FIELD STUDY ON THERMAL COMFORT IN NATURALLY VENTILATED AND AIR-CONDITIONED UNIVERSITY CLASSROOMS

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ABSTRACT

Maintaining a satisfactory thermal environment is of primary importance, especially when the goal is to maximize learning such as in schools or universities. This paper presents a field study conducted in Milan during summer 2017 in 16 classrooms of Politecnico di Milano, including both naturally ventilated and air-conditioned environments. This study asked 985 students to report their thermal perception and their responses were evaluated according to the measured thermal comfort parameters to assess the prediction as given by Fanger and Adaptive models, according to ANSI/ASHRAE 55-2017 and EN 15251:2007 standards. Furthermore, an analysis regarding potential effects of gender in comfort perception was performed. The results confirmed the fitness of Fanger's model for the prediction of occupants' thermal sensations in air-conditioned classrooms with a reasonable accuracy. In naturally ventilated classrooms the Adaptive model was proven to be suitable for predicting students' comfort zone according to ASHRAE 55 Standard, while the adaptive comfort temperatures recommended by EN 15251 were not acceptable for a large number of students. No significant differences in thermal comfort perception between genders has been observed, except for two naturally ventilated classrooms in which females' thermal sensation votes had resulted closer to neutrality in comparison to males, who expressed a warmer thermal sensation.

Keywords: Thermal comfort, Field study, Fanger model, Adaptive model, Natural ventilation; Gender

INTRODUCTION

Thermal comfort is a condition of mind that expresses satisfaction with regards to the thermal environment[1] and is known to influence both productivity and health[2]. Schools and universities students spend most of their daytime inside classrooms, highlighting the importance of a satisfactory and healthy thermal environment in order to maximize performances in terms of close attention and learning.

In the last two decades research in thermal comfort has recognised new paradigms in determining the relation between the thermal environmental conditions and user perception. First of all, the introduction and acceptance of an empirically based adaptive comfort model, more suitable for naturally ventilated building then the analytical and physically based Fanger's comfort model, which remains well established for air conditioned buildings. Another noticeable shift has been from the undesirable toward the desirable qualities of air movement. [3]

First of all, the field study carried out under Project ASHRAE RP-884[4] showed that the range of optimum indoor temperatures observed in naturally ventilated buildings was about twice as large as that predicted by the Fanger's model, suggesting that physiological (acclimatization) and psychological (shifting expectations) adaptive processes were superimposed on the behavioural adaptations of clothing and air speed adjustment in the naturally ventilated context. These findings led to the revised~~ion of~~ ASHRAE Standard 55-2004.[5] Another relevant field study, mainly focused on naturally ventilated office buildings, was carried out under EU project Smart Controls and Thermal Comfort (SCATs). [6]

The data collected in SCATs Project was used to derive the equation for thermal comfort for buildings in the free-running mode (Annexe A2) in European Standard EN15251:2007.[7] Based on SCATs survey, Humphreys has further investigated what are the various ways in which evaluation of the several aspects of the indoor environment might combine to form an occupant's overall assessment of that environment, concluding that, due to the complexity of the matter, it is wise to assess each of the several aspects separately rather than rely only on a combined index.[8]

Concerning thermal comfort in university classrooms, several field studies have already been conducted. The emerging picture is variegated with some common outcomes which highlight the need of further investigation on whether and which actual standards are appropriate or need to be extended. Most of them have been recently collected and classified by two extensive reviews by Zomorodian at al.[9] and Rupp at al.[10]. According to Zomorodian at al.[9] most of the studies concluded that students' thermal preferences were not in the comfort range provided in the standards. Moreover, they highlighted that ventilation as an essential determinant of indoor air quality and thermal comfort.

In the study by Yao et al.[11], carried out for a year in university classrooms in China, the comfort range found was broader than that recommended by the ASHRAE 55, with the exception of the hottest and coldest months, in which the range was narrower.

The results of the study by Cândido et al.[12], performed in the hot and humid climate of the city of Maceió, Brazil, demonstrated the importance of occupants' thermal history and their preference for higher air movement. Main results indicated that the minimal air velocity required were at least 0.4 m/s for 26°C reaching 0.9 m/s for operative temperatures up to 30°C. Subjects were not only preferring more air speed but also demanding air velocities closer or higher than 0.8 m/s ASHRAE limit. According to the authors, people who are under steady conditions in their thermal environment (air-conditioned – AC – environments) have less tolerance and are less able to adapt to the dynamic conditions of naturally ventilated spaces.

Buratti and Ricciardi[13] performed a field study in classrooms of three universities located in Italy, University of Perugia, Terni and Pavia, in autumn, winter and spring. The correlation of the responses from questionnaires and PMV (Predicted Mean Vote) showed significant differences between them. Higher (warmer) values of thermal sensation were found from the questionnaire than predicted by the Fanger's model, having as input the instrumental environmental measurements.

