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Development of Indoor Environmental Index: Air Quality Index and Thermal Comfort Index

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Abstract. In this paper, index for indoor air quality (also known as IAQI) and thermal comfort index (TCI) have been developed. The IAQI was actually modified from previous outdoor air quality index (AQI) designed by the United States Environmental Protection Agency (US EPA). In order to measure the index, a real-time monitoring system to monitor indoor air quality level was developed. The proposed system consists of three parts: sensor module cloud, base station and service-oriented client. The sensor module cloud (SMC) contains collections of sensor modules that measures the air quality data and transmit the captured data to base station through wireless. Each sensor modules includes an integrated sensor array that can measure indoor air parameters like Carbon Dioxide, Carbon Monoxide, Ozone, Nitrogen Dioxide, Oxygen, Volatile Organic Compound and Particulate Matter. Temperature and humidity were also being measured in order to determine comfort condition in indoor environment. The result from several experiments show that the system is able to measure the air quality presented in IAQI and TCI in many indoor environment settings like air-conditioner, chemical present and cigarette smoke that may impact the air quality. It also shows that the air quality are changing dramatically, thus real-time monitoring system is essential.

INTRODUCTION

People normally spend their time in indoor environments unless they are travelling to other places, or working on outdoor activities. Therefore, it is no surprise when a study by the United States Environmental Protection Agency (EPA) found that Americans spend about ninety percent of their time in indoor environments [1]. Studies also showed that people's health is highly related to the quality of indoor environments, especially when the indoor air is polluted [2]. For those reasons, it is essential to make sure that the indoor environments are safe and comfortable to live in, including the air we breathe in. To achieve this, continuous IAQ monitoring system is proposed. Currently, researches on IAQ focused on sampling of the indoor air in order to monitor the IAQ in certain public places. Very limited researches have focused on continuous monitoring of IAQ. In addition, this continuous monitoring system also offers an added advantage where it transforms the indoor air information into an index of IAQ. This indoor air quality index (IAQI) enables the users to be informed about the current status of the IAQ (the status is shown as healthy, moderate, unhealthy or hazardous). Apart from the IAQI, this paper also proposes another important index in indoor environment: thermal comfort index. Thermal comfort plays an important part in indoor environment as it dictates the comfort level of the building occupants. Thermal comfort index or TCI as proposed in this paper would show the status of thermal comfort as most comfort, comfort, not comfort or least comfort. Finally, an enhanced IAQI or Indoor Environmental Index which combines both indexes is formulated to find the comfort level of an indoor environment.

Indoor air quality (IAQ) refers to the quality of air in a building and its structures which affect the health and comfort of the people living in the building [1]. The air quality may be affected by various sources of pollutants

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including radon, mold and moisture and environmental asthma triggers [3]. The IAQ may be worsening by poor air ventilation systems, temperature and humidity. More countries have taken serious steps in dealing with the issues of IAQ. The US EPA in the United States for example, has come out with its own methodology and standards to monitor and provide alert to their citizens about the human health and the environments. The US EPA uses Air Quality Index (AQI) to measure the quality of air by using the six (6) common air pollutants as identified by The Clean Air Act. The common air pollutants are (1) particle pollution (often referred to as particulate matter), (2) ground-level ozone, (3) carbon monoxide, (4) sulfur oxides, (5) nitrogen oxides, and (6) lead. These pollutants can harm human's health, the environment and cause damage to property[3].

The main objective of this research is to modify the AQI used in outside environment into indoor air quality index (IAQI). The second objective is to propose thermal comfort index (TCI) since thermal comfort plays an important role in determining the building occupants' comfort level. In order to achieve these objectives, a system for indoor air quality (IAQ) monitoring was already developed for previous studies [4][5][6]. This system is used to monitor the parameters of IAQ continuously in real-time.

BACKGROUND OF THE STUDY

Air Quality Index (AQI)

Air Quality Index (AQI) is a numerical scale with color code and is divided into several specific ranges. It has been used by government agencies to communicate with the people around their country by informing and telling them about the pollution levels especially in outdoor environment. The information given by AQI tells not only about the level of pollution but also the potential health risk it would impose to people. The information about this status level is very important especially to children, elderly people and people with pre-existing condition of cardiovascular and respiratory diseases[7]. However, this index system is implemented only on outdoor environment instead of indoor environment even though indoor environments such as work place, hotels, homes, bedrooms and theater halls have bigger health impact on human than outdoors environment.

