ARTICLE IN PRESS
Journal of King Saud University – Engineering Sciences (2014) xxx, xxx–xxx

King Saud University
Journal of King Saud University – Engineering Sciences
www.ksu.edu.sa
www.sciencedirect.com

ORIGINAL ARTICLE

Air-conditioned university laboratories: Comparing CO_2 measurement for centralized and split-unit systems

M. Hussin [a,b,*], M.R. Ismail [a], M.S. Ahmad [b]

[a] *School of Housing, Building and Planning, Universiti Sains Malaysia, 11800 USM, Penang, Malaysia*
[b] *Development Department, Universiti Sains Malaysia, 11800 USM, Penang, Malaysia*

Received 6 February 2014; accepted 6 August 2014

KEYWORDS
Indoor CO_2 concentration;
Outdoor CO_2 concentration;
Laboratory;
Indoor air quality;
Air condition;
Ventilation

Abstract Universities are designed for higher education learning, and improving university indoor air quality (IAQ) is essential to the enhanced performances of students and staff members alike. The majority of IAQ problems are due to inadequate ventilation in university buildings. Carbon Dioxide (CO_2) measurements have become a commonly used screening test of IAQ because measurement levels can be used to evaluate the amount of ventilation and general comfort. This paper examines CO_2 field measurement for undergraduate practical classes. Ten air conditioned laboratories with ventilation were chosen for CO_2 field measurement. CO_2 was monitored under indoor and outdoor conditions. Indoor CO_2 concentration for Laboratories 1 and 10 is observed to be higher than 1000 ppm which indicated inadequate ventilation, while other laboratories showed CO_2 concentrations less than 1000 ppm. Air capacity and outdoor air were calculated based on the design documentation. A comparison between design and actual outdoor air/person values indicates that the air conditioning systems of the laboratories had adequate ventilation.

1. Introduction

Literature shows that human beings spend 80–90% of their time in enclosed spaces, such as houses, office buildings, and schools (Righi et al., 2002; Yrieix et al., 2010). Such spaces have restricted air circulation. Therefore, indoor air quality may be worse than outdoor air quality (Xu and Little, 2006; Watson, 2013). In many buildings, the occupants themselves are a major source of indoor air contaminates. Although carbon dioxide (CO_2) (a gas that is produced when people breathe) may not be considered to pose serious health effects, some research has indicated that individuals in schools with

* Corresponding author at: School of Housing, Building and Planning, Universiti Sains Malaysia, 11800 USM, Penang, Malaysia. Tel.: +60 4 6533301; fax: +60 4 6587688.
E-mail address: hussinm@usm.my (M. Hussin).
Peer review under responsibility of King Saud University.

Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.jksues.2014.08.005
1018-3639

high CO_2 concentration have been associated with increased frequency of health symptoms (Siskos et al., 2001). Ventilation plays a crucial role in promoting the comfort and health of building occupants (Rackes and Waring, 2014). However, measuring the actual ventilation rate is expensive and potentially problematic. Measuring the indoor CO_2 concentration is often used as an alternative to determine the ventilation rate of each occupant. Measuring CO_2 concentration has become a common method to determine the air exchange rate in buildings (Bulińska et al., 2014). CO_2 is a natural air component, and CO_2 in a given air sample is commonly expressed in parts per million (ppm). CO_2 levels that exceed 1000 ppm indicate a lack of adequate ventilation (Sulaiman and Mohamed, 2011). High CO_2 levels indicate that the indoor air is not refreshed enough, which causes CO_2 build-up.

