# Measurements of $CO_2$ levels in a Classroom and its effect on the performance of the students

**R. Greene [1] BSc, MSc Dr. M.Eftekhari [2] BSc, D.phil, MASHRAE and Prof. D.Clements-Croome[3] BSc, MSc, PhDCEng, FCIBSE, FInstP, FIOA, FASHRAE G.Georgiou[2] BSc, MSc**

(1) P. O. Box N-9222, Nassau, Bahamas; keli_11@hotmail.com
(2) Department of Civil & Building Engineering, Loughborough University, Loughborough, LE11 3TU, m.m.eftekhari@lboro.ac.uk
(3) School of Construction Management and Engineering, University of Reading, Reading, RG6 6AW, d.j.clements-croome@reading.ac.uk

**Abstract**
This paper will describe the effects of high $CO_2$ concentration on the thermal comfort and academic performance of students during winter and summer in a large occupied lecture room.
An experimental method including objective measurements of air quality monitoring and building physical measurements was used with subjective measurements combined with academic performance and thermal comfort questionnaire.
The results show average performances for a sixty percent attendance rate per class at approximately 48%-62%. The maximum daily average $CO_2$ levels for the sample was 2,714 parts per million (ppm). This is much higher than the 1,500 ppm daily requirements***.*** The condition of the lecture room during the summer period, based on a five point Predicted Mean Vote (PMV) scale of subjective responses of the students were found to be slightly hot, slightly humid, slightly stuffy, slightly bright and slightly noisy.
A computer model produced daily ventilation rates ranging from 0.25 – 0.93 litres per second per person. This is also much lower than the required minimum background ventilation rates of 3 litres per second per person.

**Key Words:** lecture rooms**,** classrooms**,** carbon dioxide, academic performance, thermal comfort,

## 1.0 Introduction

Billions of pounds will be spent over the next decade to build and refurbish educational facilities within the United Kingdom. As a result guidelines are put in place to help decision makers to design and implement proper standards for schools since the 1900s. Upgrades and suggestions will assist in providing safer and more comfortable learning environments for students.
The minimum ventilation rate of 3 litres/second/person with a capacity of 10 litres/second/person for lecture halls ***[i,ii]*** has been set as a new performance specification.
This study will determine the effects of $CO_2$ on the academic performance and thermal comfort of students within a typical mix ventilated large lecture room. The results will be compared to the daily requirements as outlined above through the use of questionnaires with subjective responses, air quality monitoring and a simple computer model.

## 2.0 Effects of $CO_2$ on Students

Studies carried out by Awbi et al [***iii]***, showed that $CO_2$ levels as high as 4,000 ppm show effects on the student's ability to properly concentrate. Another study by Nkwocha & Egejuru ***[iv]***, showed that some symptoms of high $CO_2$ concentrations cause prevalent conditions such as, "common colds, coughs, phlegm, sinusitis, and bronchitis amongst students. The Environmental Protection Agency (EPA) ***[v]*** states that signs of lethargy, dis-coordination, headaches, asthma and respiratory infections are other symptoms of poor ventilation and high $CO_2$ levels. Therefore, good ventilation and air quality is essential to a student's health and performance ***[vi]***. In naturally ventilated classrooms ***[vii]***, internal air have been shown to have $CO_2$ levels ranging from 690 ppm to 2,909 ppm. In addition, ventilation rates were measured as low as 0.5 litres per second per person.

In mechanically ventilated classrooms ***[viii]***, $CO_2$ levels were as high as 3,127 ppm with ventilation rates as low as 0.5 litres/second. This was confirmed by an alternative method using a continuity equation based on the occupant's age, weight and gender. Humidity and temperature measurements were used as parameters of air quality and the occupant's response to thermal comfort. The low ventilation rates and high temperatures and humidity levels suggest that the thermal comfort of the students have been compromised. These factors confirm that $CO_2$ should be used as the controlling factor for measuring ventilation and air quality within and occupied space.

## 3.0 Methodology

A large lecture room was chosen as the sample. This room was typical of other lecture rooms on the university's campus and similar to the other Universities within the UK.

The test was performed during the winter and summer periods under controlled conditions. The mix ventilated room contained two manually operated windows.