This research intends to improve the existing index use in determining the IAQ. This IAQI is developed based on existing ratio method which has been introduced by the U.S. EPA in 2006 for calculation of outdoor air quality index (AQI) [7]. The U.S. EPA defines the national outdoor air quality standards based on the six common air pollutants and the index was calculated using the following linear interpolation formula:

$$I_p = (C_p - BP_{Lo}) \times \frac{I_{Hi} - I_{Hi}}{BP_{Hi} - BP_{Lo}} + I_{Lo} \tag{1}$$

Where:

I_p = Index value for pollutant p
C_p = Rounded concentration of pollutant p
BP_{Hi} = Higher Breakpoint value of Cp
BP_{Lo} = Lower Breakpoint value of Cp
I_{Hi} = Index Breakpoint value of BP_{Hi}
I_{Lo} = Index Breakpoint value of BP_{Lo}

This equation was calculated based on air pollutant concentration data and breakpoint table shown in Table 1 below. From the table, it shows that the index was divided into six categories with specific color-coded and range: Good (0-50), Normal (51-100), Unhealthy for sensitive groups (101-150), Unhealthy (151-200), Very unhealthy (201-300) and Hazardous (>300).

To calculate the AQI, each pollutant namely ozone (O_3), particulate matter (PM_{10} and $PM_{2.5}$), carbon monoxide (CO), sulphur dioxide (SO_2) and nitrogen dioxide (NO_2) was measured either at 1,8 or 24 hour average depending on type of pollutants. Then, average value from each pollutant was converted into individual index based on breakpoint table. For example, if the individual index for CO is 70, the AQI status for CO therefore is "Moderate". Each individual index is then compared and the highest index value becomes the final value for AQI. Let's say the CO is 70 or "Moderate", O_3 is 45 or "Good" and NO_2 is 120 or "Unhealthy", then the final AQI value is 120 and the status is "Unhealthy".

However, the information provided by EPA is only in an aggregated index alerting the harmful condition and was limited to outdoor location. Moreover, the information is static and is an averaged value, while air quality is changeable. Also, some of the indoor air quality parameters in breakpoint table are missing such as in the case of carbon dioxide (CO_2) and Volatile organic compound (VOC) [8].

TABLE 1. EPA's breakpoint and AQI Index

O_3 (ppm)	PM_{10} (ug/m^3)	$PM_{2.5}$ (ug/m^3)	CO (ppm)	SO_2 (ppm)	NO_2 (ppm)	AQI Values	Level of Health Concern
0.000 – 0.059	0 – 54	0.0 – 15.4	0.0 – 4.4	0.000 – 0.034	–	0 – 50	Good
0.060 – 0.075	55 – 154	15.5 – 40.4	4.5 – 9.4	0.035 – 0.144	–	51 – 100	Moderate
0.076 – 0.095	155 – 254	40.5 – 65.4	9.5 – 12.4	0.145 – 0.224	–	101 – 150	Unhealthy for Sensitive Groups
0.096 – 0.115	255 – 354	65.5 – 150.4	12.5 – 15.4	0.225 – 0.304	–	151 – 200	Unhealthy
0.116 – 0.374	355 – 424	150.5 – 250.4	15.5 – 30.4	0.305 – 0.604	0.65 – 1.24	201 – 300	Very Unhealthy
–	425 – 504	250.5 – 350.4	30.5 – 40.4	0.605 – 0.804	1.25 – 1.64	301 – 400	Hazardous
–	505 – 604	350.5 – 500.4	40.5 – 50.4	0.805 – 1.004	1.65 – 2.04	401 – 500	Hazardous

Indoor Air Guideline

There are only six (6) parameters for outside air quality measurement, but for indoor air quality there are additional parameters such as carbon dioxide (CO_2), volatile organic compounds (VOCs), radon and formaldehyde. Oxygen is not classified as a factor that could affect the poor IAQ. However, the concentration level of oxygen is important for indoor air environment.