The average breath of an adult contains 35,000–50,000 ppm of CO_2 (Prill, 2000). CO_2 is continuously generated and accumulates in the absence of adequate ventilation which dilutes and removes the CO_2. The outdoor CO_2 level is reported to be in a range of 350–450 ppm (Seppanen and Fisk, 2004). Prill (2000) reported that the indoor CO_2 level is 100 times greater than the outdoor CO_2 level, even in buildings where complaints with regard to indoor air quality are few. If indoor CO_2 levels are more than 1000 ppm, ventilation is probably inadequate, and occupants may commonly complain about headaches, nose and throat ailments, tiredness, lack of concentration, and fatigue (Siskos et al., 2001; Carlsson et al., 2000; Makowski and Ohlmeyer, 2006). However, low CO_2 levels do not necessarily indicate the absence of internal air quality (IAQ) issues. Problems can also occur in buildings where CO_2 concentrations are below 1000 ppm. Moreover, identifying CO_2 levels may determine the ventilation level, but source control measures need to be set when strong contaminant sources are present to prevent IAQ problems.

Current technology allows easy and relatively inexpensive CO_2 measurement, which ensures that ventilation systems of high-density occupancy zones provide the recommended minimum quantities of outside air to buildings (Xu and Zhang, 2004). Hu et al. (2007) reported that several buildings have poor indoor air quality, especially CO_2 concentration. The Korean Standard (1991) and ASHRAE Standard (2001 & 2004) indicate the significant role of ventilation in generating a comfortable indoor environment; current air cleaning systems cannot remove CO_2 in the air (Farhad, 2009). Daisey et al. (2003) observed that school ventilation systems were inadequate and caused health problems. Lee and Chang (1999) observed five classrooms in five different schools in Hong Kong and found that the value point data sample of CO_2 concentration exceeded the Hong Kong indoor air quality limit because of high outdoor concentration and inadequate ventilation; this finding was determined when the indoor and outdoor air quality were investigated (Awbi and Pay, 1995). The CO_2 concentration in most schools and offices is below the 5000 ppm occupational safety standard for industrial workplaces (i.e., the time-weighted average for an 8-hour workday within a 40-hour work week). CO_2 levels below 5000 ppm do not pose serious health threats, but individuals in schools and offices with elevated CO_2 concentration commonly report drowsiness, lethargy, and a general sense of staleness in the air. Yau et al. (2012) studied the IAQ data of pharmaceutical laboratories and identified the average performance for air conditioning systems of the laboratories included in the study. Researchers are attempting to link elevated CO_2 concentration with reduced productivity and achievement (Lee and Chang, 1999). Lisa et al. (2012) reported on methods to simultaneously reduce building energy consumption while maintaining or improving indoor air quality.

Various studies have reported the adverse effects of IAQ, particularly in residences and offices. However, few studies are concerned with the indoor environment of school buildings (Awbi and Pay, 1995; Bako-Biro et al., 2007). Moreover, even fewer studies are concerned with classrooms occupied by adult students. Awbi and Pay (1995) observed university classrooms with different air capacities and reported poor IAQ during occupancy. Classrooms function as the basic space where teaching and learning are the main priority; therefore, IAQ issues in classrooms are seen as risks. Singhvi et al. (2001) studied the IAQ of a laboratory. They studied real-time metallic mercury vapor levels in the laboratory to evaluate the effectiveness of site clean-up operations. They found that exchanges in room air (per hour) were not the main parameter in determining good air quality and laboratory health and safety. The prime objective of laboratory ventilation was to protect the health and safety of laboratory personnel. Previous studies describe factors that affect air exchange rates in laboratory design and present decision logic to determine acceptable air exchange rates based on proper laboratory design for controlling airborne emissions (DiBerardinis et al., 2009).

Several studies recommend using indoor CO_2 concentration to evaluate IAQ and ventilation. However, characterizing

Table 1 Description of practical class for the 10 laboratories.

