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Thermal Comfort and Air Change Rate Study for a Naturally Ventilated Classroom: A Case Study of El-baida City, Libya

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Abstract Nowadays in building and environment, it is of a functional requirement to fulfill a robust design by diminishing the energy consumption while keeping the environmental factors surrounding the individuals within a comfort range. Natural ventilation in buildings is considered as an advantageous attempt serving those purposes. In Libya, most of the educational buildings are utilizing the natural ventilation systems where the energy consumption is minimized while the internal temperatures and humidity are constrained, indoor air is replenished and all other contaminants are reduced. Although extensive oversea researches have been carried out in this regard, few studies have touched the thermal comfort and internal environmental attributes influencing the performance of students in Libya. The main objective of this study was to investigate qualitatively and quantitatively the thermal comfort and air change rate of a naturally ventilated classroom located in El-baida City-Libya. The thermal comfort of one classroom, was evaluated by calculating the values of the Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) indices. This was accomplished by measuring the six main indoor parameters of the thermal comfort, namely were, air temperature, Mean Radiant Temperature (MRT), relative humidity, air velocity, activity level and clothing insulation. Also, (PMV) and (PPD), were calculated in parallel to ASHRAE 55-2010 and ISO 7730 by using MATLAB. Additionally, a field survey was completed by distributing comfort questionnaires to estimate Thermal Sensation Votes (TSV), which were then compared with computed (PMV) and (PPD). The results highlighted that while computed values of (PMV) and (PPD) for the classroom, were thermally satisfactory according to ASHRAE standard 55 and ISO 7730, the Thermal Sensation Vote (TSV) based on the questionnaire, showed that the classroom did not satisfy the thermal criteria in ASHRAE.
Keywords: Air exchange rate; Indoor air quality; Thermal comfort; Tracer gas decay.

دراسة الراحة الحرارية ومعدل تغير الهواء في فصل دراسي ذو تهوية طبيعية: دراسة الحالة بمدينة البيضاء– ليبيا

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الملخص في وقتنا الحاضر يعتبر تحقيق تصميم جيد من المتطلبات الوظيفية في عملية البناء وتحقيق بيئة داخلية ملائمة، وذلك من خلال تقليل استهلاك الطاقة والحفاظ على العوامل البيئية المحيطة بالأفراد ضمن نطاق الراحة الحرارية. وتعتبر التهوية الطبيعية للمباني أحد الاشياء المفيدة لخدمة تلك الأغراض. في ليبيا، تعتمد معظم المباني التعليمية على نظام التهوية الطبيعية حيث يتم تقليل استهلاك الطاقة إلى الحد الأدنى بينما يتم تقييد درجات الحرارة والرطوبة الداخلية، ويتم تجديد الهواء الداخلي وتقليل جميع الملوثات الأخرى. على الرغم من انه تم إجراء أبحاث مكثفة في هذا الصدد، إلا أن القليل من الدراسات قد تطرقت الى الراحة الحرارية والسمات البيئية الداخلية التي تؤثر على أداء الطلاب في ليبيا. إن الهدف الرئيسي من هذه الدراسة هو االتقييم النوعي والكمي للراحة الحرارية ومعدل تغير الهواء في فصل دراسي ذو تهوية طبيعية يقع في مدينة البيضاء –ليبيا. تم تقييم الراحة الحرارية في فصل دراسي واحد من خلال حساب قيم متوسط الأصوات المتوقعة (**PMV**) والنسبة المئوية لغير الراضيين (**PPD**). حيث تم ذلك من خلال قياس العوامل الداخلية الستة الرئيسية للراحة الحرارية، وهي درجة حرارة الهواء، ومتوسط درجة الحرارة اللإشعاعية (**MRT**) ، والرطوبة النسبية ، وسرعة الهواء ، ومستوى النشاط ، وعزل الملابس ومن ثم ، تم حساب (**PMV**) و (**PPD**) وفقا ل **ASHRAE 55-2010** و **ISO 7730** باستخدام **MATLAB**. بالإضافة إلى ذلك، تم إجراء مسح ميداني من خلال توزيع استبيانات الراحة لتقدير أصوات الإحساس الحراري (**TSV**) للطلبة وتمت مقارنتها بعد ذلك مع (**PMV**) و (**PPD**) المتحصل عليها حسابيا. بينت النتائج أنه في حين أن القيم المحسوبة لـ (**PMV**) و (**PPD**) للفصل الدراسي كانت مرضية من الناحية الحرارية وفقا لمعيار **ASHRAE 55** و **ISO 7730** ، الا ان تصويت الإحساس الحراري (**TSV**) للطلبة والذي تم الحصول عليه من الاستبيان بين أن الفصل الدراسي لم يكن مريحا من الناحية الحرارية وفقا **ASHRAE**.