Table 2 below shows the parameters for indoor air quality index measurement. Due to different environment, the parameters use to measure IAQ level is slightly different in different countries. Table 2 below is the summarized indoor air pollutants for EPA, Hong Kong Environmental Protection Department (HKEPD), Singapore Indoor Air Quality Guideline (SIAQG) and Department of Occupational Safety and Health (DOSH) Malaysia [7][9][10].

TABLE 2. Indoor air pollutants at different countries

Parameter	EPA	HKEPD	SIAQG	DOSH
Carbon Monoxide (CO)	50 ppm	8.7 ppm	9 ppm	10 ppm
Ozone (O_3)	0.06 ppm	0.06 ppm	0.05 ppm	0.05 ppm
Particulate Matter (PM_{10})	0.6 mg/m^3	0.18 mg/m^3	0.15 mg/m^3	0.15 mg/m^3
Nitrogen Dioxide (NO_2)	1 ppm	0.080 ppm	N/A	N/A
Formaldehyde (H_2CO)	2.4 ppm	0.081 ppm	0.1 ppm	0.1 ppm
Carbon Dioxide (CO_2)	N/A	1000 ppm	1000 ppm	1000 ppm
Volatile Organic Compound (VOC)	N/A	0.261 ppm	3 ppm	3 ppm
Temperature (°C)	N/A	20 – 25.5°C	23 - 26 °C	23 - 26 °C
Humidity (%)	N/A	40 – 70%	40 – 70%	40 – 70%

RELATED WORKS

Some researchers proposed a framework of monitoring and control of IAQ with wireless sensor network such as Choi, Choi, & Jang, (2009), Bhattacharya, Sridevi, & Pitchiah (2012) and Preethichandra (2013). Some researches proposed their own index calculation. For example, Postolache, Pereira, & Girao, (2009) designed a wireless sensing network Bluetooth for continuous monitoring of indoor humidity and temperature conditions. It helps monitor the asthma triggering factors and other pulmonary related diseases. The Bluetooth application allows the device to send the information over to a smart phone and a laptop PC. They presented an air quality index based on the following calculation:

$$x_{airQ} = \gamma . v_{RL} + \delta \tag{2}$$

where the air quality index (represented by X_{airQ}) is determined by the specific IAQ parameters (represented by γ and δ). The parameters are obtained from measurement calibrated result which considers the voltage obtained from clean air (V_{RL}) and the voltage from the sample indoor air (maximum voltage is 5V). X_{airQ} =100% represents clean air while X_{airQ}=0% represents highly polluted air.

This kind of index calculation is weak because they can only determine two (2) status level of indoor air quality which are clean air and highly polluted. Therefore, when the index shows a middle figure (e.g. 72%), they could not determine the status of the pollution level whether the pollution level in within acceptable range.

Later that year, they presented a network which could help in monitoring the overall air quality either in indoor environments or outdoor environments. The network consists of sensor nodes with variety kind of gas sensors (MOX type). The experiments were set in different locations, and the data collected were sent to the central monitoring unit wirelessly. To prevent data faulty, the temperature and humidity of the gas sensors were measured.

An advanced processing, to accurately measure the air quality and to detect air pollution, was applied based on artificial neural network (ANN). The ANN has three layers which produce a single output from multiple inputs. With some changes in the equation, the dependence between the voltage value acquired and the AQI remains the same X_{airQ} =100% represents clean air and X_{airQ}=0% represents highly polluted air. The air pollution or air quality index was calculated by following relation:

$$x_{airQ}(\%) = \frac{V\_pal}{V\_AirQ} \times 100 \tag{3}$$

where *V_AirQ* in volt is voltage from air quality sensor channel in clean air condition (no pollution) and *V _pal* in volt is voltage in pollution present. Although, the equation of AQI has been changed, the problem of unable to determine the status of a middle index is still not solved.

