Thermal comfort and Indoor Air Quality assessment in university classrooms

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Abstract. Investigation of thermal comfort in various types of buildings is a rather intense research activity by recent years. Besides thermal comfort, the Indoor Air Quality (IAQ) is also important for the sensation of humans in indoor environments, as well as for their health. In the proposed work, a systematic measurement campaign in university classrooms in the Educational School of the University of Western Macedonia, Florina, Greece, is presented; the campaign was performed through winter time, noting that the University lies on the coldest thermal zone on a country level. Measurements include thermal comfort parameters, as well as IAQ ones, namely volatile organic compounds (VOCs), aldehydes and NO2 concentration. As far as thermal comfort is concerned, Fanger’s thermal comfort indices are calculated, on the basis of the measured data; a comparison is made through the support of questionnaires investigating the actual thermal comfort level of the students while being in the classrooms, aiming at providing information on an adaptive sensation level. In terms of air quality, measurements are made both indoors and outdoors, allowing the determination of indoor/outdoor correlations.

1 Introduction
Thermal comfort and Indoor Air Quality issues have gained significant interest in the scientific and technical community involved in buildings analysis, as demonstrated also by the recent amendment of the Directive 2010/31/EU on the energy performance of buildings[1], well known as EPBD, and Directive 2012/27/EU on energy efficiency[2]; that is Directive 2018/844/EU[3]. Concentrating on thermal comfort (“that condition of mind which expresses satisfaction with the thermal environment”, ASHRAE 55[4], specific standards have been developed, while presenting regular revisions; these standards are the ISO7730[5], ASHRAE 55[4] and EN 15251[6]. In principle two main approaches appear, the PMV approach (based on Fanger’s model), as well as an adaptive one, being related to the adaptability of the human body on specific parameters, influencing its actual thermal comfort expression[7]. The discussion in relevant literature has indicated the suitability of the adaptive model for Naturally-Ventilated Buildings (NV) Buildings, against its use for Mechanically-Ventilated ones[8-10]. Another aspect, that of IAQ, is also of major importance. According to ANSI/ASHRAE 62[11], acceptable air quality is defined as “airin which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction”. Even though IAQ is not related directly to thermal comfort, the term comfort is used for the case of odour and sensory irritation[10].
The case of University Classrooms presents high interest, as the maintaining of comfort and healthy indoor climate can positively affect the occupants’ learning performance and participation in the educational procedure[12-13]. Related studies, concentrating on thermal comfort include the ones of[14-16].

It should be noted that most investigations which combine thermal comfort and IAQ parameters concentrate to CO₂ values[17-18], while in principle, visual and acoustic aspects are also of importance[19].

In the proposed work, a systematic measurement campaign in university classrooms in the Educational School of the University of Western Macedonia, Florina, Greece, is presented; the campaign was performed through winter time, noting that the University lies on the coldest thermal zone on a country level. Measurements aim to assess thermal comfort (on the basis of Fanger’s thermal comfort indices), as well as IAQ, through the determination of the concentration of substances as CO₂, volatile organic compounds (VOCs) and NO₂. Especially in terms of thermal comfort, additional data through the support of questionnaires were collected, aiming at providing information on an adaptive sensation level for the students.

2 Methodology
2.1 Description of the classrooms
The building under investigation is that of the School of Primary Education of the University of Western Macedonia, located three kilometers outside of the town of Florina, on the Florina-Niki National Road. The climate of Florina is characterized as the coldest one, regarding Greece (Florina is ranked on D climate zone according to the Greek version of the EPBD[20]), because of its location and altitude (687m); rainfall is generally moderate, summers are mild and snowfall is frequent in the winter months. Average annual temperature of 12 °C is reported[21], while in the winter months, temperature may reach -20°C or even lower. Especially for the month of December, when the investigation took place, the average temperature is 2.2° C, with maximum average temperature at 6.3 °C and minimum average temperature at -1.6 °C[21]. The relative humidity in December is 81.8%, while 69.2% annually.