الكلمات المفتاحية: الراحة الحرارية، جودة الهواء الداخلي، إضمحلال غاز التعقب، معدل تغير الهواء.

Introduction

This study was conducted in El-Baida, a city located in north-east of Libya at latitude and longitude coordinates of 32.75° and 21.74°, respectively. El-Baida's elevation from sea level was about 630 meters. The winter climate was characterized by low temperature and high relative humidity which was hitting up to 100% at some whiles. In summer, the average temperature was about 26.1°C and the average relative humidity was approaching 57.3% as verified by Hamad (2007) [1]. The study field was one site, which was a classroom on the second floor of the Languages Centre building at The University of Omar Al-Mukhtar as shown in

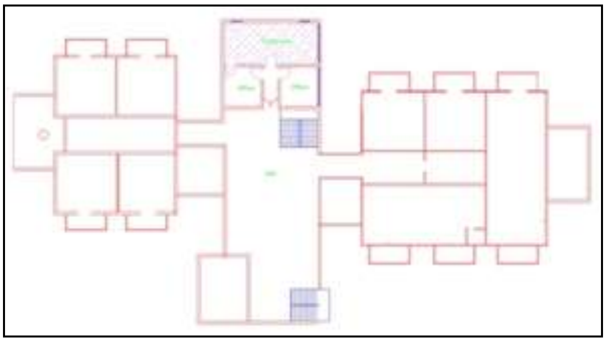

Figure **1**.

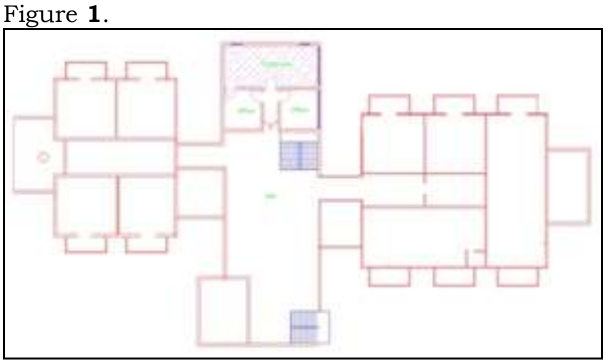

Figure 1. Languages Centre

The length, width and height of the classroom, were specifically 9, 4 and 2.8 m, respectively. The numbers of occupants, were 20 students (12 females, 8 males) and a teacher as depicted in Figure 2. The classroom was naturally ventilated in which a normal flow of external air, was offered. In addition, the classroom was equipped with a split unit air conditioning system, which was controlled and operated by the occupants during schooling prime time.