Some researches on IAQ monitoring system implemented outdoor index measurement. There are some problems when they use outdoor AQI because AQI do not cover all of the indoor air quality parameters such as CO2 and VOCs. Al-Ali, Zualkernan, & Aloul (2010) proposed an air pollution monitoring system with online GPRS-Sensors Array. The system was integrated with high-end Pollution-Server with Internet connectivity to gather information about pollutants level (CO, NO2, and SO2) and GPS physical time, date and location. Each pollutants levels and GPS locations was displayed in real-time on Google Maps. The pollutant level is calculated using outdoor AQI formulated by the UAE government. The calculation is as follow:

$$AQI = \left(\frac{Pollution\ Level}{Pollution\ Standard}\right) \times 100 \tag{4}$$

Some researchers refer to the U.S. EPA AQI without any moderation. The same problem with index calculating using outdoor AQI arises due to different parameters use in calculation of indoor and outdoor air quality index. Kim et al., (2014) developed a smart integrated air quality monitoring system with multi-air pollutants sensor network for indoor environment. In the calculation of their index, they used indoor air parameters such as CO_2 and VOCs. But, since they referred to the U.S. EPA, the question arises as how did they derive the break point for these parameters as these parameters are not included in the U.S. EPA report [7].

SELECTION OF IAQ PARAMETERS

Parameters or pollutants for indoor air quality measurement are slightly different from the parameters used in outdoor air quality measurement. The US EPA has divided the pollutants of indoor air into four (4) categories: physical condition; poor ventilation system; radiation; and other common indoor air pollutants. Other common indoor air contaminants include chemical contaminants, biological contaminants and respirable suspended matters (PM_{10}). For the purpose of this research, only certain types of chemical contaminants and respirable suspended matters are being included. The selected parameters are as illustrated in Table 3 and 4.

The AQI use by the U.S. EPA has a breakpoint table for the parameters used in determining the outdoor air quality index. This breakpoint is specifically to be used for outdoor air index alone. Therefore, if an index for indoor environment is to be calculated or modified, the breakpoint table also needs to be modified to fit the indoor environment. Based on guidelines provided by some countries like Hong Kong, the United States and Malaysia, and environmental agencies like EPA, OSHA, WHO and ACGIH, the breakpoint table for indoor environment is modified as in Table 3 and 4.

The IAQI breakpoint developed in this research is quite different compared to the U.S. EPA AQI index. In term of index status, the IAQI value and status is divided into four categories with specific color and range which are: Good (100-76), Normal (75-51), Unhealthy (50-26) and Hazardous (25-0). This status is a reversal to the U.S. EPA IAQ since the U.S. EPA IAQ is used to determine the pollution level whereas this IAQI is used to measure the quality of air. For index calculation, the EPA used 1 or 8 hour average of pollutant in order to get the index value but for IAQI, one minute average is used – air quality can change dramatically.

In addition to the indoor air, thermal comfort is also taken into consideration. Temperature and humidity (the agents for thermal comfort) are taken into account because these two factors are the most common physical factors that could affect the occupants of a building [9]. Even though both indoor air quality and thermal comfort could affect occupants of a building, they usually do not affect each other (may not be true in certain cases). For example, when the temperature is high, this temperature usually does not affect the air quality.

Thus, it is concluded that the indoor air quality and thermal comfort should have different index status (please refer to the Table 3 and 4). Let’s say that the IAQI level is 80 and the thermal comfort index level is 40. The IAQI status is therefore “Good” and the thermal comfort index is “Not Comfort”. It means that the air quality at that particular time is good (within acceptable range), but the comfort of the building’s occupants is affected by the thermal parameters where the condition is not comfortable (may be due to high temperature).

TABLE 3. Breakpoint table for indoor environment – IAQI and TCI status

CO_2 (ppm)	CO (ppm)	NO_2 (ppm)	O_3 (ppm)	IAQI	IAQI Status	TCI	TCI Status
340-600[a,b]	0.0-1.7[d,i]	0.000-0.021[d,i]	0.000-0.025[d,i]	100-76	Good	100-76	Most Comfort
601-1000[a,c]	1.8-8.7[d,j]	0.022-0.08[d,i]	0.026-0.05[c,e]	75-51	Moderate	75-51	Comfort
1001-1500[a]	8.8-10.0[k]	0.09-0.17[l]	0.051-0.075[n]	50-26	Unhealthy	50-26	Not Comfort
1501-5000[g,h]	10.1-50.0[k,g]	0.18-5[m]	0.076-0.1[o,p]	25-0	Hazardous	25-0	Least Comfort

