, acceptability and comfort. Building and Environment 2008;43:44–50.
[21] Nicol F. Adaptive thermal comfort standards in the hot–humid tropics. Energy and Buildings 2004;36:628–37.
[22] Bouden C, Ghrab N. An adaptive thermal comfort model for the Tunisian context: a field study results. Energy and Buildings 2005;37:952–63.
[23] Van Der Linden AC, Boerstra AC, Raue AK, Kurvers SR, De Dear RJ. Adaptive temperature limits: a new guideline in The Netherlands. A new approach for the assessment of building performance with respect to thermal indoor climate. Energy and Buildings 2006;38:8–17.
[24] Sharma A, Tiwari R. Evaluation of data for developing an adaptive model of thermal comfort and preference. Environmentalist 2007;27:73–81.
[25] Goto T, Mitamura T, Yoshino H, Tamura A, Inomata E. Long-term field survey on thermal adaptation in office buildings in Japan. Building and Environment 2007;42:3944–54.
[26] van Hoof J, Hensen JLM. Quantifying the relevance of adaptive thermal comfort models in moderate thermal climate zones. Building and Environment 2007;42:156–70.
[27] Mui KW, Chan WT. Application of the building environmental performance model (BEPM) in Hong Kong. Energy and Buildings 2005;37:897–909.
[28] McCartney KJ, Nicol JF. Developing an adaptive control algorithm for Europe. Energy and Buildings 2002;34:623–35.
[29] Mui KWH, Chan WTD. Adaptive comfort temperature model of air-conditioned building in Hong Kong. Building and Environment 2003;38: 837–52.
[30] Kaynakli O, Kilic M. Investigation of indoor thermal comfort under transient conditions. Building and Environment 2005;40:165–74.
[31] Lin Z, Deng S. A study on the thermal comfort in sleeping environments in the subtropics – developing a thermal comfort model for sleeping environments. Building and Environment 2008;43:70–81.
[32] Buratti C, Ricciardi P, Simoncini C. Il benessere termoigrometrico nelle aule universitarie: primi risultati di una campagna sperimentale presso le Università di Perugia e Pavia effettuata secondo nuove metodologie basate sul modello adattivo. 5° Congresso Nazionale CIRIAF – Atti, Perugia; 8–9 aprile 2005.
[33] Buratti C, Milone A, Milone D, Pitruzzella S, Ricciardi P. Determinazione degli indici PMV e PPD attraverso misure strumentali e questionari nel modello adattivo. 6° Congresso Nazionale CIRIAF – Atti, Perugia; 7–8 aprile 2006.
[34] Buratti C, Ricciardi P. Thermal-hygrometry comfort in university classrooms: experimental results in north and central Italy Universities conducted with new methodologies based on adaptive models, 3rd International Building Physics Conference, Montreal; 27–31 agosto 2006.
[35] Wray WO. A simple procedure for assessing thermal comfort in passive solar heated buildings. Solar Energy 1980;25:327–33.
[36] Fanger PO. Thermal comfort. New York: McGraw Hill; 1970.
[37] ASHRAE fundamentals handbook. Atlanta, GA, USA: American Society of Heating Refrigerating and Air-conditioning Engineers; 2001.
[38] Corgnati SP, Fracastoro. Linee guida per la modellazione di grandi serre. Condizionamento dell'Aria 2002;XLV(3):54–63.
[39] Humphreys MA, Nicol JF. Understanding the adaptive approach to thermal comfort. ASHRAE Transactions 1998;104(1B):991–1004.
[40] De Dear RJ, Brager GS. Developing an adaptive model of thermal comfort and preference. ASHRAE Transactions 1998;104(1A):145–67.
[41] De Dear RJ, Brager GS. A standard for natural ventilation. ASHRAE Journal 2000;42(10):21–8.
[42] ISO 7726. Ergonomics of the thermal environment – instruments for measuring physical; 1998.
[43] Höppe P. Different aspects of assessing indoor and outdoor thermal comfort. Energy and Buildings 2002;34:661–5.
[44] Abu-Mostafa Y, Song X, Nicholson A, Magdon-Ismail M. The bin model, Computer science technical report, CaltecCSTR, 2004.002. California Institute of Technology; July 2004.