A non-dispersive infrared air quality monitor (Figure 1) was used to record daily $CO_2$ levels in a secure mode. This monitor was connected to a laptop via an adapter and the information was downloaded to create visual graphs for comparison of $CO_2$, temperature, relative humidity and dew point.

A daily log was taken for each of the testing periods providing their names and the number of students, the behaviour of the students and time of the course. There were approximately 2,818 periods recorded at one minute intervals over two weeks during the summer and winter seasons.

A ten minute combined questionnaire was created for academic performance and thermal comfort. The questions for the academic performance section included ten basic mathematics questions ranging in topics from trigonometry and algebra. This was used to test the student's ability to analyze and perform problem solving techniques, simultaneously while the air quality monitor recorded $CO_2$ levels. This test was given in the last ten minutes of the regularized fifty minutes class time. At this time, the $CO_2$ levels are greater during the end of the sessions, due to a build-up of $CO_2$, stale air and odours.


**Figure 1 - Quest Suite AQ5000 Pro Indoor Air Quality Monitor on Desk**

The thermal comfort section of the questionnaire used a prior tool obtained from the literature research by Clements-Croome et al, ***[ix]*** which contained subjective questions on a 100 mm predicted mean vote (PMV) scale. This questionnaire was adjusted to suit the occupants of the sample with questions relative to air quality, air movement, temperature, lighting, humidity, acoustics and sick building syndrome on a five point PMV scale.

The intent was to offer this test to the same group of students on different days. This test was administered to three separate classes of a total sum of one hundred and seventy students.

## 4.0 Measurements

Daily measurements were taken during two testing periods. The first testing period during the winter was December $1^{st}$-$5^{th}$, 2008 (Figure 2) and the second period in the summer was May $5^{th}$-$8^{th}$, 2009. Each morning there was a rapid increase in $CO_2$ concentration measurements, once the students, lecturers and other occupants entered the lecture room. The recorded levels raised above the recommended daily requirements of 1,500 ppm. The $CO_2$ concentration decayed during breaks, lunch periods or simply at the beginning or ending of each day corresponding to the average external $CO_2$ concentration of 615 ppm.

The recording provided maximum, average and minimum $CO_2$ values which were used to create informative graphs. External temperatures were recorded by a Building Engineering Management System (BEMS) on campus and alternatively the Exeter Devon Meteorological offices in United Kingdom provided hourly temperatures for each day of testing.

A summary table of $CO_2$ concentration for testing period two is shown is Table 1 below.

**Days of Sampling for Testing Period 2, May $5^{th}$-$8^{th}$, 2009**

| **$CO_2$ (ppm)** | **Tuesday** | **Wednesday** | **Thursday** | **Friday** |
|---|---|---|---|---|
| Maximum | 2,150 | ****3,423*** | 3,366 | 1,918 |
| Minimum | 787 | 1,851 | 1,798 | 593 |
| Average | 1,245 | 2,623 | 2,712 | 1,149 |

**Table 1 - Maximum, Minimum and Average $CO_2$ concentrations, *Highest daily concentration- Testing Period 2**

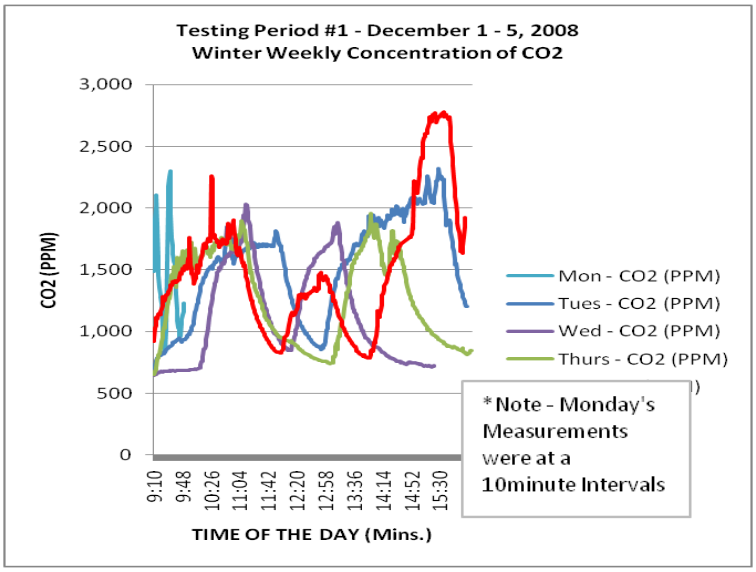


**Figure 2 - Daily Measurements of $CO_2$ Levels – December 1st & 5th, 2008**

The first day (December 1st, 2008) of the week for testing period one (Figure 3) the recording device was set-up just before the room became fully occupied. The controlled environment included the existing mechanical ventilation with vents opened and both windows closed, unless the student's thermal comfort had been compromised.

