International Journal of Sciences & Applied Research

www.ijsar.in

Monitoring of carbon dioxide concentration in closed environments

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Abstract
People in the modern society spend most of their time in closed environments due to present day activities and lifestyles. Hence, the air quality inside closed environments plays an important role for maintaining healthy mental and physical conditions. However, the concentration of carbon dioxide has not been used as an index of indoor air quality. It has been reported that the high concentration of carbon dioxide in closed environments affects the human health. The importance of monitoring of carbon dioxide level in closed environments has not yet been fully recognized. The American Society of Heating, Refrigerating and Air-Conditioning Engineers, has set a standard for indoor carbon dioxide concentration as 700 ppm. In the present project, an electronic device was designed to simultaneously measure the carbon dioxide concentration and the relative humidity with ambient temperature. The research was carried out to measure the concentration of carbon dioxide inside vehicles with passengers, functioning laboratories and hospital rooms. Due to human respiration metabolism, carbon dioxide concentration inside those closed environments is continuously increased. Although air conditioners control the indoor temperature and relative humidity, it does not control the concentration of carbon dioxide. The present results show that the carbon dioxideconcentration in all closed environment with people exceeds the limit of 700 ppm. Inside the closed vehicles, the concentration of carbon dioxide increaseover 5000 ppm creating an uncomfortable feeling for passengers. Therefore, the results verify that monitoring and controlling of the carbon dioxideconcentration inside closed environments are important for human health.

Keywords: Closed environment, Indoor air quality, Carbon dioxide concentration, Carbon dioxide monitoring.

1. Introduction

High concentration of carbon dioxide (CO_2) affects adversely to health and comfortability of people living in closed environments.The background level of CO_2 in ambient airis generally 0.04% or 400 ppm. Evidence suggests risks for human health with increasing CO_2 concentrations as a result of increase in time spent in closed environments. Atmospheric CO_2 is not considered as an air pollutantas shown ASHRAE Standard (2010) and in World Health Organization Air Quality Guidelines for Europe(2000).However, it is responsible for the global climate change (Manabe and Stouffer,1980). The atmospheric CO_2

concentration to be at 350 ppm is a suggested aim for healthy living (Hansen *et al*. 2008).The global CO_2 increase at the rate of 3 ppm per year will directly affect the indoor CO_2 concentration to rise to 700 ppm by 2050 (Spengler2012). Therefore, the concentration of $CO_2$is monitored and recorded in worldwide through the year. The human respiration also produces CO_2 which is insignificant in open environments but can reach harmful levels in closed environments with increase in time spent indoors. Thus, the air quality of such closed environments plays an important role with breathing of quality air for a healthy life. Therefore, monitoring the air quality related to $CO_2$is essential to maintain good health and comfort.

The indoor air quality index is composed of the concentration of nitrogen dioxide, carbon monoxide, sulfur dioxide, ozone and particulate matter. But, the concentration of CO_2 is not classified under that air quality index. However, medically proven literature states the adverse human health effects related to high concentration of CO_2.

The decision making performance of humans at different concentrations of CO_2tested in a controlled environmentshows a drop in of six of nine scale decision-making performance when CO_2concentration was at 1000 ppm compared to the 600 ppm concentration. The decision making performance was further reduced to seven of nine decision-making performance at CO_2concentration of 2500 ppm (Satish *et al* 2012). The study further elaborates that some of the performance metrics decreased to levels associated with marginal or dysfunctional performance. The study shows the reduction in the decision making performance and the cognitive abilities which illustrates the importance of monitoring CO_2 concentrations in closed environments.

The effect of CO_2 concentration as a risk of sick building syndrome is described by relating to ventilation rates and CO_2 concentrations conducted in commercial and institutional buildings(Seppanen*et al*. 1999). Further the study explains the decrease of sick building syndrome symptomswith decreasing CO_2 concentrations below 800 ppm.At CO_2 concentration level of 3000 ppma decline in both capacity of mental concentration attention and human well-being is observed (Kajtar*et al.* 2006).The effect of a rise in the atmospheric CO_2 concentration predicts a decline in human health (Robertson 2001).

The importance of continuous monitoring of CO_2 concentration in closed environments has not yet been established. The American Society of Heating, Refrigerating and Air-Conditioning Engineers, has set a standard CO_2 concentration for indoor environments as 700 ppm (ASHREA 2010).