Memon at al.[14] conducted a field assessment of thermal comfort at Mehran University of Engineering and Technology, situated in the subtropical region of Pakistan. The results showed that people of the area were feeling thermally comfortable at effective temperature of 29.85°C (operative temperature 29.3°C). A comparison of this neutral effective temperature was made with the neutral effective temperature determined from adaptive models. The neutral effective temperature determined during this study closely match that of the adaptive model based on either indoor temperature or both indoor and outdoor temperatures. The results of thermal acceptability assessment showed that more than 80% of occupants were satisfied at an effective temperature of 32.5°C, which is 6.5°C above the upper boundary of ASHRAE thermal comfort zone.

Liuzzi et al. [15] conducted an experimental study involving a total of 126 students in one air-conditioned and one naturally ventilated classroom during spring. Fanger's model and the Adaptive model results were compared to occupants' votes and their thermal sensations were investigated considering the possibility to adjust indoor microclimatic conditions. The PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied) values were found to be similar to the votes reported in the questionnaires, and the optimal operative temperature determined by the Adaptive model was found to be consistent with students' thermal sensations. Furthermore, Liuzzi et al.[15] observed that when the individual control was reduced, the occupants were more dissatisfied.

Not many studies were conducted looking at the gender dimension. Fanger[16] conducted an experimental study involving a college-age American group of students (360 males and 360 females) showing no significant differences in comfort conditions between males and females. However, he observed that females were more sensitive to temperatures variations from optimum in all groups, especially in cool conditions. Kim at al.[17] performed a statistical analysis on a large, predominantly North American, Post-Occupancy Evaluation (POE) database (N = 38257). Statistical analyses indicated that female occupants' satisfaction levels were consistently lower than male occupants for all fifteen IEQ factors (including thermal comfort, air quality, lighting, acoustics, office layout and furnishings, and cleanliness and maintenance) addressed in POE questionnaire. Zaki at al.[18] conducted a study on adaptive thermal comfort in university classrooms in Malaysia and Japan. A total of 1428 responses were obtained. In Japan, 93.5% of the sample was male, while more even gender distributions were found in Malaysian samples. Additionally, clothing values were generally higher amongst male respondents. Comfort temperatures in free running mode were compatible with Comité Européen de Normalisation (CEN)[7] and American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standards,[5] while those in air conditioning mode were mostly within Chartered Institute of Building Services Engineers (CIBSE) guidelines.[19]

This paper presents the results of a field study conducted at Politecnico di Milano with the aim of assessing the predictions of the Fanger’s model and of the Adaptive model according to ASHRAE 55 and EN 15251 standards comparing them to the reported students’ thermal sensations in large naturally ventilated and air-conditioned classrooms. This study also investigated the presence of potential effect of gender on thermal comfort perception.

FIELD STUDY

Politecnico di Milano is based in Milan, located in the northern Italy, in a flat region characterized by a temperate climate with warm and humid summers and mild winters.

The field study was conducted during June 2017 in 12 naturally ventilated (NV) and 4 air-conditioned (AC) classrooms. The planimetry of each classroom, with attention to windows and doors position, was analysed - in the design phase and on field - for the placement of the environmental measurement stations, in order to avoid disturbance on the instruments by direct sunlight and by wind draughts and to have the monitoring points close to the students. The main classroom features are reported in Table 1. Typical configurations of the measurement points are reported in Figure 2.

Table 1. Classrooms features and information.

Classroom ID	Type	Subjects	Capacity	Windows (open/total)	Activity
1	NV	117	312	7/8	Lesson
2	NV	38	48	5/6	Workshop
3	NV	37	101	3/3	Lesson
4	NV	52	144	5/5	Lesson
5	NV	60	310	8/9	Lesson
6	AC	24	28	0/5	Workshop
7	NV	41	380	3/3	Lesson
8	AC	75	260	0/3	Lesson
9	NV	41	96	6/6	Lesson
10	AC	60	62	0/5	Workshop
11	NV	39	310	9/9	Lesson
12	NV	73	200	5/5	Lesson
13	NV	26	80	3/3	Lesson
14	NV	99	312	8/11	Lesson
15	AC	99	174	0/6	Lesson
16	NV	90	200	5/5	Lesson

Almost every naturally ventilated classroom, except for ID number 2 and 4, had fans on the ceiling for increasing air velocity, their speed could be manually adjusted throughout the room, during the measurement it was kept uniform and constant. In every naturally ventilated classroom, windows and sometimes doors were fully opened, while in air-conditioned rooms they were kept closed.

Sample

The sample was composed by 985 students in the college-age group (19-25 years old) equally divided in males and females in almost every classroom (Figure 1). The nationality of subjects involved is mostly Italian, with 856 students from Italy and 115 foreigners.