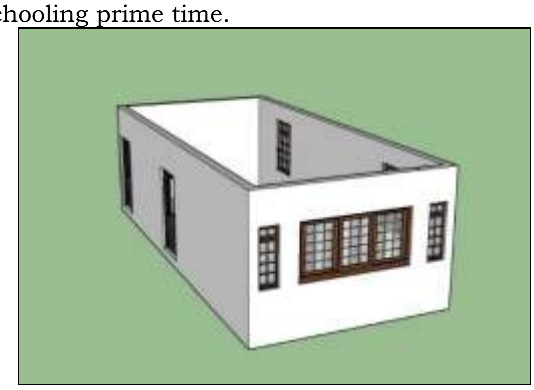

Figure 2 . Classroom

Daghigh et al. (2012) highly recommended that the thermal conditions inside the classroom, was to be meticulously considered particularly when the classroom was densely populated. The thermal conditions had a detrimental effect upon the occupants' psychological, physiological and behavioral statues, which in turn, led to poor performance and low achievement[2]. That's why, attaining the institutional thermal comfort, was pivotal. The same conclusion was confirmed by Haddad, King and Osmond (2012). There were a tradeoff between the educational achievement and both the relative humidity and the temperature inside the classroom. The low temperature could weaken the handy craft and production compared to relatively warmer temperatures[3].

The researchers have targeted the issue of the institutional thermal comfort. As an attempt to shed light on effort exerted by other, a literature review was chronologically presented herein after.

Fanger (1970) identified that if several people within a room experienced the same climatic conditions, satisfaction of all occupants was rarely realized, owing to the physical contrast. It was added that the relative humidity, air temperature, air velocity and mean radiant temperature, were able to be calculated for any level of activity and clothing that all together created thermal comfort by using the comfort formula[4]. Madsen (1976) continued the study of Fanger (1970) and enhanced a new thermal comfort index which was called the predicted mean vote (PMV-index)[5]. Dear, Leow and Foo (1991) conducted thermal comfort field experiments in air conditioned and naturally ventilated buildings in Singapore. The results showed that although the internal environment of the building was consistent with the ASHRAE, ISO standards and Singapore's indoor climatic standard, one-third of the occupants felt cold thermal comfort sensations[6]. Kwok (1997) studied the thermal comfort of a number of naturally ventilated and air-conditioned classrooms in the tropics region in Hawaii and found most of the classrooms failed to meet the specifications of the comfort zone according to the ASHRAE standard, while more than 80% voted by accepting for both natural ventilation and air-conditioned[7]. Huizenga and et al. (2006) carried out a questionnaire for residents of about 215 office buildings in Canada, Finland, and the United States in order to find out the response of people to thermal comfort and indoor air quality. The results of the field survey revealed that just about 11% of the buildings were thermally acceptable as more than 80% expressed their satisfaction. Only 26% of the buildings were suitable in terms of indoor air quality and over 80% voted for their satisfaction with indoor air quality[8]. Hamad (2007) managed a research study of thermal comfort applications in two Libyan schools in different cities and found that there were no thermal comfort zones despite the differences in thermal comfort between both schools[1]. Mumovic and et al. (2007) investigated the thermal comfort and indoor air quality in three new secondary schools in England within a massive program to rebuild and renovate schools in England and Wales, commissioned by the British government (Building Bulletin 101). The finding was that many rooms did not meet the recommended level in terms of thermal comfort, whereas the recommended ventilation performance was satisfactory for all the schools[9]. Maarof and Jones (2009) examined the thermal comfort factors in Malaysia to determine the decisive factor which influenced the outcome of the comfort level. Air temperature and relative humidity, were studied thoroughly and was revealed that the relative humidity was more influential in the comfort level assessment compared to the air temperature[10]. Longo and et al. (2011) analyzed the thermal comfort of occupants of a naturally ventilated building, located in Florianopolis, Brazil. In order to improve the natural ventilation efficiency, automated and manual control windows located in different areas were simulated. It was found that the automated control of windows was the best alternative for improving thermal comfort[11]. Salleh and et al. (2011) finished a review study about the school environments in Kuala Lumpur, Malaysia to evaluate the indoor air quality (IAQ) which were carbon dioxide as well as ventilation rate. The finding was obvious that the indoor environment was not complying with ASHRAE, The National Institute for Occupational Safety and Health (NIOSH), American Conference of Governmental Industrial Hygienists (ACGIH) and Occupational Safety and Health Administration (OSHA), where the majority of the children were subjected to an inadequate environment throughout their time in the classroom[12]. Ioana and el al. (2014) ended a field survey in a naturally ventilated university classroom in Bucharest, Romania. A comparison between Predicted Mean Vote (PMV) and Thermal Sensation Vote (TSV), was made and the final results exhibited a difference between PMV values and (TSV) values[13]. Hou, Liu and Li (2015) handled a research study to evaluate indoor air quality in classrooms of two primary schools in Beijing, China. The final results revealed that the concentration of CO_2 could increase over 2500 ppm inside a classroom. Furthermore, it was obtained that the ventilation rates were less than 1 l/s/p. It also indicated that mechanical ventilation equipment with purification function was highly recommended to be used to ensure good indoor air quality[14]. Pereira, Neto and Silva (2015) directed a study to assess thermal comfort and indoor air quality in two schools in Portugal. A field questionnaire was carried out on the students, as well as monitoring the physical parameters of the building. The results of the questionnaire showed that the concentration of carbon dioxide exceeded the permissible limits, while the air temperature was within the acceptable limits[15]. Vilčeková and et al. (2017) investigated the indoor environment quality in classrooms during the winter and summer semesters at the University of Kosice, Slovakia. Results showed that it was very important to recommend optimization procedure to decrease the CO_2 concentrations and thermal load during the summer period[16]. Ranjbar (2019) presented an experimental research in Interior Architecture and Environmental Design Department at Bilkent University, Ankara, Turkey. The study was aimed at investigating the relationship between the performance of the students and the ventilation mode, also to check out the different ventilation modes effect on indoor air quality and thermal comfort both in-studio and classroom environments under three states of ventilation: closed doors and windows, naturally ventilation and ventilation mode using the Heating, Ventilation and Air Conditioning system (HVAC). The obtained results showed that the HVAC unit mode was the most acceptable for indoor environment in both seasons (summer and winter) for the occupants as well as the student performance[17].