In the study, an electronic device is constructed to simultaneously measure the CO_2 concentration, ambient temperature and the relative humidity. The research project aims to measure the change in CO_2 concentration due to human respiration metabolism inside passenger vehicles, laboratories and hospital rooms with air-conditioning.

2. Materials and Method

An electronic device was constructed with several sensors with an Arduino platform to measure the carbon dioxide concentration, ambient temperature and the relative humidity. The non-dispersive infrared (NDIR) optical sensor MH-Z14A and DHT11 sensor was used as two main sensors.

2.1 Sensors

The use of NDIR type gas sensorto measure the concentration ofaccumulated CO_2 is due to the high accuracy (Frodl and Tille 2006). The sensor is based on the absorbance spectroscopy of $CO_2$and is in accordance with the Lambert-Beer law.For the measurement of CO_2 concentration, the MH-

Z14A NDIR sensor was used. The reason for the use of NDIR sensor is due to the high accuracy as the sensor only measures CO_2.

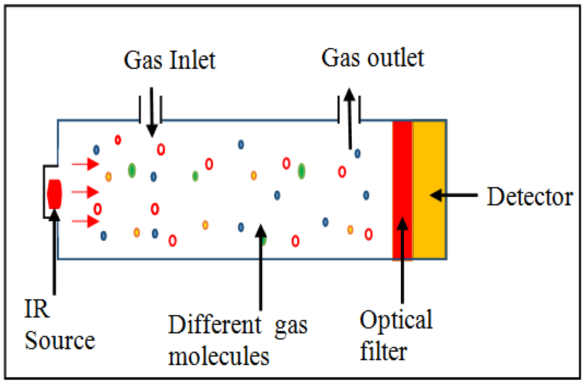

Figure-1 Diagram of working principle of the NDIR MH-Z14A CO_2 sensor

The following equation governs the operation of the CO_2 NDIR sensor corresponding to the Lambert-Beer law.

$$I = I_0 \exp(-kCL)$$

(1)

I= light power intensity after absorption by CO_2measured at the detector (W m^{-2})

I_o= light power intensity at the source (W m^{-2})

k= absorption index of CO_2 (ppm^{-1} cm^{-1}) at 4.3×10^{-6} m

C = concentration of the gas (in ppm)

L= length of the absorption path (cm)

As shown in Figure- 1, the air entering into the gas inlet of the MH-Z14A sensor is allowed to pass through an IR source. CO_2 being a symmetrical molecule having non-symmetrical and symmetrical modes of vibration would absorb IR at the wavelength of 4.26×10^{-6} m (Hansen 1997). A wavelength selective optical filter made from a band pass filter associated to the peak absorption bandof $CO_2$is placed in front of the detector. Thus, the detector will only detect the filtered IR intensity proportional to the concentration of CO_2 gas. The MH-Z14A sensor was calibrated through command according to the data sheet Intelligent Infrared Carbon Dioxide Module (Model: MH-Z14) User's Manual V2.4.

For the measurement of ambient temperature and relative humidity, the DHT11 sensor was used. DHT11 element is pre-calibrated in the laboratory that is extremely accurate on humidity calibration. The calibration coefficients are stored as programs in the one-time programmable (OTP) memory. The operation of the sensor was carried out with respect to the instructions of the data sheet of the DHT11 sensor provided by Temperature and Humidity Module DHT11 Product Manual. In addition, a 10Ω pull up resistor has to be used with the signal terminal and the supply voltage terminal (V_{cc}) to ensure the inputs of the logic are at expected levels of 0 V and 5 V. Figure -3 represents the picture and the technical details of the DHT 11 sensor.

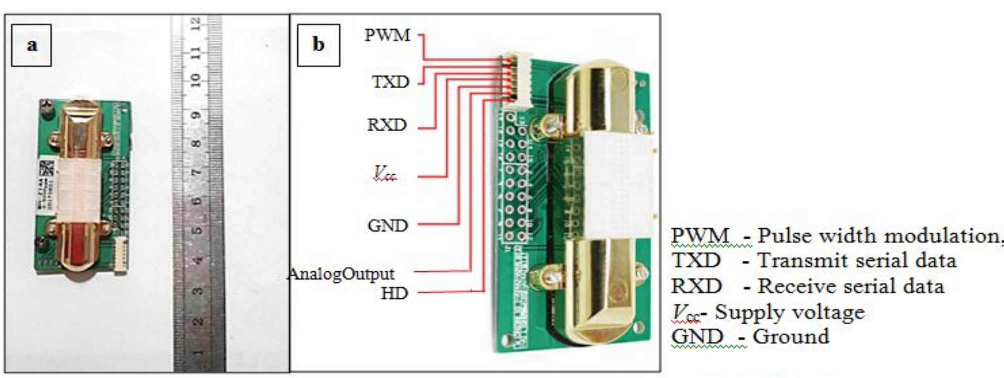

Figure-2 (a) Picture of MH-Z14A sensor (b) Pinout representation of the MH-Z14A sensor