TABLE 4. Breakpoint table for other pollutants

PM_{10} (mg/m^3)	VOC (ppm)	O_2 (%)	Temp (°C)	Humi (%)	IAQI	IAQI Status	TCI	TCI Status
0.000-0.020[d,i]	0.000-0.087[d,i]	23.5[t]-20.9[t,w,x]	20.0[c] - 26.0[c]	40.0[c] -70.0[c]	100-76	Good	100-76	Most Comfort
0.021-0.150[c,e]	0.088-0.261[d,i]	20.8-19.5[u,v,t,w]	26.1-29.0[y]	70.1-80.0	75-51	Moderate	75-51	Comfort
0.151-0.180[d,i]	0.262-0.43[s]	19.4-12.0[u,v,t]	29.1-39.0[y]	80.1-90.0	50-26	Unhealthy	50-26	Not Comfort
0.181-0.600[q]	0.44-3.00[c,e]	11.9–10.0[u,t,v,x]	39.1-45.0[y]	90.1-100.0	25-0	Hazardous	25-0	Least Comfort

Legends

a. [16]
b. [17]
c. [10]
d. [9]
e. [18]
f. [19]
g. [20]
h. [21]
i. [22]
j. [23]
k. [24]
l. [25]
m. [26]
n. [27]
o. [28]
p. [29]
q. [7]
r. [30]
s. [31]
t. [32]
u. [33]
v. [34]
w. [35]
x. [36]
y. [37]

RESULTS AND DISCUSSIONS

After all individual index has been obtained, an EIAQI is formulated which combines all the previous 3 indices. This EIAQI informs the users about the overall comfort status in the room. The calculation procedure for this EIAQI is shown in Figure 1. For the formulation of EIAQI, each sub-index is first given its own weightage. This technique is known as weightage summation. It is the best known and simplest multi-criteria decision analysis method for evaluating a number of alternatives in terms of a number of decision criteria (Chen and Copes, 2013). Based on Figure 1, the status of IAQ index is given the following weightage: Good – 3, Moderate – 2, Unhealthy – 1, and Hazardous – (-4). Each status is given different weightage to differentiate the overall result in EIAQI. The hazardous status is given weightage of -3 to override the ttal weightage of 4 if thermal index give its best weightage: TCI at Most Comfort (weightage 3). The weightage for the status of TCI is given as follow: Most Comfort – 3, Comfort – 2, Less Comfort – 1, and Least Comfort – 0. Next, the weightage in each sub-index is summed and the total weightage is assigned to certain status as follow: total weightage is 7 = excellent, total weightage is between 4 and 6 = good, total weightage is either 2 or 3 = bad and total weightage is less than 2 = worst. For example, at any given time, the status of IAQI is Good (weightage 3) and the TCI status is Comfort (weightage 2), then the total EIAQI weightage is 5 which refers the overall condition of the room as good.