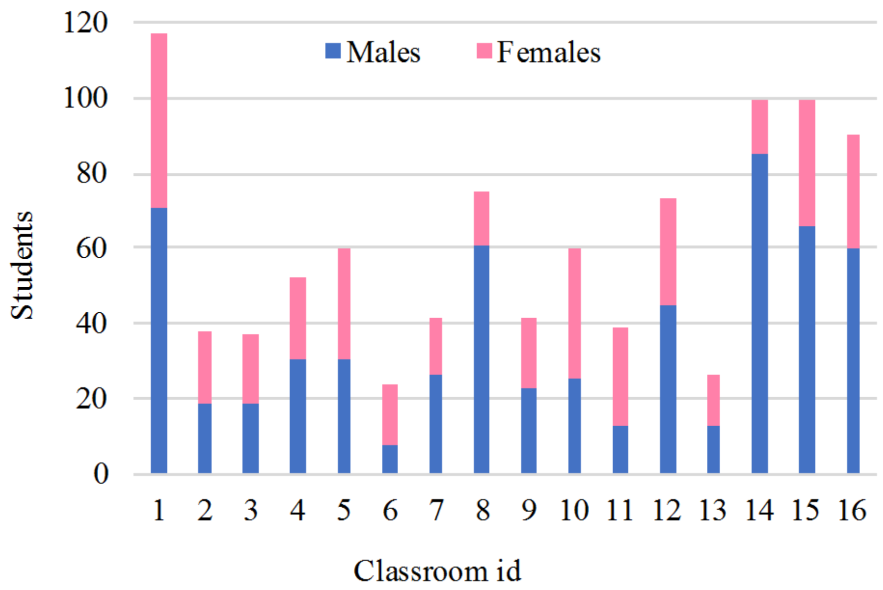

Figure 1. Male and female students in each classroom.

Data collection

The procedure used to measure environmental parameters and to gather thermal comfort surveys involved a total timespan of 1 hour and 15 minutes. The first 15 minutes were used to correctly position the measurement stations near the subjects, in places where they were more concentrated. Then, for the following 45 minutes, the environmental parameters were measured. When measurements ended, the thermal comfort questionnaires were given to the occupants, explaining how to compile them for evaluating the thermal sensations experienced in the last hour.

Comfort survey

A comfort survey was carried out in compliance with ASHRAE 55 Standard to obtain students' thermal comfort perception. Students' thermal sensation votes were reported based on the seven points ASHRAE thermal sensation scale.

In addition, four questions were introduced to directly assess the actual (degree of) satisfaction or dissatisfaction based on a four points scale (Very Satisfied/Comfortable, Satisfied/Acceptable, Dissatisfied, Very Dissatisfied) with regards to the thermal environment, the air quality, the visual and acoustic conditions. The corresponding indicators are reported in Table 2.

Table 2. Indexes of dissatisfaction and their definition.

Index	Definition	Method
PPD	Predicted Percentage of Dissatisfied	Fanger's model
APD	Actual Percentage of Dissatisfied	$\lvert Vote \rvert \geq 2$
TEPD	Thermal environment percentage of dissatisfied	Direct question
AQPD	Air quality percentage of dissatisfied	Direct question
VCPD	Visual conditions percentage of dissatisfied	Direct question
ACPD	Acoustic conditions percentage of dissatisfied	Direct question

To evaluate clothing insulation values of the garments worn by the students, they were asked to answer a multiple-choice question where they had to check all the garments that they were wearing at the moment of the measurements. A clo value taken from the ASHRAE Handbook[20] was assigned to every garment and the result was calculated as the sum of all checked ones.

The metabolic rates were obtained by asking the subjects to report their activity level. Met values that were assigned for each answer were: seated-relaxed 1.0 met; seated-writing 1.1 met; standing-relaxed 1.2 met; standing-drawing 1.4 met.

Measurements

The measurements were performed using the portable instruments of the Laboratory of Building Physic at the Dept. of Energy.

The following probes were used to measure classrooms environmental parameters:

- Globe thermometer (Pt100, 150 mm diameter, accuracy: ±0.21°C at 30°C)
- Omnidirectional hot-wire anemometer (Tungsten wire, 9.45 µm diameter, accuracy: ±0.05 m/s in 0 ÷ 0.5 m/s range)
- Psychrometer (Pt100, forced ventilation, temperature accuracy: ±0.21°C at 30°C, relative humidity accuracy: 1% in 40 ÷ 70% range)

Every probe had its own calibration certificate and the differences between the measurements of same-type probes were lower than their accuracies.