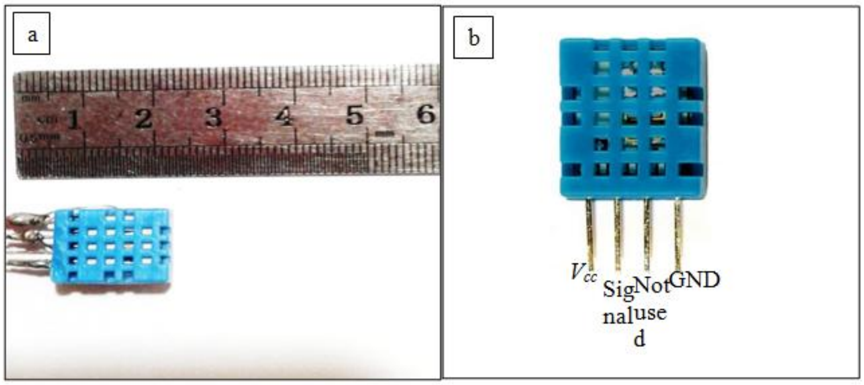

Figure-3 (a) Picture of DHT11 temperature, humidity sensor(**b**) Pinout diagram of DHT 11

The DHT11 sensor consist of two electrodes with moisture holding substrate between them. The resistance between these electrodes changes with the change in the relative humidity. This change in resistance is measured and processed by the integrated circuit and sends a signal to the microcontroller unit (MCU).The measurement of temperature is carried out using a negative temperature coefficient thermistor inside the DHT11 sensor. The temperature sensor is made using sintering asemi-conductive ceramic.Thus, a large change in the resistance is obtained for a small change in the temperature. The resistance decreases with the increase in the temperature. The integrated circuit measures the change in resistance and send a signal to the MCU.

Data logging and display facility were also added to enhance the productivity of the device.In order to facilitate the device with on time data logging, a micro SD card was used. A micro SD card module (Arduino compatible) was used for this data logging process.This gave the advantage of collecting data which provided a greater advantage in analyzing the collected data. The device was fabricated using an Organic Light Emitting Diode display (OLED). The OLED displays the measured CO_2 concentration, ambient temperature and the relative humidity.

2.2 Circuit Design

The schematic of the circuit was designed using Fritzing (Version 0.9.3.0) software. Figure-4 shows the schematic diagram of the connections of the respective components to the microcontroller unit.

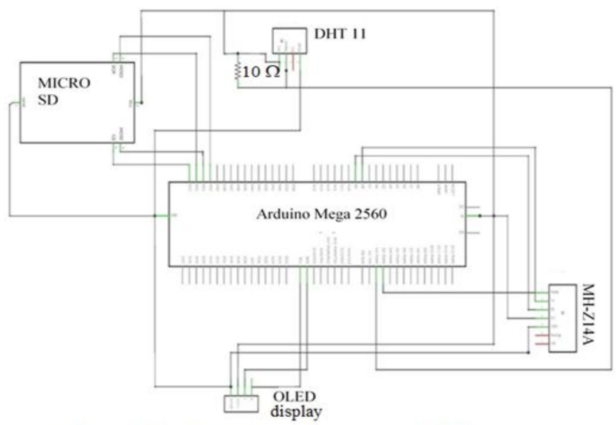

Figure-4 Circuit diagram of the constructed device

The program codes of the devicewere written and uploaded to the Arduino Mega 2560 using Arduino IDE. The program processes the following tasks. The program is written with facilitating data logging. Thus, all the measuring values will be saved in the micro SD card as a text file for every 10 second interval. The data can also be viewed using Arduino IDE or any serial terminal software when the device is directly connected to a computer. The data saved in the micro SD card can be viewed through any text file reader.