Lab	Duration of practical class	Air-conditioning system/campus	Type of experimental
1	10 am–1 pm	Air handling unit (AHU)/ engineering campus	Electric/electronic circuit
2	2–4 pm		Chemical reaction
3	2–5 pm		Electric/electronic circuit
4	2–6 pm		Materials properties and characterization
5	2–6 pm		Materials properties and characterization
6	2–5 pm	Split unit/main campus	Electronic circuit
7	2–5 pm		Electronic circuit
8	10 am–11.40 am		Cell culture and life science
9	10 am–1 pm		Cell culture and life science
10	10 am–1 pm		Drug used evaluation and calibration of volumetric glassware

indoor CO_2 concentration adequately is difficult because it is a function of occupancy and ventilation rate, which both vary as a function of time. Ventilation system operations and effectiveness are evaluated to investigate the relationship between indoor CO_2 concentration and air exchange rates (Nabinger et al., 1994). Limited studies focus on the ventilation effectiveness on laboratory CO_2 levels. Several university students spend most of their time in classrooms, libraries, laboratories, hostels, and other indoor environments. Therefore, the quality of indoor environments likely affects student health and performance. Studying CO_2 concentration in laboratories along with ventilation effectiveness is important. Thus, we carried out CO_2 measurements of ten undergraduate laboratories in two campuses (Engineering Campus and Main Campus) of the Universiti Sains Malaysia during practical classes. We compared the CO_2 concentrations of the laboratories with and without practical classes. Measurements were conducted in air-conditioned laboratories with closed doors and windows for 160–240 min, which represents an actual daily routine for practical classes in student laboratories.

2. Methodology

Air quality measurements were taken by using the multi-sensor instrument Fluke AirMeter Test Tool 975. Data acquisition interval was 10 min (160–240 min). The instrument measured CO_2 concentration from 0 ppm to 5000 ppm with a display resolution of 1 ppm. The accuracy of the CO_2 reading was 2.75% + 75 ppm. Readings were taken during three different days.

Practical classes were conducted in closed air-conditioned rooms. The capacity of the ten laboratories ranges from 18 to 67 students at one time. The laboratory situation consists of student movement during practical classes. In this study, the duration and frequency of incoming and outgoing students opening the doors during the practical classes were not considered. The air conditioning system [air handling unit (AHU)] in the Engineering Campus was designed into the building installation. The air conditioning system (split unit) in the Main Campus was installed only upon the request of the building occupants. Table 1 summarizes the main features of the laboratories.