The average $CO_2$ concentration for the day was 1,433 ppm which was just below the daily recommended $CO_2$ concentration of 1,500 ppm. Fortunately, none of the courses were filled to capacity; as a matter of fact, there was a 60% attendance rate. It appears that the average value would have been much higher, if all the registered students were present. Illustration of this can be shown by isolating the occupied periods and taking the average of those values.

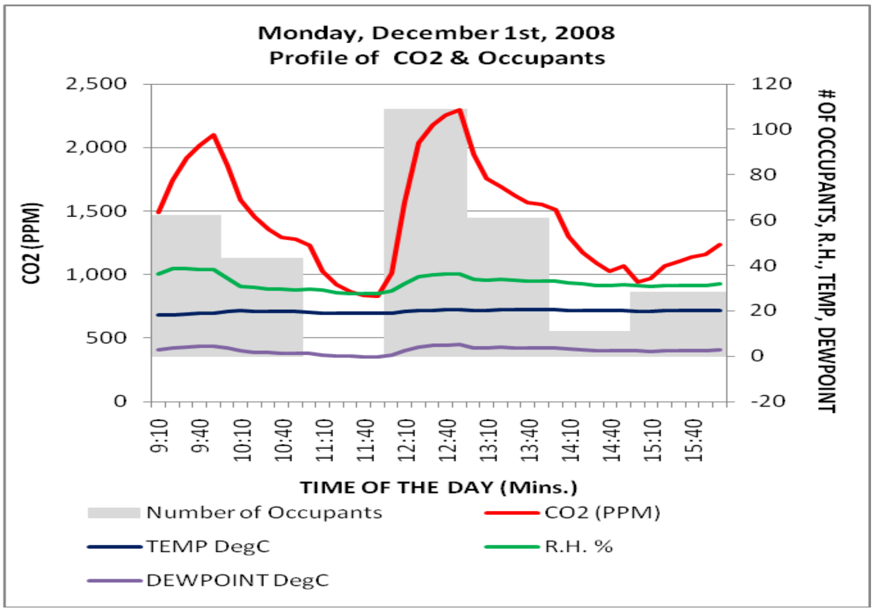


**Figure 3 - Daily Measurements of $CO_2$ Levels December 1st, 2008**

The internal temperature seemed constant with rises in relative humidity and the dew point harmonized with the levels of $CO_2$ concentration. The average internal temperature was approximately 19.8°C with an average relative humidity of 32%. The environmental conditions were fairly normal.
On another day December 5th, 2008, during testing period one (Figure 4), the maximum and average concentration of $CO_2$ for the day was 2,814 ppm and 1,498 ppm respectively, just a small amount below the daily requirement. A student manually opened one of the windows at 10 am, which explains the drop in $CO_2$ for a brief period and then it slowly rises again.