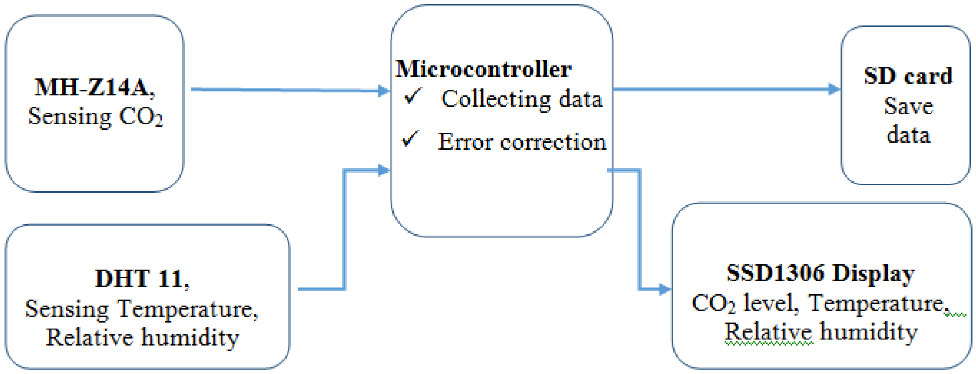

Figure-5 Functional block diagram of the device.

2.3 Test Environment

Measuring of CO_2 concentration, ambient temperature and the relative humidity was carried out in closed environments such as air-conditioned vehicles, laboratories, hospital rooms and auditoriums. The ordinary lifestyle of people was followed through maintaining the conditions of the closed environment as in daily routine. Thus, all the measurements correspond to the ordinary living styles of human beings. At each test, the device was always positioned at the middle of the closed environment. The outdoor CO_2 concentration was measured prior to measuring CO_2 concentration inside a closed environment.

3. Results and Discussion

Figure -6 represents the variation of CO_2 concentration inside the tested car of cabin volume of 3.3 $m^3$with 4 passengers, travelling a journey of 116 km from city A to city B, Kandy to Colombo, Sri Lanka.

All windows were closed and air-conditioner was in recirculation mode with level 2. The air-conditioner temperature was set to 20 °C. The outside CO_2 concentration at the starting location was 350 ppm. The CO_2 concentration inside the car on start was 1064 ppm which was a result from the previous drive. Therefore, in order to continue the observation of CO_2 build-up, all the windows of the car were opened and was allowed to set the CO_2 concentration equal with that of the outside CO_2 concentration of 350 ppm.

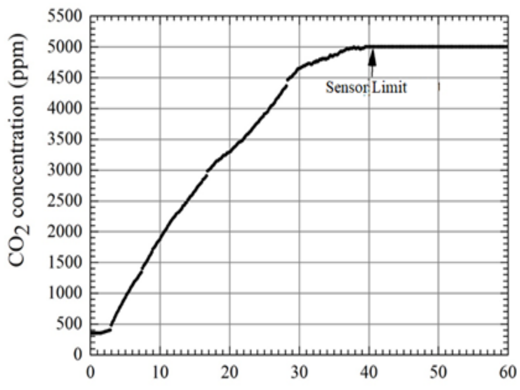

Figure-6 Variation of CO_2 concentration with time in the car.

Examining the observations in a closed car which uses the air-conditioner in recirculation mode, high amount of CO_2 will remain inside even after 8 hours of stop. The amount of CO_2 remaining inside will depend on the car door insulation. For a car with time-worn insulation will result in removing and balancing the build-up CO_2 with the outside CO_2 concentration.

According to the graph, the increase in CO_2 concentration shows a linear relation with time. This suggests that the CO_2 given out as a result of human respiration metabolism was constant. The graph emphasizes that the CO_2 concentration inside the car reached 5000 ppm (sensor limit) within 40minutes. The reach of CO_2 concentration to 5000 ppm within quarter of the journey would suggest that at the end the passengers will be exposed to a CO_2concentration above 10000 ppm.

Figure-7 represents the variation of relative humidity in the passenger car. The relative humidity level inside the car was reduced to 47%. Thus, the air conditioning system has set the relative humidity around to the most comfortable level with respect to the standard range (Satish 2012).

However, the important fact that emerge from the above level of relative humidity is that passengers will get thirst. Thus, having drinkable water inside the vehicle is essential.The air-conditioner maintained the inside temperature of the car around 26 ºC. Hence, the observed results suggest that both the relative humidity and the temperature inside the car were maintained in favor of human comfort(ASHRAE 2010).

Figure-8 shows the CO_2 variation in amini bus with a cabin volume of 36.4 m^3 travelling a distance of 132 km between two cities, Kandy to Anuradhapura, Sri Lanka.