The Premises of the School of Primary Education (Figure 1) can be divided in three main departments. Section I is the oldest one (built in the late '70s), while by the early '90s Section II was built, and later on Section D; the later hosts administrative services. Section D is two-floored, while Sections I and II are one-floored. The building shell consists of cement-brick walls with double glazed windows, presenting inadequate thermal insulation (mean U values of 1.12-1.48 W/m²K are reported for the different floors and Departments[22]), especially taking into account the strict requirements of climatic zone D[20]. The total area of the building is 10,297.63 m², of which 9,360.99 m² refer to heated spaces.

Figure 1. General view of the School of Primary Education, University of Western Macedonia

Thermal comfort and air quality were investigated in two classrooms, located in the ground floor. One classroom (small amphitheater, indicated thereafter as Amph) lies in Section II with total surface 125m² and the other one (indicated thereafter as Cls) lies in Section I, with total surface 89m². Both classrooms are heated through conventional heating appliances, carrying hot water (Amph uses radiation type ones and Cls fan-coil), while ventilation is performed naturally through the opening of
the windows and doors. Amph has a very limited windows area, ventilated through the door, while for Cls the N and NW side is dominated by windows presence.

2.2 Experimental measurements set-up
The measuring quantities, in terms of thermal comfort, are the temperature (T) and the relative humidity (RH) of indoor air, radiant temperature, air-speed, while outdoor air meteorological conditions, i.e. temperature and relative humidity were also recorded. In terms of IAQ, CO₂ concentration was measured, as well as VOCs and NO₂ concentration. Instrumentation is presented in table 1; the information provided in the table includes the type of instrument, its measuring characteristics, along with the indication referring to its position.

Especially regarding VOCs, it is indicated that air-samples were taken using low-volume personal pumps (SKC) and pre-conditioned glass tubes filled with Tenax TA (Chrompack) at flow ratios of about 80 ml/min for 30 min. Moreover, duplicate samples were taken, and blank tubes were analyzed for quality assurance/quality control purposes. Samples were analyzed using a thermal desorption unit (Gerstel TDSA) coupled to a gas chromatograph (Agilent 6890N), equipped with a mass spectroscopy detector.

In figure 2a the lay-out of the Cls is presented, along with the installed instrumentation, while in figure 2b the respective information for Amph is presented. In figure 3, one may see some details of the installed instrumentation.

For the needs of the present analysis, it has been attempted to surround the indoor air space of the classes, while the installed height of equipment was mostly in the range of 0.5-2.5 m, aiming to be in compliance mainly with the breathing zone of students, while considering construction and operation constraints.

| Position Indication | Measuring Quantity/ Instrument type | Measuring characteristics |
|---------------------|-------------------------------------|--------------------------|
| a1, a2, a6, b3, b4, b6 | T-RH / Hobo ONSET H08-003-02 | Accuracy: ±0.5°C (T) [2], ±5% (RH) [2]. Range: -20 – 70°C (T), 25-95% (RH) |
| a5, a4, b1, b2 | T-RH- CO₂/Telaire 7001, Hobo ONSET U12-012 | Accuracy: ±0.5°C (T) [2], ±5% (RH) [2], ±5% or ±50 ppm (CO₂). Range: -20 – 70°C (T), 5-95% (RH), 0-10000 ppm (CO₂) |
| a3, b5 | Wind Speed (Gill Instruments 3D anemometer) | Accuracy: ±1.5% RMS. Range: 0-50 m/s |
| a7, b7 | Surface temperature | Accuracy: ±0.5°C (T) [2], ±5% (RH) [2]. Range: -20 – 70°C (T), 25-95% (RH) |
| a8, b8 | NO₂ / AEROQUAL (Series 500 IAQ) | Accuracy: ±10% |
| a9, b9 | VOCs / air sampling (SKC) and chromatography (Agilent 6890N) | - |