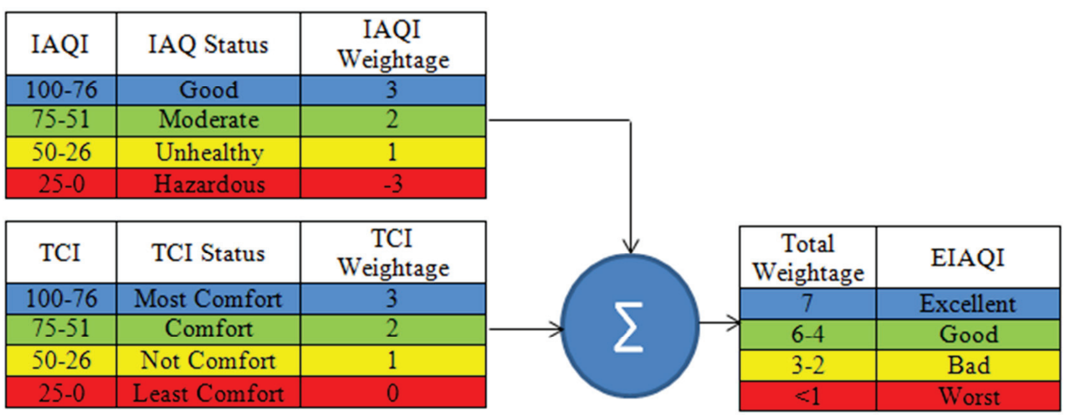

FIGURE 1. Calculation procedures for EIAQI

Several experiments have been conducted in three different environment settings – air-conditioned environment, cigarette smoke and chemical cleaning agent. These three experiments are used to illustrate the overall functionality of prototype real-time monitoring system and index determination. Figure 2 shows the IAQI, TCI and EIAQI for ambient air. The graph is plotted for both conditions: air-conditioner “OFF” and air conditioner “ON”. When the air-conditioner is “OFF”, status for IAQI, TCI and EIAQI are Good, Less Comfort (due to high temperature) and Good respectively. Once the air-conditioner is “ON”, the status for TCI improved from Less Comfort to Comfort due to the improvement in the temperature, and then after a while, the condition improved to Very Comfort. The status for other indices remained the same except for EIAQI which portrayed a little improvement. However, the total status for EIAQI did not change and stay in Good status.

Figure 3 shows the IAQI, TCI and EIAQI for presence of cigarette smoke. A person smoked in the room for 10 minutes from 10.35 a.m. until 10.45 a.m. Then, the window is opened to release the smoke from the room. Before the smoking activity took place, status for IAQI, TCI and EIAQI are Good, Most Comfort (air-conditioner is “ON”) and Good respectively. When the person smoked a cigarette in the room, the status for all index are affected except for TCI. The IAQI status fall from Good to Moderate and then to Unhealthy when the amount of cigarette smoke in the room is too high. The EIAQI status reduces from Good to Bad. Then, when the window was opened to purge out the smoke, it took quite a while before the IAQI and EIAQI status turned back to previous state.