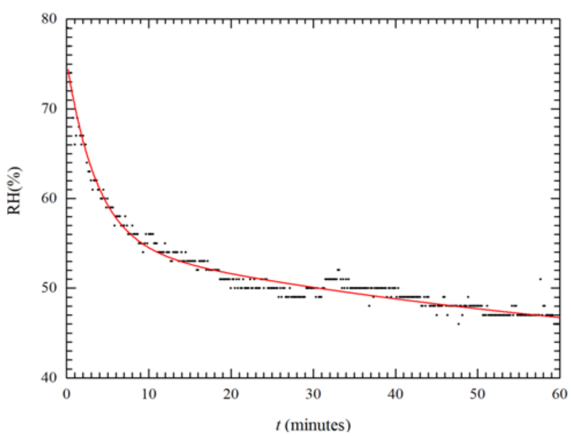

Figure-7 Variation of relative humidity(RH) with time in the car.

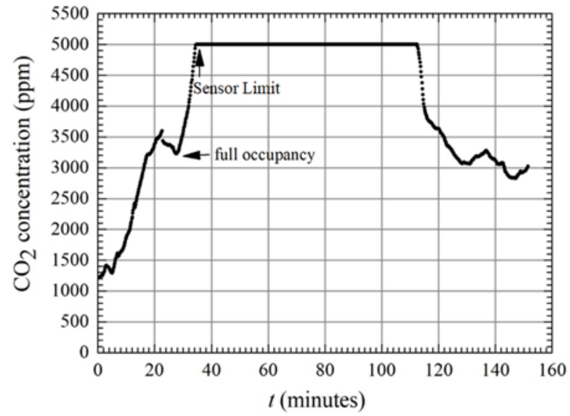

Figure-8 Variation of CO_2 concentration with time in a mini bus.

The outside CO_2 concentration at the beginning city was 380 ppm and there were 10 passengers seated when the device was taken inside the mini bus. The initial concentration of CO_2 inside the bus at the beginning was 1219 ppm.The bus started the journey at 05:30 hrs.with 24 passengers. The mini bus stopped at few places and opened the door for passengers. Within half an hour, the mini bus was fully occupied with passengers.The CO_2 level inside the mini bus reached the limit of the sensor, 5000 ppm, within 34 minutes after starting the journey.The drop in CO_2 concentration at 112 minute can be described as follows. The mini bus was stopped at a town for about 10 minutes where few passengers got down. In addition, the shutter of the driver's side was opened. The bus left the town having only 16 passengers.

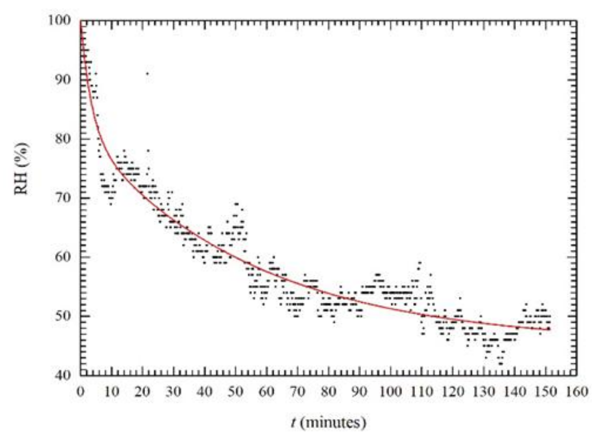

Figure-9 Variation of relative humidity(RH) with time in a minibus.

This caused the reduction in the CO_2 concentration inside the mini bus to3024 ppm at the reach of the final stop.

The corresponding variation of the relative humidity inside the mini bus is shown in Figure-9. The relative humidity inside the bus was maintained in the range of 40-60 % for a large period of the journey. The temperature was maintained within a range of 26-30 ºC.

These results show that during the journey the air-conditioner maintained the relative humidity and the temperature inside the mini bus at human comfort levels. However, considering the entire journey, the CO_2 level was at the sensor limit of 5000 ppm for around 80 minutes. This suggests that during this period of time, the CO_2 level could be above 5000 ppm.

Figure-10 describes the variation of CO_2 concentration in a laboratory at the Department of Statistics and Computer Science, Faculty of Science, University of Peradeniya, Sri Lanka. The interior volume of the laboratory is 48.9 m^3. The laboratory session was attended by 18 students and 2 instructors and held from 14:00 hrs. to 17:00 hrs. The device was placed in the middle of the laboratory.