[1] The Telaire 7001 instrument was connected to HOBO ONSET U12-012 in order to record temperature and relative humidity.
[2] Aging effects have been considered
Figure 2. Classroom lay-out and relevant instrumentation position: a. Amph, b. Cls

Figure 3. Placement of sensors for measuring indoor air temperature, relative humidity, CO₂ concentration, air speed and surface temperature (indication according to table 1 and figure 2)

3 Results
3.1 Thermal comfort parameters
In the following tables (tables 2 and 3), the average, minimum and maximum values of most important parameters for each class, and outdoors are presented. The values presented refer to the average indication of all sensors (excluding sensor b6 as it will be discussed later on) for the periods the classes were crowded; these periods are presented in table 4.

| Parameter     | Indoor space | Outdoor area |
|---------------|--------------|--------------|
|               | Mean | Min  | Max  | Mean | Min  | Max  |
| T(°C)         | 22.8 | 18.3 | 26.3 | 6.8  | 0.29 | 10.6 |
| RH (%)        | 40.8 | 37.5 | 43.8 | 51.8 | 47.2 | 55.8 |
| CO₂ (ppm)     | 1315.9 | 525.6 | 2252.1 | -    | -    | -    |
| Wind Speed (m/s) | 0.068 | 0.018 | 0.222 | -    | -    | -    |
Table 3. Indoor and outdoor air climatic parameters during measurement period for Cls

| Parameter          | Indoor space |          | Outdoor area |          |
|--------------------|--------------|----------|--------------|----------|
|                    | Mean         | Min      | Max          | Mean     | Min      | Max      |
| Τ(°C)              | 20.9         | 18.2     | 23.7         | 2.24     | -4.44    | 5.81     |
| RH (%)             | 40.3         | 34.5     | 46.2         | 56.1     | 52       | 61.2     |
| CO₂ (ppm)          | 1920         | 502      | 2500         | -        | -        | -        |
| Wind Speed (m/s)   | 0.056        | 0.03     | 0.117        | -        | -        | -        |

Table 4. Periods of crowded classes

| Amph              | Cls               |
|-------------------|-------------------|
| Period 1 (Day 1)  | 05/12/2018 11:45-13:15 |
|                   | 11/12/2018 15:15-17:00 |
| Period 2 (Day 1)  | 05/12/2018 17:00-18:00 |
|                   | 11/12/2018 18:00-20:00 |
| Period 3 (Day 2)  | 07/12/2018 09:15-14:30 |
|                   | 12/12/2018 09:15-12:00 |

In figures 4a and 4b, the air temperature and relative humidity in various positions of the Classrooms during a typical day (day 2) is presented.

Figure 4a. Air-Temperature in various positions of the Classrooms during a typical day (day 2)

Figure 4b. Air relative humidity in various positions of the Classrooms during a typical day (day 2)

As one may see, the temperature in both classes lies in the range of 18-25°C (during periods of classes), indicating rather higher values for Amph. The sensor b6, at the Amph, has been affected by the end-heating appliances (all located on the North side), as demonstrated by the respective high values of temperature indicated. The values of the other sensors for the Amph are within a range of 2°C, while
significant differences, up to 4°C, are reported for Cls. One should note that Cls presents significant window surface on the S and W side; this can be related to the temperature on that side being lower, despite the fact that most heating appliances are on these sides.

Regarding relative humidity, the sensors present values on the range of 30-43% (during crowded periods) for the Amph, while for the Cls the values are higher, reporting a range of 33-56%. The trend of relative humidity values, for both classes, is in compliance with the crowding of the classes, i.e. the time the lectures take place, and the consequent opening of doors and windows for ventilation. The sensor b6 has not been included in the charts, as its indications have been affected by the proximity to the heating appliances. Concerning homogeneity of the indoor air, in the Cls there is a significant difference in the order of 10% between window (W, SW) and non-window side (E, NE).

It is noted that the even though a systematic investigation of the effect of the sensors installation height to the results was not performed at this stage of the proposed research, the above analysis demonstrated that non-homogeneity was merely affected by the windows presence; that is the case of the Cls, as in the Amph the values did not reveal significant differences.