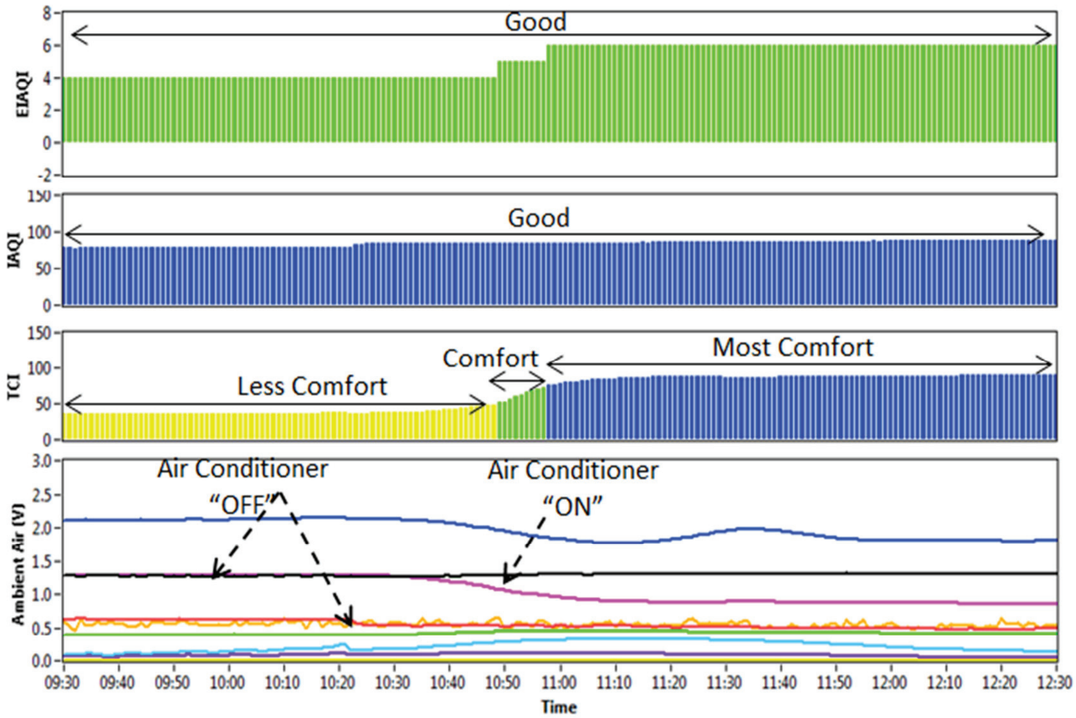

FIGURE 2. Overall index for ambient air

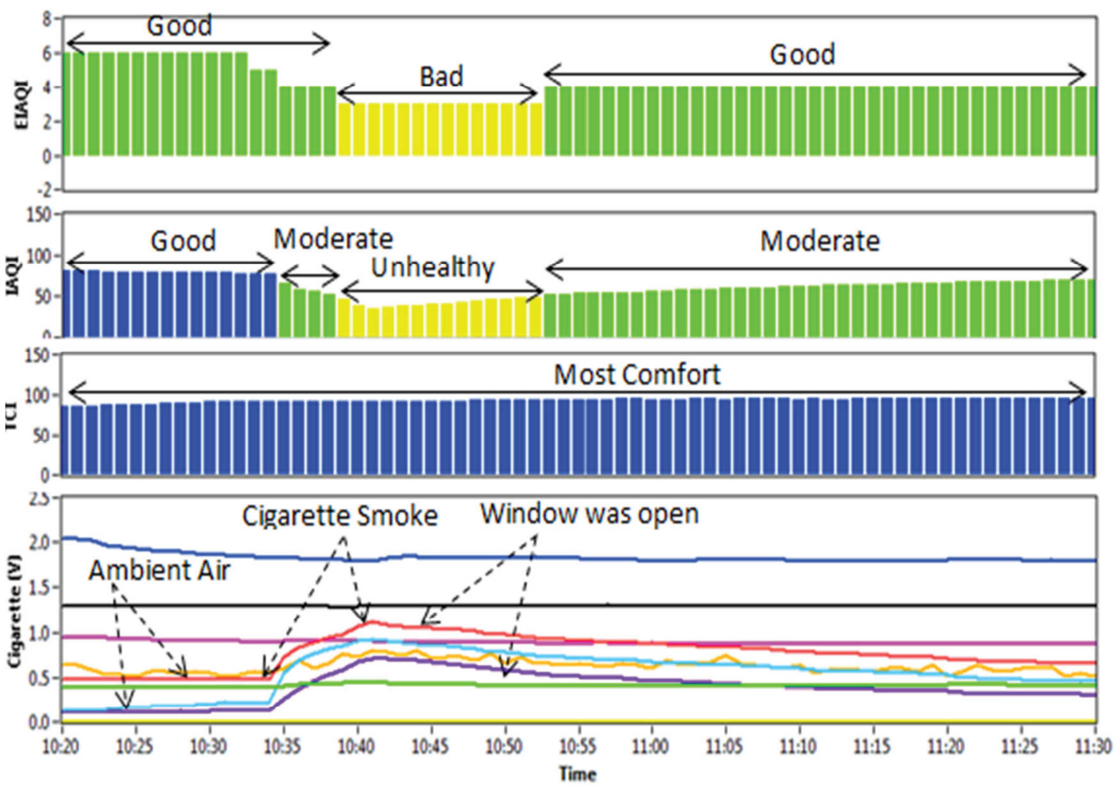

FIGURE 3. Overall index for presence of cigarette smoke

Figure 4 shows the IAQI, TCI and EIAQI for presence of chemical product. A beaker containing cleaning product was placed in the room from 9.45 a.m. The initial status for IAQI, TCI and EIAQI are Good, Most Comfort (air-conditioner is “ON”) and Good respectively. As soon as the cleaning product is placed, status for IAQI and EIAQI plunged dramatically from Good to Hazardous for IAQI and from Good to Worst for EIAQI. Based on the result of application of EIAQI in controlled environment, it is clear that the EIAQI, IAQI and TCI status changed according to simulation.