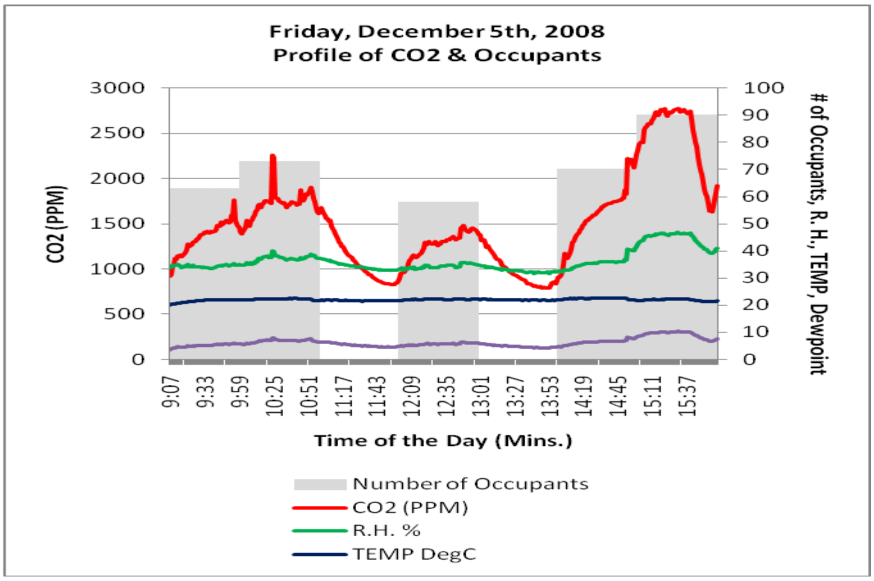


**Figure 4 - Daily Measurements of $CO_2$ Levels, December 5th, 2008**

## 5.0 Ventilation Rates

The ventilation rates for this lecture room were calculated using the equations used in the research of Coley et al ***[x]*** and Griffith & Eftekhari ***[xi]***. These equations were use along with the calculated body's surface area of each occupant. The average assumed $CO_2$ emissions in Litres/hour with a conversion in Litres/second/person of the lecture room is presented below. An average was taken between male and female occupants. Equations presented in those researches were used to determine these values.

| Assumed $CO_2$ Emission | Litres/second/person |
|---|---|
| Student | 0.00484 |
| Adult | 0.01186 |

Equations 1 and 2 could be used to calculate the unoccupied and occupied ventilation rates, carbon dioxide concentration and internal exchange rates ***[x]***.

$$C_{(t)} = C_{ex} + \frac{G}{Q} + (C_{in} - C_{ex} - \frac{G}{Q})*e^{((-\frac{Q}{V})*t)}$$ Occupied: **Equation 1**

$$C_{(t)} = C_{ex} + (C_{in} - C_{ex}) * e^{(-Q/V*t)}$$ Unoccupied: **Equation 2**

Where:
$C_{(t)}$ :Calculated Concentration of $CO_2$ using one (1) minute intervals
$C_{in}$ :Initial Concentration of measured $CO_2$ @ $t=_{0,1,2}$

$C_{ex}$ :Average External Concentration of $CO_2$
G :4.84 $m^3$/s per student and 11.86 $m^3$/s per adult
Q : fresh air ventilation rate for the classroom while occupied ($m^3$/s)
V :Volume of the Lecture Room ($m^3$)
t :time of interval (seconds)

As shown in the equation, the generation rate (G) of carbon dioxide in the lecture room was removed from equation 2, because there were no occupants. This simplified equation 2 and allowed for solving for internal exchange rates and ventilation rates for the lecture room while unoccupied ***[x]***.

$Q = -V/t * \ln((C_t – C_{ex})/(C_o – C_{ex}))$ ($m^3$/s) **Equation 3**

The overall unoccupied ventilation rate for the lecture room was calculated as 28 litres per second with vents opened and windows closed. The value for the air change rate was approximately 0.0979 air changes per hour. Table 2 shows that the ventilation was inadequate within the existing lecture room for the daily maximum occupancy.

| Date | Maximum Amount Of Occupants per Day + 2 Adults | Ventilation Rate per Person (Litres/second) |
|---|---|---|
| Monday, Dec. 1, 2008 | 111 | 0.25 |
| Tuesday, May 5th, 2009 | 88 | 0.32 |

**Table 2 - Ventilation Rates for Maximum Occupants/day on Selected Days**

A spreadsheet for the computer model was developed to calculate the $CO_2$ concentration at one minute intervals. The equation was used to perform simulations for each day of testing and using Equation 1 and the associated parameters ***[x]***.
The simulations showed an approximate 1% difference between the calculated and modelled $CO_2$ levels.