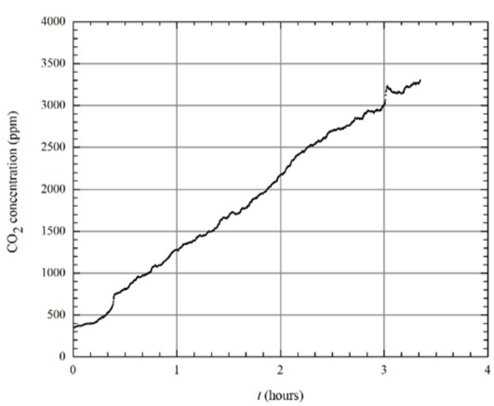

Figure-10 Variation of CO_2 concentration with time in computer laboratory.

During the test, a linear increase in the CO_2 concentration was observed. Within 50 minutes, the CO_2 concentration inside the laboratory reached 1000 ppm. The laboratory session was continued for 3 hours and 20 minutes. The concentration of CO_2 at the end reached 3299 ppm. The CO_2 concentration is considerably high equivalent to the hours spent and considering the occupancy and the volume of the laboratory.

It has been revealed that the increased CO_2 concentration has reduced the mental concentration of the students attending an indoor class and caused drowsiness for some of them (Liu *et al*. 2017).Similarly, students attending a three-hour laboratory session have also felt tiredness after an hour and have suffered from concentration ability and productivity during the rest of the laboratory session. This might affect the concentration, cognitive ability and the productivity of the students during the rest of the laboratory session (Zhang *et al.* 2016).

Similar conditions can be observed in air-conditioned office spaces and shops of small building space volumes. People who work in such office spaces and shops will expose themselves highCO_2 concentrations. The bad odor created with respect to such environments would harm the living standards of the people who are engaged at work.

Furthermore, the fact of CO_2 concentration can be drawn into attention on building constructions. The construction field relies and purpose the comfort of people. The attention towards build-up CO_2 in indoor environments have not been adhered properly. Thus,a field is opened to exercise maintaining indoor air quality through reducing the build-up CO_2. Thedevelopment of proper ventilation systems, addition of ventilation fans with proper operation schedules are few suggestions to maintain the balance of CO_2 in an indoor environment.In addition, the attention should be drawn towards installation of new air-conditioners in a room, office, etc. which was previously used without an air-conditioner. Depending on the room volume and the purpose of use,the occupancy level should be changed to maintain the air quality for a comfortable living.

Figure-11 shows the variation of relative humidity with time in the laboratory. the relative humidity was in the range of 50-70%. The temperature was around 27 ºC.

The change of relative humidity inside the computer laboratory shows a linear decrement with respect to that of a change in relative humidity inside a vehicle, due to the difference in the interior volumes and the air conditioning machine.

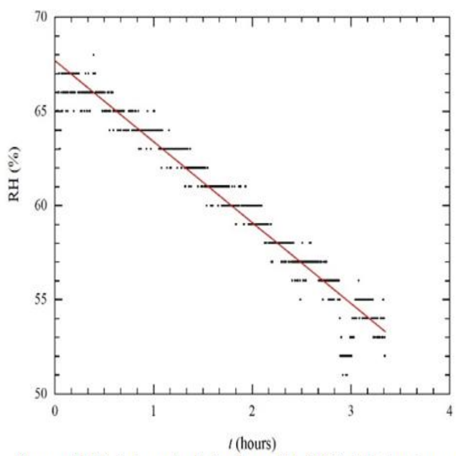

Figure-11 Variation of relative humidity(RH)with time in computer laboratory.

Figure-12 describes the variation of CO_2 concentration in a hospital room. The interior volume of the hospital room is 72.5 m^3. The CO_2 concentration inside the room indicated a value of 1366 ppm when the device was switched on. Therefore, the windows of the room were opened until the CO_2 concentration inside the room became equal with the outdoor level of 380 ppm. Thus a proper increase in CO_2 concentration due to human respiration was observed.

The room was occupied by two persons including the patient. Within 40 minutes, the CO_2 concentration reached 1000 ppm. Thereafter, the CO_2 concentration reached 1739 ppm within another 80 minutes. Thus, the CO_2 concentration reached to 1739 ppm within two hours.