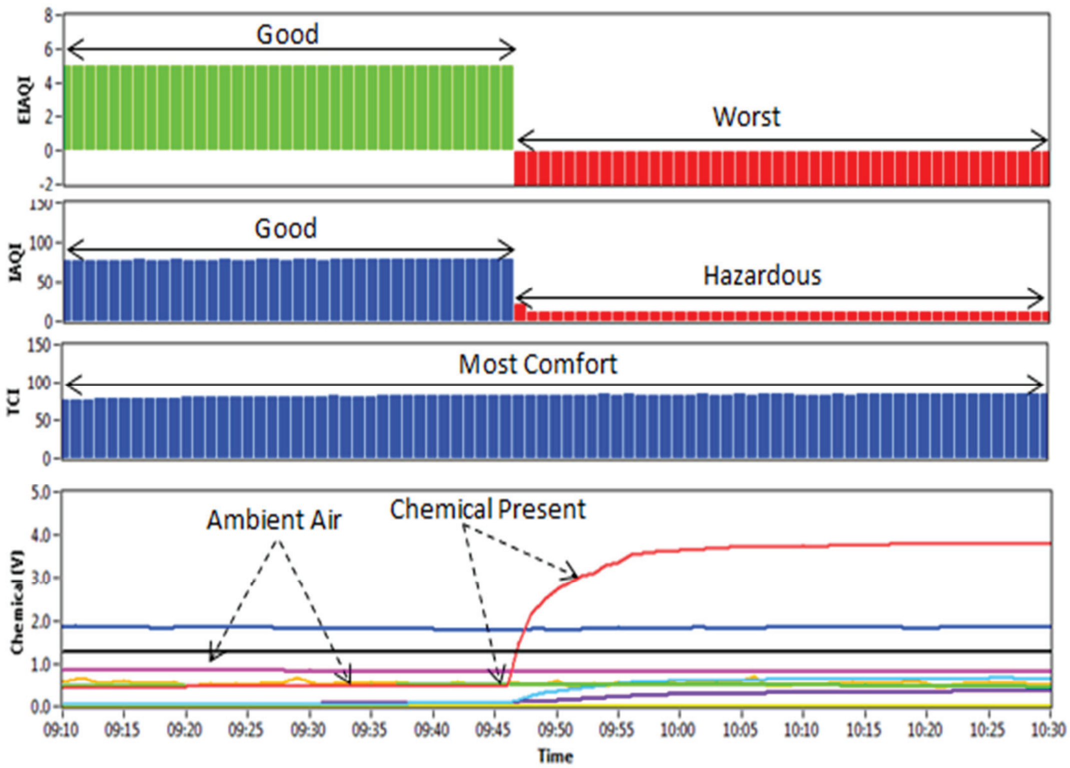

FIGURE 4. Overall index for presence of chemical product

CONCLUSION

In this paper, index for indoor air quality (also known as IAQI) and thermal comfort have been developed. The IAQI was actually modified from previous outdoor air quality index (AQI) designed by the U.S. EPA. This paper proposed that the IAQI and thermal comfort index should be reported together to describe the real situation of the air quality and comfort level. Finally, an enhanced IAQI or Indoor Environmental Index (EIAQI) which combines both indexes is formulated. This EIAQI informs the users about the overall comfort status in the room. In order to measure the index, a real-time monitoring system to monitor indoor air quality level was developed. The proposed system consists of three parts: sensor module cloud, base station and service-oriented client. The sensor module cloud (SMC) contains collections of sensor modules that measures the air quality data and transmit the captured data to base station through wireless. Each sensor modules includes an integrated sensor array that can measure indoor air parameters like Carbon Dioxide, Carbon Monoxide, Ozone, Nitrogen Dioxide, Oxygen, Volatile Organic Compound and Particulate Matter. Temperature and humidity was also being measured in order to determine comfort condition in indoor environment. All sensor signal was measures in real-time with 1 minutes time interval. The signal value was transmits to base station wirelessly. There is one server connected to base station and its function as data logger to keeps track the data received from base station. It stores the data in database, processes the data, performs an analysis and provides information about IAQ index through Web Service. The result from several experiments show that the system is able to measure the air quality in many settings like human present, chemical present and cigarette smoke that may impact the air quality. It also shows that the air quality are changing dramatically, thus real-time monitoring system is essential.

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