3.2 IAQ parameters

In figure 5, the CO₂ concentration is presented for both classes; the same day, as in previous charts has been selected (day 2). As noted also just above for the case of relative humidity, one may clearly observe the crowding pattern of the classes through CO₂ concentration values. Values for both classes clearly exceed the acceptable level of 1000-1100 ppm[11,23]; the peak values are quite high, especially for Cls. One should note the limitations of the measuring equipment (actually of the recording logger), not demonstrating values higher than 2500 ppm. Observations demonstrated, for Cls, values in the order of 5000 ppm, which is the limit for long-term exposure in workplaces, according to the Occupational Safety and Health Administration of the United States.

![Figure 5. CO₂ concentration in various positions of the Classrooms during a typical day (day 2)](image)

Regarding NO₂, the values observed during periods of classes, indoors and outdoors, are presented in table 5. As expected, values are comparable indoors and outdoors, due to the absence of indoor NO₂ sources; the higher outdoor values for Cls, period 1, can be attributed to the fact that by that time there was some activity by a truck on the measurement field.

In figure 6, VOCs’ concentration is presented, indoors and outdoors, for day 1, during periods of classes. As one may see, the values are significantly higher for the case of the Amph. The chemical compounds with the highest values are Hexane, Benzene and Toluene; significant concentrations were detected regardless of the crowding pattern of the classes. Outdoor values are lower than indoor ones, indicating that indoor sources affect the air quality of the classrooms.
### 3.3 PMV calculation

The Predicted Mean Vote index (PMV) and the Percentage of People Dissatisfied index (PPD) (Fanger’s thermal comfort indices) were calculated according to the relations proposed by EN ISO 7730, Annex D\(^5\). Calculation was implemented for each specific period the classes were crowded. Regarding the measured parameters entering calculations, it is noted that the radiant temperature was estimated with regard to the measured parameters of surface temperatures, taking also into account verification during specific periods through the support of a thermal imaging camera (FLIR TG167). The operation temperature (\(T_{op}\)) was calculated as the mean of radiant and air-temperature, due to the fact the measured air-speed is too low (<0.2 m/s)\(^5\). Clothing parameter was estimated per person according to the questionnaire analysis (see section 3.5).

As can be seen in table 6, PMV values for both classes lie within the range of (-0.5, 0.5) for thermal sensation satisfaction. The PPD values are in compliance with the PMV ones, while operation temperature (\(T_{op}\)) is lower for CIs as discussed also above, and verified by the lower PMV values, especially for Periods 2 and 3.

#### Table 6. Calculated thermal comfort values

| Parameter         | PMV     | PPD     | \(T_{op}\) | PMV     | PPD     | \(T_{op}\) |
|-------------------|---------|---------|-------------|---------|---------|-------------|
| **Amph**          |         |         |             |         |         |             |
| Period 1 (Day 1)  | -0.09±0.19 | 5.89±0.83 | 21.49±1.17  | 0.17±0.24 | 6.77±4.20 | 21.19±0.66  |
| Period 2 (Day 1)  | 0.04±0.17 | 5.55±0.75 | 21.64±0.58  | -0.26±0.19 | 7.16±2.34 | 19.97±0.69  |
| Period 3 (Day 2)  | 0.49±0.09 | 10.20±2.00 | 24.42±2.51  | -0.45±0.27 | 10.80±4.87 | 19.2±0.97   |
| **CIs**           |         |         |             |         |         |             |

In the following chart (figure 7), the PMV versus thermal insulation of clothing (Icl) is presented. As one may observe, for both classes, heavier clothing is related to higher values of PMV.
3.4 Questionnaire analysis

A questionnaire was prepared and used for the scope of the presented research. The questionnaire included anthropometric information for each person, namely gender, height and weight, if they felt healthy or sick at that moment, their length of exposure to the thermal environment in the room, information regarding their clothing and information regarding their perception towards specific parameters of thermal environment, air quality, odors, lighting and noise. The following discussion focuses on thermal environment issues.