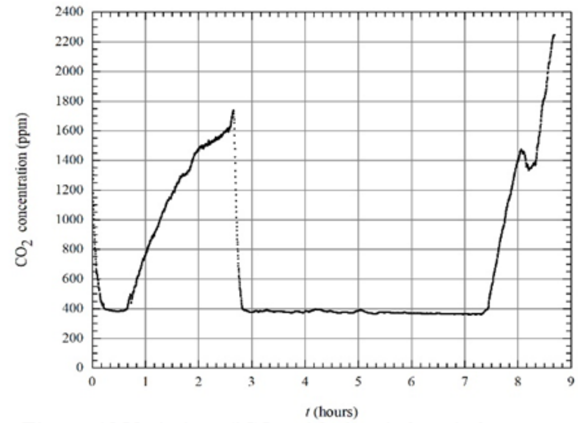

Figure-12 Variation of CO_2 with time in hospital room.

As the request of the patient, the door was kept opened which reduces the CO_2 concentration inside the room to that of the outside concentration. The condition was kept for four and a half hours. Once the door is closed back and air-conditioner is switched on, the CO_2 level rise to a value of 2242 ppm. This increase in build-up CO_2 would adversely effect on the areas such as physiology of patients. More research has to be conducted to identify such effects, and to find possible solutions. The relative humidity was in the range of 40-60% and the temperature was in the range between 24-26 ºC. Thus, the relative humidity and temperature inside the hospital room was in the range which satisfies the human comfortability.

The operating theaters in hospitals which are air-conditioned might also contain build-up CO_2 exceeding the standard limit. Remarkably, the effect of high build-up CO_2concentration might discomfort the medical personals' and patients during operations. Therefore, a comprehensive attention has to be given to maintain the indoor air quality with respect to CO_2 concentration.

Figure-13 shows the variation of CO_2 concentration in an air-conditioned auditorium at a musical concert. The interior volume of the auditorium is 114.0 m^3. The CO_2 concentration outside the auditorium was 390 ppm. There were 100 people presented at the concert. The CO_2 concentration was 919 ppm when the device was switched on. The CO_2 concentration increased with variations due to several traits. The audience was moving in and out of the auditorium from time to time. Thus, the increase in the CO_2 concentration was not in a linear manner. As the interior volume of the auditorium is comparatively high, the build-up of CO_2 will correspond to a low rate. Hence, the increase in CO_2 concentration is not linear.At the end of the program, refreshments were given which change the activity of people in the auditorium. This corresponds to the time at 74 minutes in Figure-13, at which the critical rise in CO_2 concentration was observed. The rise of CO_2 to a value of 1809 ppm at 88 minutes describes clearly the enhance metabolism of human respiration at the time of food consumption. The decrease in the CO_2 concentration of 1472 ppm corresponds to people leaving the auditorium. The above observations verify increase of exhaled CO_2 during high activity level.

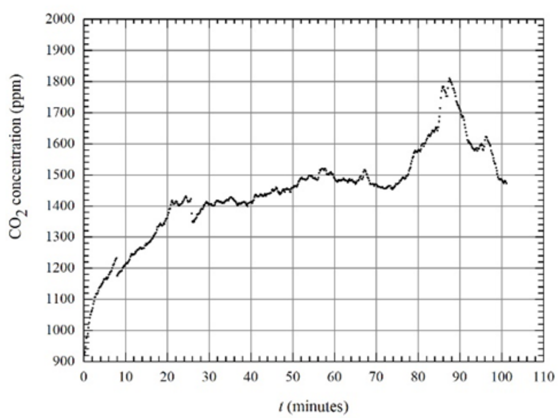

Figure-13 Variation of CO_2 with time in an auditorium.

Figure-14 shows the variation of relative humidity with time in the auditorium. The relative humidity was maintained in a range between 45-50% during the time period. The temperature was maintained around 28 ºC. With respect to the above observations, the relative humidity and the temperature inside the auditorium was maintained in favor of human comfort.

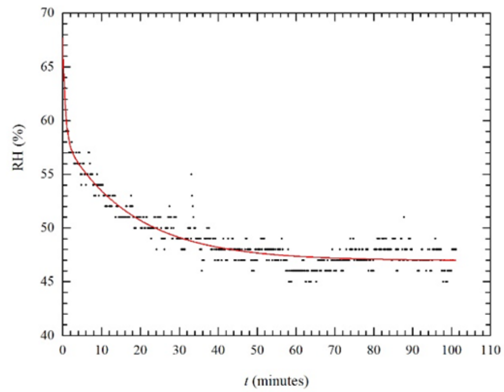

Figure-14 Variation of relative humidity (RH) with time in an auditorium.

Considering buildings constructed in the Kandy city, Sri Lanka through observations done on places where people gather most, the measurements of the concentration of CO_2 at selected locations were carried out as shown in Table 1.