## 6.0 Academic Performance Assessment

There were ten equations created by the author from basic mathematics principles, which were taught to students during early Primary Educational Training. This ten minutes performance test was administered between 10:45 – 10:55 am for three days during the second testing period in the summer. The same time allocated for each day was chosen because we wanted to determine if there were similar behavioural patterns at the same time on different days, however, the additional variety of times which were selected were cancelled due to reviews for final exams.
The results were tallied and the passing mark was set to 50%. These results were correlated with *measurements of $CO_2$*, Temperature, Relative Humidity, and Dew Point in order to establish a direct relationship between the student's performance and thermal comfort.
On May 6th, 2009 during testing period two, this class had a total of sixty-six students plus two adults. There were only ten Females and fifty-six males.
The external temperature was 17.1℃ at 11 am and the internal temperature was 22.4°C.
The scores ranged from 0% through 85% with a low average grade of 53% a low "C" rating. The $CO_2$ average daily concentration was approximately 2,500 ppm which was much higher than 1,500 ppm daily requirement. This day was much warmer on both the inside and outside than Tuesday's (5th May) results. Between the hours

of 10am thru 11am (Figure 5) the $CO_2$ concentration continued to rise from 2,000 ppm to 3,500 ppm. These were extremely high recordings during this hour of testing. The graph shows that during the hour only 51% of the students obtained a grade higher than 50%. The high concentration of $CO_2$ and hot conditions caused the students to be less focused and more talkative. There was a 5% rise in relative humidity compared to the other days.

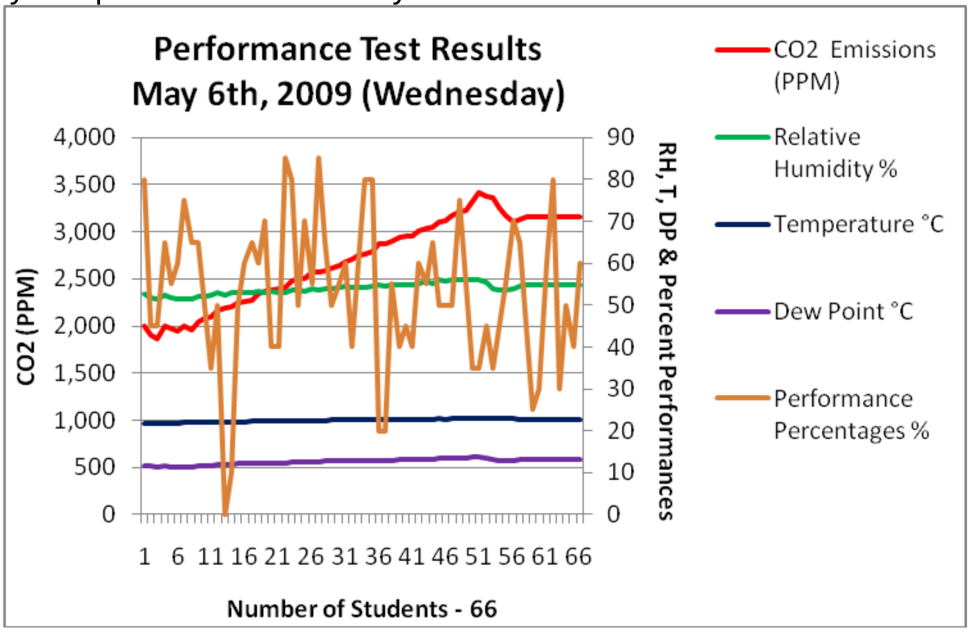


**Figure 5 - Performance Test Scores, $CO_2$ Levels, RH, T & DP, May 6th, 2009**

The high internal and external temperatures, high $CO_2$ concentration proves that $CO_2$ is a microcosm to the low productivity and poor Indoor Air Quality.

## 7.0 Thermal Comfort Assessment

The combined questionnaire also included aspects of thermal comfort and sick building syndrome (S.B.S.) ***[v]***. However, this report will only focus on subjective responses of the students relative to conditions of air quality, air movement, humidity, temperature, lighting and acoustics. Spreadsheets have been created with all participants' responses, gender, age, and average summation of the results. They were rated on a five point scale for thermal sensations and conditions. Column charts were created to display the responses for each of the parameters.

The Health and Safety Executive (HSE) suggest that there should be "a minimum of 80% of occupants as a minimum limit of persons who should be thermally comfortable within one environment." CIBSE Guide A ***[ii]***, has stated that during the summer periods the internal temperature for lecture halls should range from 21°C-23°C.