According to UNI EN ISO 7726,[21] environmental parameters were measured at a height of 1.1 m above the floor level, in a timespan of 45 minutes. The measurements were acquired every 10 seconds and were averaged at one minute-intervals. A convergence criterion was defined to filter stable temperature values, as described by Eq. 1.

$$|T_{n+1} - T_n| \leq \varepsilon_{\Delta T} \qquad (Eq. 1)$$

Where T_{n+1} and T_n are respectively the temperature at minute n and n+1, and $\varepsilon_{\Delta T}$ is the temperature difference tolerance set equal to the accuracy of the instrument. Because of the instrumental response time of the globe thermometer and of the psychrometer, the first 15 minutes of data recording were not considered and only the following 30 minutes were taken in account for the calculation of the environmental parameters. Instruments and measurements were classified as Class II, according to the standards for instrumentation and procedures.

Three measurement stations were used to measure the environmental parameters of classrooms. Depending on how occupants were distributed, these stations were placed in different positions of the room (Figure 2) and the measured parameters were used to assess the homogeneity of thermal environments in order to evaluate whether was necessary to allocate a division in different thermal zones. A thermal environment was considered homogeneous if environmental parameters can be considered practically uniform around the subjects. According to UNI EN ISO 7726, this condition was verified when the differences between measured quantities at their locations and average values do not exceed thresholds depending on measurements class type. These deviations were calculated and found to be lower than the thresholds for Class C (Comfort) for all classrooms, with values between ±0.2°C for dry-bulb and globe temperatures, ±0.1 m/s for air velocities and ±1% for relative humidity. The thermal environments were then considered homogeneous and the environmental parameters were calculated as the average of values measured by each measurement station.

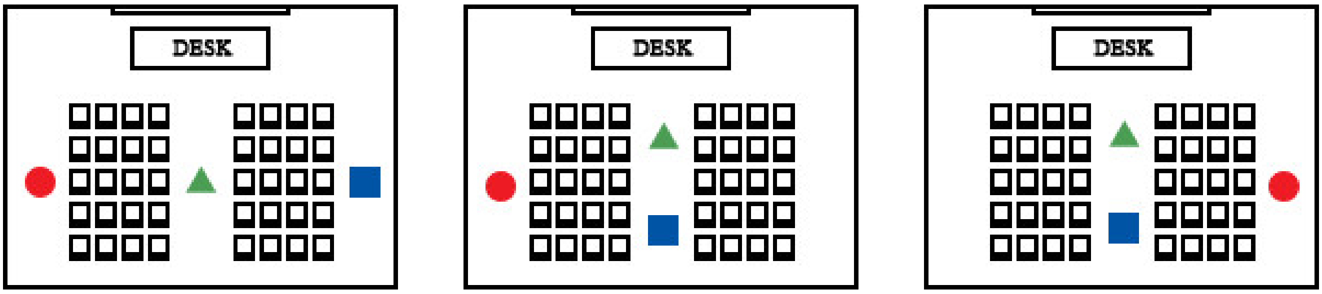

Figure 2. The three different positions at which the three measurement stations were placed inside the classrooms.

The values of the outdoor air temperature were taken from measurements performed by SeedLab weather station located in the campus. Then, these values were averaged on a daily basis to get daily mean outdoor temperatures that were used to calculate the outdoor mean running temperatures of each day of the campaign. According to Nicol at al. ,[22] this calculation was performed considering an interval of 7 days before the one in which measurements were taken (Eq. 2).

$$T_{mr_n} = \frac{\sum_{i=1}^{7}(\alpha^{i-1} T_{n-i})}{\sum_{i=1}^{7} \alpha^{i-1}} \qquad \text{(Eq. 2)}$$

Where $T_{mr,n}$ is the mean running temperature at day *n*, T_{n-i} is the daily mean outdoor temperature of the previous seven days ($1 \leq i \leq 7$) and α is a constant parameter, set between 0 and 1, that governs how quickly the running mean depends on the outdoor temperature of the past days. Considering that α equal to 0.8 was chosen, the progression to the last day of the interval was shown to have decreasing values according to what adaptive theory suggests. The 7-days interval was chosen to consider the process of human adaptation to outdoor temperatures, considering that people are influenced by their past thermal experience with more importance given to the most recent one.

RESULTS AND DISCUSSION

Fanger's model

Classrooms environmental parameters and the values of clothing insulation and metabolic rate from students' surveys were used to calculate the PMV and the PPD according to UNI EN ISO 7730:2005.[23] The PMV was calculated individually for each subject because clothing insulation and metabolic rate values were different among occupants and then averaged by the number of subjects in the classroom. The results regarding air-conditioned classrooms are presented in Table 3.

The Fanger's model reasonably predicts occupants' mean vote in almost every case, also considering that an uncertainty of 0.1 clo has an impact of about 0.2 on the PMV and of 4-6% on the PPD (when the PMV is around ±0.5). The actual percentages of dissatisfied are in line with model predictions, with slightly lower values, except for Classroom 10 where students who expressed dissatisfaction for the thermal environment were considerably higher than predicted. This could be attributed to an ineffective ventilation as expressed by some occupants in the questionnaire's free notes.