Although most of the educational buildings, whether schools, universities or institutes have its own natural ventilation systems, nevertheless, there have been handful studies providing a thorough investigation pertaining to thermal comfort in Libya. Also, the internal environment influencing the performance of the students and other occupants, has not been well understood. A question arises "Are those buildings considered to be well-designed in terms of thermal comfort and air change rate?"

Providing thermal comfort was extremely affected by six environmental and personal factors. These factors together contributed to the occupants' thermal comfort:

Environmental factors:

- Air temperature
- Mean radiant temperature
- Relative humidity
- Air velocity

Personal factors:

- Activity level
- Clothing insulation.

The main objectives of this study were to satisfy the following:

- To evaluate the level of thermal comfort of the classroom and compare it with ASHRAE 55 and ISO 7730.
- To determine Air Change rate (ACH) and compare it with ASHRAE standard 62.
- To investigate the student perception of the comfort degree and indoor air quality in the classroom.

Data collection took place during the period between the first of December 2018 and the first of January 2019. Gas tracer decay was conducted in the middle of February. The classroom course was held daily except Friday from 10:00 am to 12:00 pm, with a break time from 11:00 am to 11:15 am.

Methodologies:

This study was a quantitative and qualitative research. The thermal comfort factors and air change rate, were quantified as well as the occupant's thermal sensation, was explored as follow:

1. Determining the Main Comfort Factors:
One objective was attempted by evaluating the thermal comfort of the classroom as the values of the Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) indices, were all calculated. To obtain (PMV) and (PPD), the six main factors of thermal comfort, were measured and assessed. Five locations were selected inside the classroom, in which, the air temperature, relative humidity and air velocity were measured at a height of 0.1, 1.1 and 1.7 m for each point at a time interval of 15 minutes.