On Wednesday (May 6th, 2009) the sixty-six student's discipline of study was in mechanical engineering. The average internal temperature was approximately 22.4°C and was 5% more humid than Tuesday (May 5th). The external temperature was approximately 17.1°C and assisted in the change of environment. The overall thermal comfort was compromised especially when less than 80% of the occupants suggested feeling slightly stuffy (Figure 6), slightly humid and slightly hot. Only 33% of the students assessed the lecture room as slightly bright with a 44% who suggests the room was quiet. 91% of the students felt no air movement.

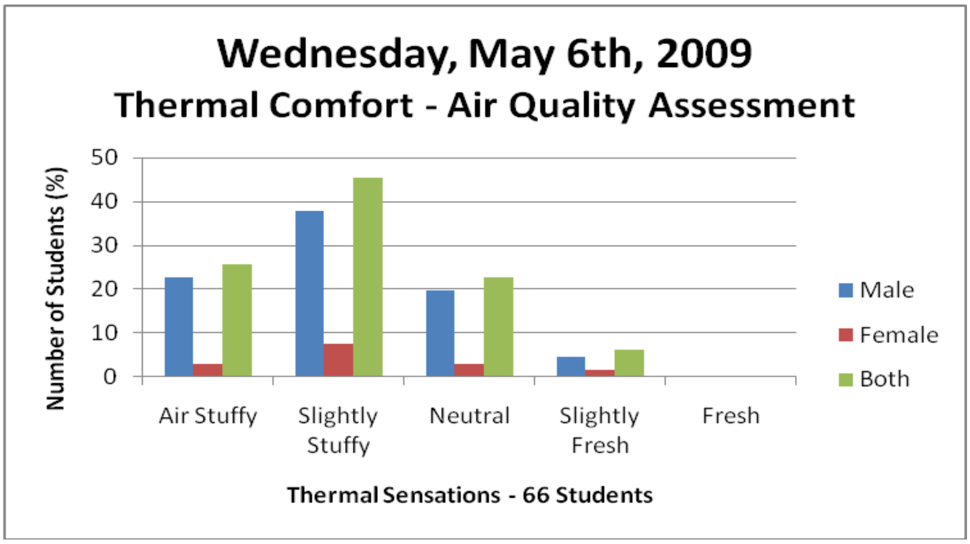


**Figure 6 - Air Quality Assessment for Male & Female Testing Period**

- **Air Quality**

According to 45% of the students the air was slightly stuffy and 32% felt neutral.

- **Humidity**

Almost 49% of the students felt the conditions were normal, with a close percentage who felt slightly humid, 36%.

- **Temperature**

Unlike Tuesday, more persons were slightly hot at 53% and 31% felt neutral.

- **Lighting**

The lighting in the lecture hall seems to be similar to Tuesday's evaluation with 42% responding that it is neutral and 33% felt that the room was slightly bright.

- **Acoustics**

A 44% response was neutral and 21% agreed that the room was slightly noisy.

- **Air Movement**

A greater percentage relative to Tuesday felt no air movement, 91%.

## 7.0 Results

In comparing the results of all the days which the performance and thermal comfort tests were administered it can be seen that there were performance averages for the three days between 10am-11am to be 48%, 53% and 62%. Average high $CO_2$ results were ranging from 2,623 ppm and 2,712 ppm (Figure 7).
The averages prove to be higher than the daily requirement of 1,500 ppm and in addition the thermal comfort of the students were compromised due to the lecture room being slightly stuffy, slightly hot, slightly bright and slightly noisy as 91% of the students who felt no air movement.