Table 3. Fanger's model and surveys results for air-conditioned classrooms.

Classroom ID	$N_{students}$	PMV	PPD (%)	AMV	APD (%)
6	24	-0.50	10.15	-0.88	8.33
8	75	-0.86	20.45	-0.91	10.67
10	60	0.25	6.29	0.57	28.33
15	99	-0.68	14.77	-0.61	13.13

Considering naturally ventilated classrooms (Table 4), in four cases (Classrooms 1, 4, 5 and 14) the differences between actual and predicted mean votes were below 0.1. In six cases (Classrooms 2,3,7,9, 11 and 16), the actual mean thermal sensation vote was higher than predicted of about 0.4-0.8, except in only two cases in Classrooms 12 and 13, where the mean thermal sensation was lower. Looking at the percentage of dissatisfied, in five situations, the dissatisfied were greater than expected by 20-40% (Classrooms 2, 3, 7, 9 and 11), and in only one case (Classroom 13) the dissatisfied were significantly lower than predicted of about 18%. Despite these quantitative differences, qualitatively, the model predicts which situations would lead to a percentage of dissatisfied below 20% (Classrooms 1 and 12) and which would be over 20% (all the others).

Table 4. Fanger's model and surveys results for naturally ventilated classrooms.

Classroom ID	$N_{students}$	PMV	PPD (%)	AMV	APD (%)
1	117	0.76	17.18	0.72	18.80
2	38	1.25	37.59	1.92	76.32
3	37	1.45	48.04	1.84	70.27
4	52	1.30	40.25	1.38	51.92
5	60	0.90	22.17	0.92	32.79
7	41	1.35	42.88	1.73	63.41
9	41	1.63	57.77	2.44	87.80
11	39	1.33	41.87	1.69	66.67
12	73	0.81	18.81	0.53	16.44
13	26	1.67	60.17	1.12	42.31
14	99	1.02	26.99	1.11	35.29
16	90	1.91	72.75	2.49	87.91

The Adaptive model

The operative temperatures limits of the comfort zones were calculated according to ASHRAE 55 and EN 15251 standards and were compared to the operative temperatures measured in the naturally ventilated classrooms (Figure 3). The mean outdoor temperature was calculated considering an interval of seven days before the one in which measurements were taken, in order to permit the process of human adaptation to outdoor temperatures, giving more importance to the recent thermal experiences.[22]

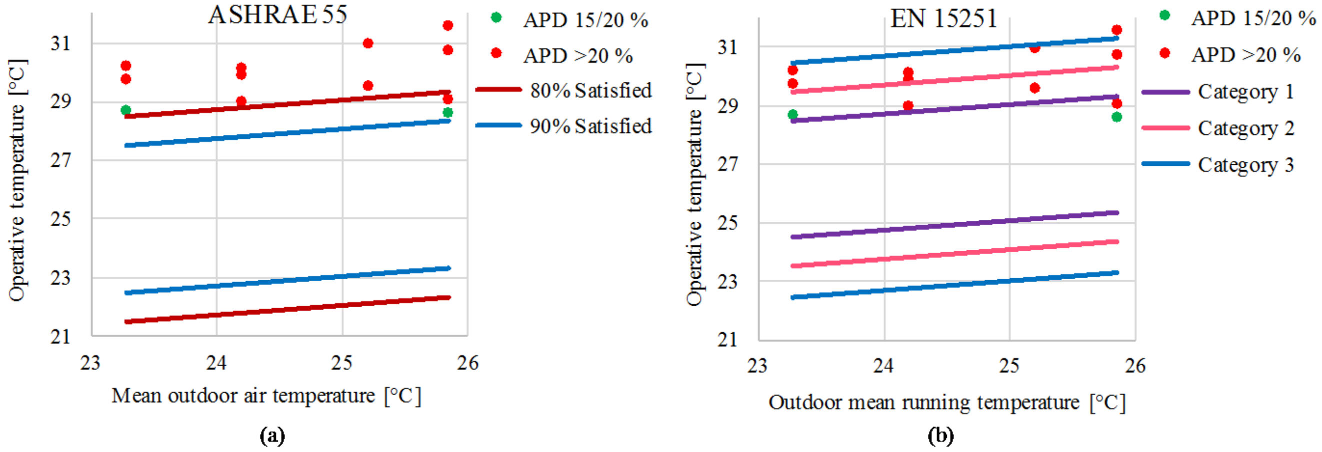

Figure 3. ASHRAE 55 (a) and EN 15251 (b) standards comfort zones and surveys results.