The mean radiant temperature was calculated as indicated by Li and et al. (2014) by summation of the product of average temperature and individual area and divided by the total surface areas of walls, floor and ceiling[18]. The temperature of each area was measured separately. The mean radiant temperature can be calculated as follow:

$$Tmrt = \frac{A_1T_1 + A_2T_2 + \cdots A_nT_n}{A_1 + A_2 + \cdots A_n} \quad (1)$$

where T_1, T_2 and T_n were the interior surface temperature(°C), A_1, A_2 and A_n were the interior surface area (m²).

It was considered that the students were standing at the central point of the classroom. The metabolic rate was estimated according to ISO 7730 as a sedentary activity with a value chosen to be 1.2 MET[19]. The clothing isolation value (clo-value) was indirectly approximated according to both ISO 7730 and ASHRAE 55-2010, by collecting the partial isolation values for each piece of clothing with neglecting the value of the insulation of the chairs. Both (PMV) and (PPD), were calculated using MATLAB computer tool according to ASHRAE 55-2010 and ISO 7730[20].

2. Determining Air Change Rate:
In order to determine the rate of air change for the natural ventilated classroom expressed in $(1/h)$, the concentration decay technique was performed according to the ASTM standard. Carbon dioxide (CO2) was selected as a trace gas for this test. As Benedettelli and el al. (2015) recommended, it was confirmed that the amount of variation in concentration of the tracer gas anywhere within the classroom did not exceed 10%[21]. With respect to ASTM standard, the mean air change rate for this period was calculated by the difference between the logarithms of the initial and final trace gas concentrations divided by the time period. As the decay of gas concentration had an exponential curve, the rate of air change can be derived from any two points on the curve[22]. Cui and el al. (2015) designated the rate of air change through the following formula[23]:

$$N = \frac{1}{\Delta t}(\ln ci - \ln cf) \quad (2)$$

where N was air change rate (ACR), ci and cf were initial and final CO2 concentration, respectively.

3. Questionnaire:
A field survey was conducted within the classroom as a pilot study. The questionnaire was prepared and given to the students in a weekly basis throughout the study interval. Students were asked to fill in the required data representing gender, age, seasonal condition, the general thermal sensation according to seven-point ASHRAE-55, location of the student in the classroom, clothing items that the students were wearing, activity level, things or devices which were adjusted or controlled by the students, satisfaction with the temperature in the classroom, reasons contributing to dissatisfaction, source of discomfort and any other related issues. Based on the data obtained from the questionnaires, PPD and the thermal sensation were to be estimated by using statistical tool IBM SPSS Statistics 23.0.

4. Measuring Instruments
Each of the parameters was recorded manually. Figure 3 depicted 'TES–1341 Hot-Wire Anemometer' to measure air temperature, relative humidity and air velocity.

Figure 3. Hot Wire Anemometer

'Portable CO2 Meter' shown in Figure 4, was utilized to gauge CO2 concentrations.

Figure 4. CO2 Meter

'Thermometer', which used to measure surfaces temperature, was shown in

Figure 5.

Figure 5. Thermometer

Results and Discussion

1. PMV and PPD

From the thermal comfort parameters, PMV and PPD were calculated for the classroom using MATLAB code as displayed in

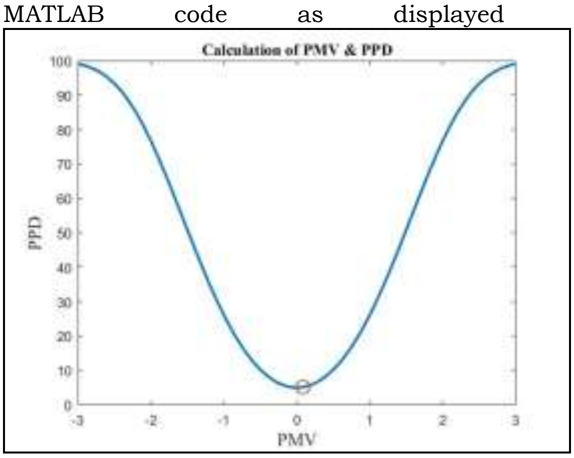

Figure **6**. It was prominent that as the Predicted Mean Vote (PMV) reading 0.09, the Predicted Percentage Dissatisfied (PPD) was just 5.15%. As highly recommended by ISO 7730 that the comfort range was to be taken as a condition when the PMV had the values between –1 and +1. The obtained results showed that the classroom was classified within Class A according to ISO 7730 which was the highest satisfaction with respect to environmental level. In this fashion, the classroom was considered to be thermally comfortable at this time with an average temperature of 18.2°C and relative humidity of 65.9%.