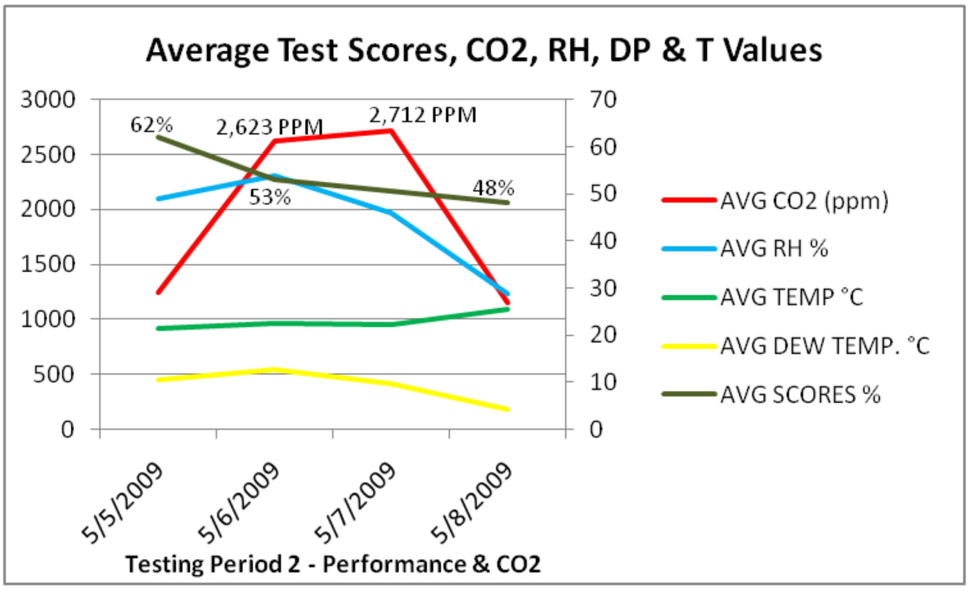


**Figure7 - Average Performance Test Scores $CO_2$, RH, DP&T – May 5th - 8th, 2009**

## 8.0 Conclusions

The main objective of this project was to determine the effects of $CO_2$ on a student's academic performance and thermal comfort proved to be successful, despite high absenteeism and insufficient samples.

The air quality monitoring resulted in $CO_2$ levels above the recommended value with maximum weekly averages of $CO_2$ concentration as 2,714 ppm, which is 1,214 ppm above the daily recommended standards.

The ventilation rates when assessed from a computer model in the form of a spreadsheet obtained daily values 0.25 – 0.93 litres/second per occupant, shows that the values were less than the 3 litres/second/person daily requirement. There was inadequate supply of fresh air being provided to the lecture room.

According to the UK standards, the overall academic performance average was 48-62% for a total of one hundred and seventy students for the three tested samples. On Wednesday May 6th, 2009, this sample confirm that high $CO_2$ concentration did affect the student's academic performance from 10am to 11am, when only 51% obtained higher than the passing 50% score on the test with $CO_2$ concentration ranging from 2,500 to 3,000 ppm. The other two samples experience sporadic points of high $CO_2$ levels but the average performances were relative to extra leisure time on a prior holiday on Monday and the weekend blues on a Friday. There was a 38%-60% daily occupancy rate for the three samples.

During the summer, the students occupying the lecture room assessed the conditions as slightly stuffy, slightly hot, slightly humid, slightly bright and slightly noisy conditions. All results varied for different samples. An average of only 20% of students experience air movement with internal temperatures averaging 22°C. These conditions confirm that the thermal comfort was compromised due to overcrowding in the lecture rooms although not fully occupied, defective HVAC equipment and poor ventilation.

The four major concerns outlined above link the ideas that this typical lecture room obtained the desired results of the research, which proves that the student's ability to function properly under these low to average conditions is questionable. It appears that both the students and the Lecturers use thermal comfort to control ventilation instead of $CO_2$. This is merely because of a lack of knowledge of the effects of $CO_2$ on their environment. The environment must be made more comfortable and conducive to learning; otherwise there will be a dilemma of a shortage of well trained professionals.

## 9.0 Recommendations

1. It should strongly be considered to install at least two $CO_2$ air quality sensors more than 1.8 meters above the highest floor level in every lecture room, connected to BEMS with lecturer's override. This sensor should be set to alert the lecturer, once the maximum required $CO_2$ levels is reached. The lecturer's discretion should be used to allow the students to take a short break or to open the windows.

2. Another suggestion would be to provide all Lecturers with small sensors of the form of a $CO_2$ watch monitor to be used at every teaching session.

3. It should be mandatory that all lecture rooms should have a maximum of one hour break every day of classes. Some lecture rooms have continuous lecturing which causes the air to be stagnant and stuffy.

Finally, the type and size of windows should be changed from the manual horizontal sliding, to larger windows which are operated by BEMS and linked to both temperature and $CO_2$.

**Acknowledgements**
The authors would like to thank all the staff and students who took part in the survey for their time and assistance.

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