Employing ASHRAE 55 standard, the Adaptive model correctly predicts the dissatisfaction observed in ten classrooms over twelve, with three points at the limits of the comfort zone. The experimental results have also been compared with the prescription of EN 15251 standard, considering all the thermal comfort zones recommended for naturally ventilated buildings associated to different building categories, even if these are not defined in terms of the expected percentage of satisfaction. This makes more difficult the interpretation of surveys results and the test of buildings compliance with the standard as already observed by J. Fergus Nicol and Mike Wilson[24]. Nevertheless, survey results show that, even if most of the operative temperature conditions fall in the second and in the third category, the percentages of dissatisfied were very large, up to 67% for Category II and 88% for Category III, which actually reveal not acceptable conditions.

Figure 3b and the comparison between Actual and Predicted Mean Votes, presented in Table 4, lead to the inference that in the monitored naturally ventilated classrooms there was not any observed higher degree of occupants' adaptability, as was expected from EN 15251. This could be due to a lack of effective individual control of the environmental parameters in the university classrooms analysed in this study, which are landscape spaces.

Relations with other indexes of dissatisfaction

Conventionally "the dissatisfied people" are the ones who vote -3, -2, +2 or +3 (APD). However, as observed by Von Grabe and Winter[25] the people voting outside the comfort range might not always dissatisfied and vice versa. In order to assess this behaviour, the students were additionally asked to answer a direct question about their thermal satisfaction, from whom the related percentage of dissatisfied (TEPD) was determined for each classroom (Figure 4).

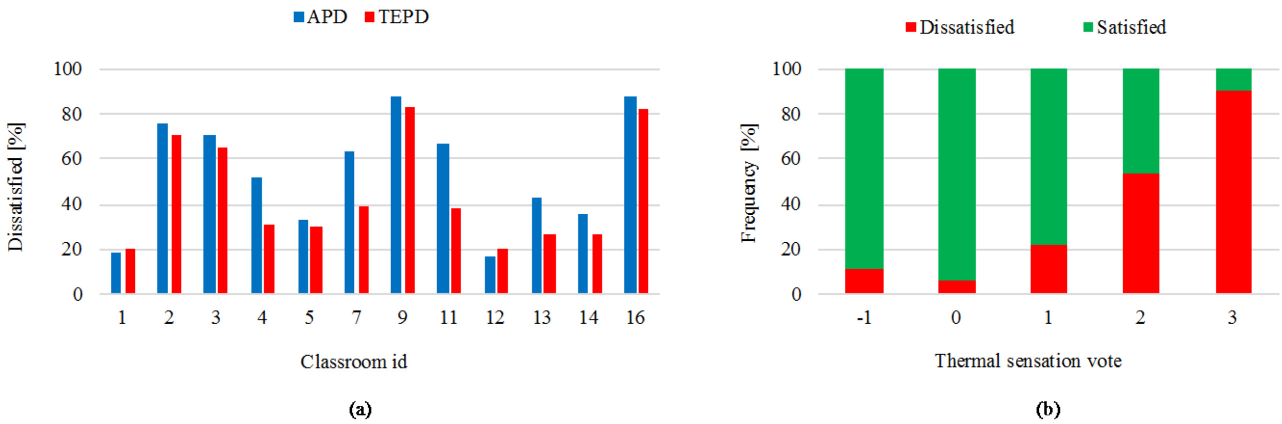

Figure 4. Comparison of APD and TEPD for (a) naturally ventilated classrooms and (b) Thermal Sensation Vote versus thermal satisfaction.

In seven cases, the TEPD results were similar to the APD, with differences below 6% (Classrooms 1, 2, 3, 5, 9, 12 and 16). In the other five cases, the TEPD was significantly lower than the APD. The difference was about 15-25% (Classrooms 4, 7, 11, 13 and 14). However, in these situations the percentages of dissatisfied were still greater than 20%, expressing a high thermal dissatisfaction.

Comparing the conventional criteria for defining actual thermal dissatisfaction (|vote| >1) with the answers to direct questions it is remarkable that, in the naturally ventilated classrooms, the 10% of students who voted +3 and the 46% who voted +2 were satisfied. Conversely, the 22% who voted +1, the 6% who voted 0 and the 12% who voted -1 were dissatisfied (Figure 4).

In order to further investigate the possible influence of other sources of dissatisfaction, the percentages of dissatisfied from visual condition (VCPD), acoustic condition (ACPD) and air quality (AQPD) were reported from students' answers to the direct questions (Figure 5).