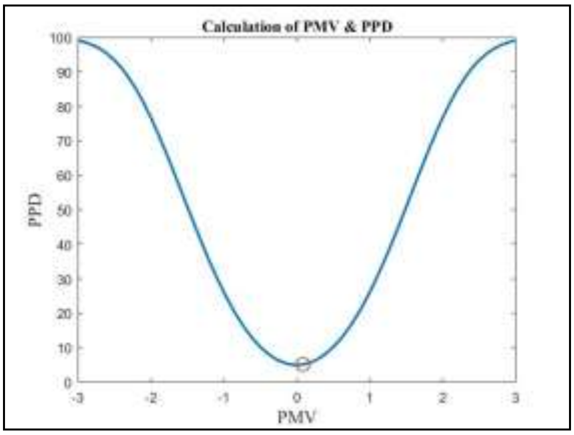

Figure 6. PMV and PPD results

2. Air Exchange Rate (ACH)

The CO2 concentration decay profile of the classroom was shown in FFigure 7. As it was clear that the mean external air velocity was 0.4 m/s which was just a synonym to low external wind pressure, the air infiltration was to be neglected. The outside air exchange rate (ACH) was governed by the initial and final CO2 concentration decay of the classroom over the time.

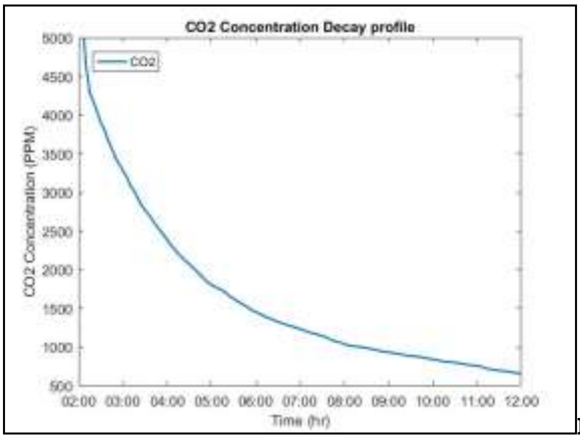

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Figure 7. The Decay of CO2 in Classroom

Table 1 tabulated the computed air exchange rate aligned with fresh air quantity. It was worth noting that the air exchange rate was 0.2 and while the amount of fresh air provision was 0.25 l/s/person based on actual occupancy, the recommended amount of fresh air provision is 3.8 l/s/person according to ASHRAE -62.

Table 1. Measurements of Air Exchange per hour (ACH) and Outside Air Quantity

Location	ACH (h-1)	Fresh Air (L/s)	Actual occupancy		ASHRAE
			No. of persons (Occ)	*Persons outdoor air rate (L/s person)*	*People outdoor air rate (L/s person)*
Classroom	0.2	5.6	22	0.25	3.8

Based on the finding, it could be inferred that the actual occupancy air amount was not adequate, as it was merely 6.5% of the recommended amount according to ASHRAE-62.

3. Evaluation of Questionnaire

Four questionnaires were managed throughout the entire study period to ensure that reliable results were to be obtained. In total, 73 valid questionnaires were collected during the whole study period where the number and percentage of students who participated in the questionnaire were illustrated in Table 2

Table 2. Total Number and Percentage of occupants

Gender	Frequency	Percentage
Male	25	34.2
Female	48	65.8
Total	73	100.0

In this study, the evaluations of the average Thermal Sensation Vote (TSV) were exhibited in Figure 8.