The average CO_2 concentration in Kandy city (Central Province) is around 390 ppm, which is comparatively higher than the concentration of other outdoor locations. This might be due to the high amount vehicle emissions due to high traffic. The measurement of CO_2 concentration in selected locations in Kandy city was carried out for a week. Figure-15 represents the CO_2 concentrations measured in selected location in Kandy City.

Table 1: CO_2 concentration in populated locations in a city (Kandy, Sri Lanka).

Location	**CO_2 level (ppm)**
Kandy Municipal Car Park	
Level 1 (Ground)	2000-2800
Level 2	970-1300
Level 3	400-650
Level 4	390-400
Kandy City Center	
Floor 1(Ground)	900-1100
Floor 2	400-700
Floor 3	400-700
Floor 4	400- 600
Food Court (Devon)	450
Cloth store (Fashion Bug)	540
Pizza Hut outlet	430
KFC outlet	510
Super Market (Food City)	560

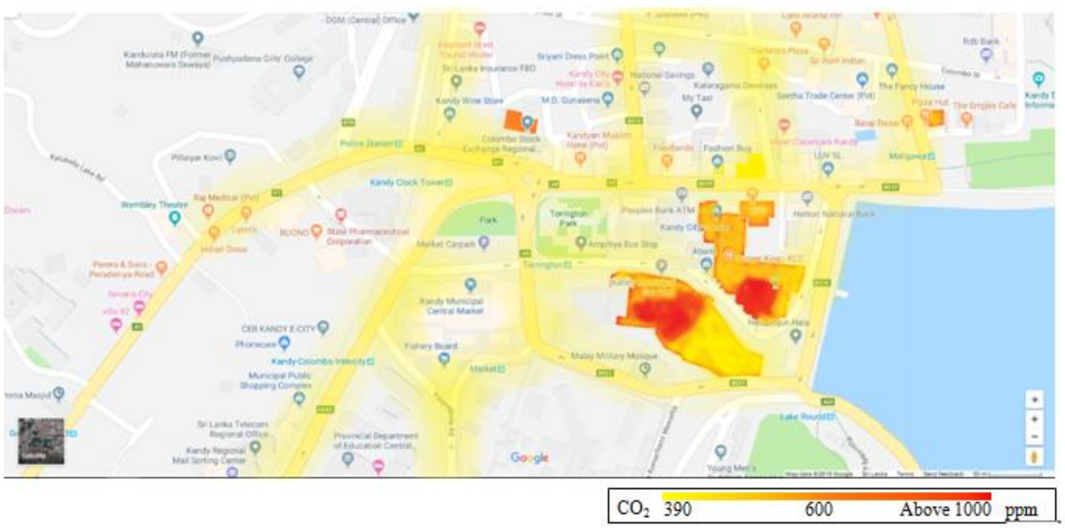

Figure-15 Map of concentration of CO_2 in selected locations in Kandy city

4. Conclusion

The increase of CO_2 concentration above the standard limit will affect the comfort of human beings. There are several medically proven health effects related to high concentrations of CO_2. Major effect related to high concentrations of CO_2 is the reduction in decision making ability, drowsiness, sleepiness, and slight nausea which are related to reduction in performance of people. The mentioned health aspects depend on the human ability to tolerate high CO_2 concentrations. With respect to the increase of CO_2 concentration in vehicles, the long exposure to high concentration of CO_2 might affect the decision making ability of the driver which will lead to road accidents. The passengers especially children and elderly persons will also experience the uncomforting feeling due to low tolerance to high CO_2concentrations. With respect to closed spaces such as laboratories, auditoriums, hospital rooms etc. the cognitive ability and the productivity of people inside such closed spaces will reduce as a result of high CO_2 concentrations. The unpleasant odors created as a result of high CO_2 concentrations is another aspect which scales down the living standards of people. Overall, the exposure to high CO_2 concentrations in closed environments will lead to several adverse health effects and will cause discomfort to people living.

From the results of the present study, it can be concluded that the CO_2 concentration in closed environments as a result of human respiration exceeds the standard limit. This can even happen in air-conditioned environments. This confirms that CO_2 concentration as an indicator of insufficient ventilation. This study also indicates that thereis a need of regular study of air circulation inside air-conditioned environments to improve the air quality.For maintaining a comfortable environment for human beings when occupying a closed environment, it is vital to maintain CO_2 concentrationin addition to relative humidity and temperature. Thus, it is important to maintain the CO_2concentration below 700 ppmto maintain a comfortable closed environment.

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