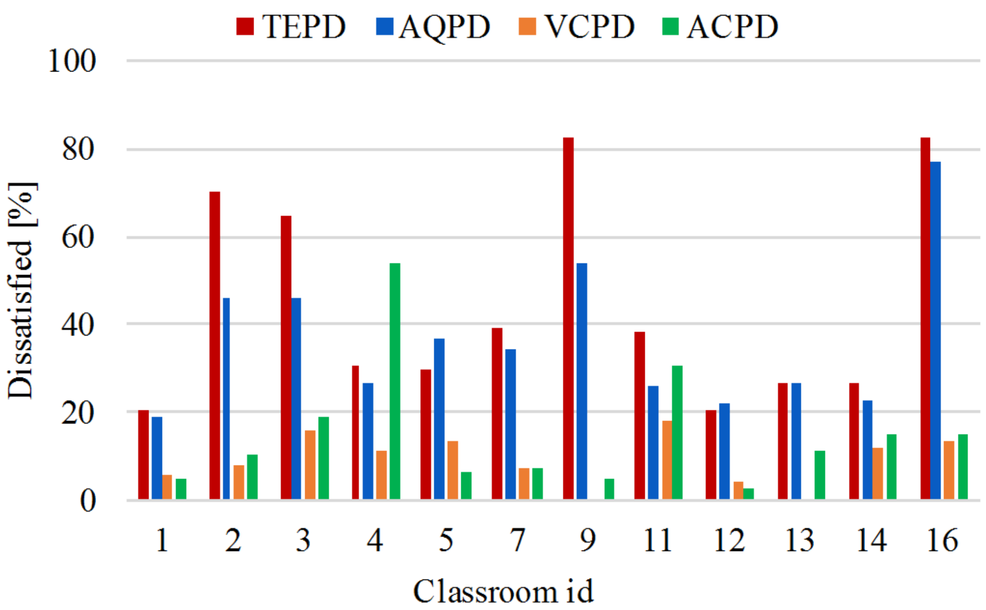

Figure 5. TEPD, AQPD, VCPD and ACPD for naturally ventilated classrooms.

The VCPD was lower than 20% in every classroom. The ACPD was lower than 20% in all classrooms except for two cases in which it was equal to 54% and 31%, respectively in classrooms 4 and 11. This was due to the noise coming from the street near these two classrooms. Anyway, considering Figure 3 and the discrepancies reported in Table 4, the results do not show a clear influence of the ACPD on thermal environment dissatisfaction indexes (APD and TEPD).

The AQPD was higher than 20% in every classroom. CO_2 measurements report most of values were in the range of 440-530 ppm, with three peak values at 670 ppm, 800 ppm and 865 ppm in classrooms 16, 5 and 1, respectively. The peak in classroom 16 was associated with the highest percentage of dissatisfied for the air quality, but there is no evidence of a general correlation between CO_2 levels and the AQPD (Figure 6).

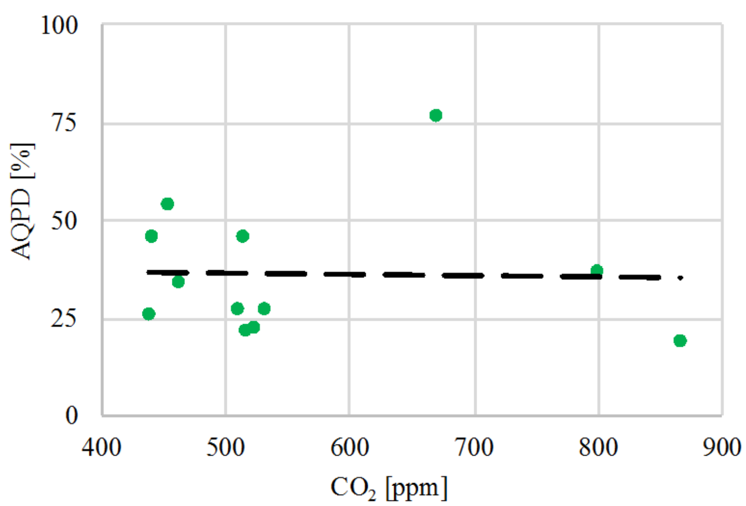

Figure 6. The concentration of CO_2 and the percentage of dissatisfied of the Air quality for each naturally ventilated classroom.

Students' notes in the questionnaires reported the lack of an "effective ventilation", which might have influenced the answers to the air quality question. Indeed, Figure 7 shows a linear correlation between the AQPD and the TEPD (with R^2 = 83%) which might express the increase of air quality dissatisfaction associated to the request of higher air velocities to compensate higher temperatures. This interpretation would result in line with the preferences and trends observed by de Dear at al.[3], Zomorodian at al.[9] and Cândido at al.[12].