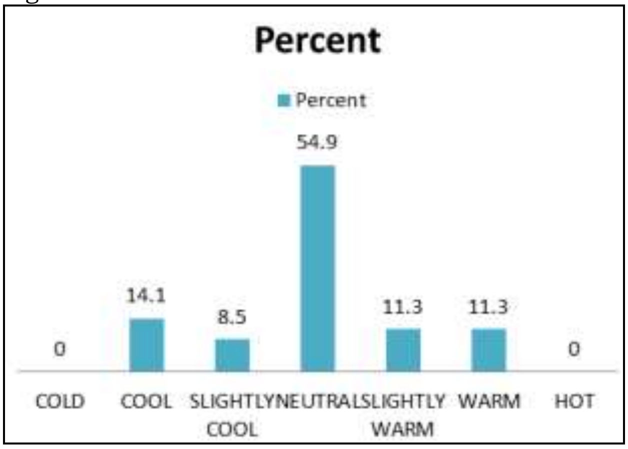

Figure 8. Average Thermal Sensation Vote

It was noteworthy that the students' thermal vote according to ASHRAE scale, was centered in a region of -2 to 2. Although, average clothing insulation for both male and female throughout the study period was 1.67 Clo, overall acquired results showed that the students inside the classroom voted 74.7% within the three central thermal sensation scales. These findings were satisfied with the thermal condition in their classroom. Comparably, 14.1% experienced uncomfortable condition as it was claimed that the classroom was cool, while 11.3 % felt a warm surrounding. It was prominent that even though the mean clothing insulation for males was less than that of females, the percentage of males who expressed their satisfaction with the thermal conditions inside the classroom was about 84% of the total number of males, while 68% from the total females shared males the same perception. Dissatisfaction can be attributed to many factors. High humidity, cold air temperature and lack of air movement, might be viable justifications. The author emphasized that occupants should be well-trained before conducting the questionnaire to attain a precise assessment as some students were not able to give any ground for their dissatisfaction.

4. Comparison between PPD and PMV Indices and Results from the Questionnaire:

Even though the majority of the occupants were satisfied with the thermal conditions of the classroom, which was 74.7%, the classroom was not found acceptable in terms of thermal comfort. This can be rationalized that the voting rate did not achieve 80% of the students.

It was noted that there was a discrepancy in the results while computing PMV and PPD indices. Despite the fact that the PPD computed through direct voting gave a 5.15%, the same PPD delivered a 25.3% when the questionnaire was tackled.

Conclusions

In this study, thermal comfort and air change rate, were evaluated for a naturally ventilated classroom in Omar Al-Mukhtar University, El-baida, Libya. Thermal comfort factors, were appraised in order to determine PMV and PPD which were used, in turn, to portray the thermal comfort. The concentration decay technique was performed to determine the rate of air change for the classroom. A field survey questionnaire was carried out within a classroom with the aim of estimating the thermal sensation vote for occupants directly.

The main conclusions were stated hereinafter:

- There was a deviation between the classroom thermal conditions and the comfort zone of ASHRAE standard 55 and ISO 7730.
- Computed values of PMV and PPD showed that the classroom had satisfactory thermal conditions according to ASHRAE standard 55 and ISO 7730.
- Estimated clothing insulation for naturally-ventilated classroom occupants' for both males and females, were considered to be about 1.67 Clo. This Clo level was approximately higher than ASHRAE clo winter comfort zone which might be justified because of the cold temperature inside the classroom.
- The outside Air Change Rate (ACH) was not adequate based on actual occupancy in the classroom according to ASHRAE-62. Experimental measurement showed that the classroom had poor indoor air quality.
- The Thermal Sensation Vote (TSV) based on the survey questionnaire, exposed that the classroom had not satisfactory thermal conditions according to ASHRAE thermal sensation scale.
- Different results can be obtained by different methods of thermal comfort assessment. There was a discrepancy in the results obtained by the survey questionnaire compared to that obtained by measuring thermal comfort factors.

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