A total number of 198 questionnaires was selected. In table 7, the anthropometric information for the complete sample is presented. The Body surface was calculated according to the Dubois relation\[24\].

| Gender   | Age     | Height (m) | Weight (kg) | Body Surface area (m²) |
|----------|---------|------------|-------------|------------------------|
| Male     | 23.3± 8.5 | 1.79± 0.1  | 75.62± 12.5 | 1.88± 0.3              |
| Female   | 22.91± 8.2 | 1.65± 0.1  | 62.68± 12   | 1.65± 0.2              |
| Male + Female | 23.01± 8.2 | 1.68± 0.1  | 65.79± 13.3 | 1.71± 0.3              |

Regarding the actual values of satisfaction with the thermal environment (AMV), these were calculated according to a seven-point scale response of their thermal sensation\[4\]. Moreover, students were also asked if they would prefer a change to the current setting, with regard to a five-point scale response\[4\].

In the following table (table 8), the average AMV, corresponding to the response of their students regarding their satisfaction with the thermal environment, and the respective APD values are reported. The demonstrated values are rather high, indicating warm environment. The high values of APD can be attributed to limited marginal values for PMV in the questionnaires.

Proceeding to a comparison between AMV and PMV values, the subjective responses demonstrated a clearly warmer environment than the predicted one for 5 out of the 6 studied periods; this can also be concluded by figure 8, demonstrating a linear regression relation between PMV and AMV (PMV = 0.237AMV − 0.21, $R^2 = 0.22$). The observed differences could potentially be related to the non-homogeneous indoor climate of the classes, as discussed also in the analysis of the indoor climate parameters (section 3), while the quite high values of CO₂, demonstrating inadequate ventilation, potentially force the students to extend their dissatisfaction on thermal comfort as well.
Table 8. Thermal comfort adaptive values

| Parameter                | AMV         | APD         | AMV         | APD         |
|--------------------------|-------------|-------------|-------------|-------------|
| Period 1 (Day 1)         | -0.22±1.35  | 35.71±28.81 | 0.91±1.17   | 45.11±30.29 |
| Period 2 (Day 1)         | 0.54±1.27   | 33.03±31.12 | 0.97±1.1    | 43.12±33.08 |
| Period 3 (Day 2)         | 1.8±0.76    | 65.60±28.10 | 0.88±1.1    | 21.24±30.54 |

4 Conclusions

The analysis of the thermal comfort perception of the students in two university classes by winter time, demonstrated values of PMV indicating neutral sensation. The estimation of the PMV was a result of a measurement survey, aiming at detecting the values of the involved thermal comfort parameters on a spatial manner as well. Insufficient ventilation was determined through the recording of quite high CO₂ concentration values, especially by the time the classes were crowded. The presence of considerably high values of VOCs for the Amph, potentially related with the insufficient ventilation of this classroom, should be investigated in more detail, while NO₂ values are comparable indoors and outdoors for both classes as there were no indoor sources. Given the above, the administration should consider means for increasing the quantity of fresh air in the classrooms; installation of an air-conditioning system could improve indoor air quality. Nevertheless, given that this is a costly solution (in terms of installation and operation), ventilation fans could be used instead. Such an intervention needs though further investigation, regarding the position of the fans, air volume capacity and their operation pattern, in order not to disturb thermal comfort sensation of the students.

The subjective response of the students demonstrated sensation of a warmer environment than the predicted one. This is in agreement with the expressed in the relevant literature weakness of the PMV Fanger model to accurately predict thermal comfort for naturally ventilated spaces, noting that both classes are ventilated through the opening of doors and/or windows. Moreover, limitations of prediction can be related to potential spatial effects of the measured parameters, while the strong insufficiency in terms of air quality, could affect the expression of the students’ response on a thermal level. Further research on these effects, leading to the establishment of a specific relation between prediction and actual sensation should be implemented.
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