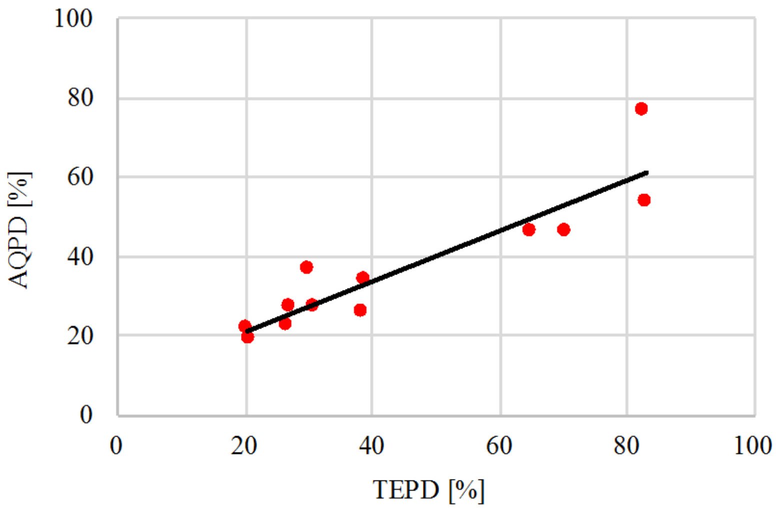

Figure 7. AQPD and TEPD linear relation.

Gender influence on thermal comfort

After calculating the clothing insulation and the metabolic rate values of the two groups of students for each classroom, these were compared, which showed no significant differences. Then, the actual mean votes of males and females were compared using the two-sample Student's t-test (Confidence interval 95%) to test the significance of any possible difference between these two samples (Figure 8).

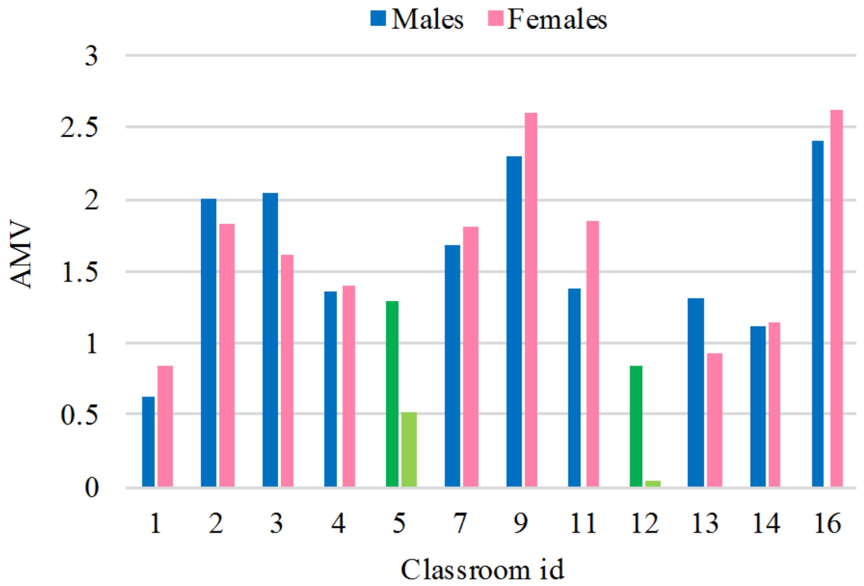

Figure 8. Comparison of actual mean votes of males and females with p-values of the two-sample Student's t-test used to test significance differences.

The results show no significant differences in thermal comfort perceptions between the two genders, except in classrooms 5 and 12 whose p-values of the two-sample t-test result were lower than 0.05 (Respectively 0.01 and 0.0003). A further analysis on the thermal sensation votes distributions of males and females in these rooms, showed that females' ones were more shifted toward neutrality in comparison to males' ones. Their thermal perceptions were more centered around warm thermal sensations.

CONCLUSIONS

This research work focused on the analysis of the dataset developed through an experimental campaign conducted during summer 2017 in 16 classrooms of Politecnico di Milano with a sample of 985 students. The comfort conditions were analysed using Fanger's model and the Adaptive model according to both ASHRAE 55 and EN 15251 standards, and were compared to occupants' thermal comfort perceptions.

The results confirm that in the air-conditioned classrooms, Fanger's model predicts occupants' thermal sensations with a reasonable accuracy. In the naturally ventilated classrooms, both Fanger's model and the Adaptive model based on ASHRAE 55 Standard proved to be suitable for predicting students' comfort zone. In addition, the survey revealed that the adaptive comfort temperatures recommended by EN 15251 standard were not acceptable for a large number of students, meaning that it might not be applicable in such landscape spaces, in which students do not have an actual individual control on their thermal environment. These findings are in line with the outcomes of the experimental study conducted by Liuzzi et al.. [15]

Comparing students' thermal sensation votes with their thermal satisfaction showed that not all the votes outside the comfort range always mean dissatisfaction and vice versa.

No significant potential effect of gender has been observed, except for two naturally ventilated classrooms in which females' thermal sensation resulted closer to neutrality in comparison to males' thermal sensation, who had expressed a desire for warmer thermal sensation.

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AUTHORS CONTRIBUTION

All authors contributed equally in the preparation of this manuscript.

CONFLICT OF INTEREST

The authors declare no conflict of interest in the submission of this manuscript.

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