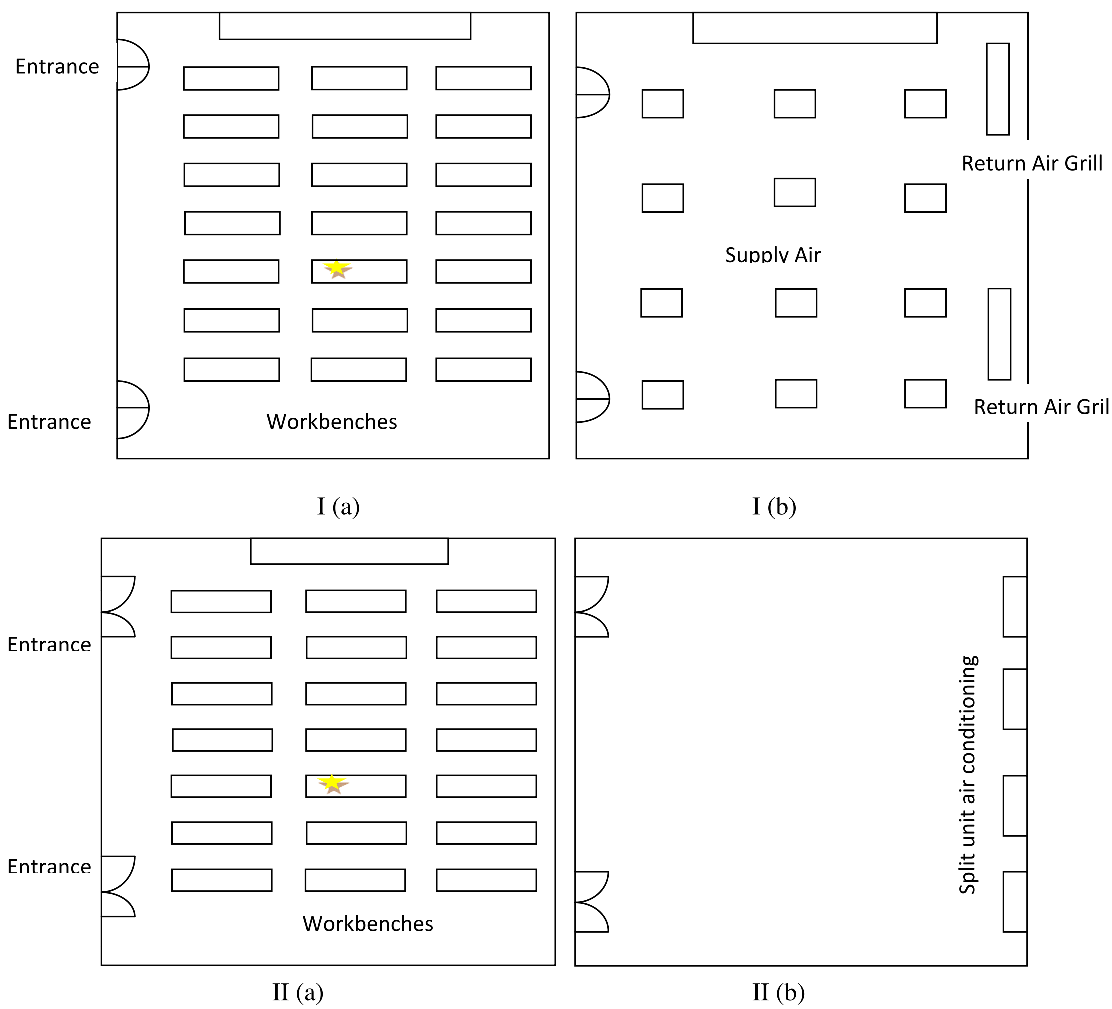

Figure 1 (Ia) Layout of laboratory with constant air volume centralized air conditioning system, workbenches and assessor location (indicated by *), (Ib) layout of supply air diffusers and return air grill of constant air volume centralized air conditioning system; (IIa) Layout of laboratory with split unit air conditioning system, workbenches and assessor location (indicated by *), (IIb) layout of supply air diffusers and location of the split unit air conditioning system.

Please cite this article in press as: Hussin, M. et al., Air-conditioned university laboratories: Comparing CO_2 measurement for centralized and split-unit systems. Journal of King Saud University – Engineering Sciences (2014), http://dx.doi.org/10.1016/j.jksues.2014.08.005

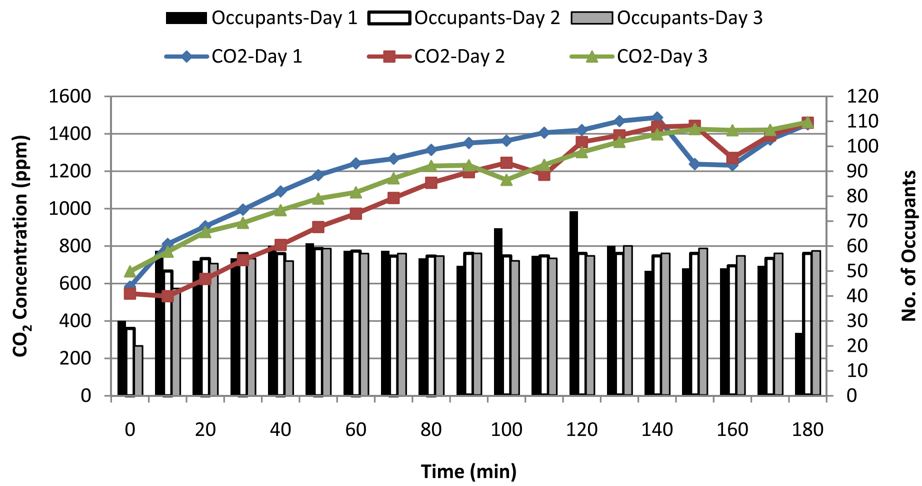

Figure 2 CO_2 concentration and number of occupants with time in Laboratory 1.

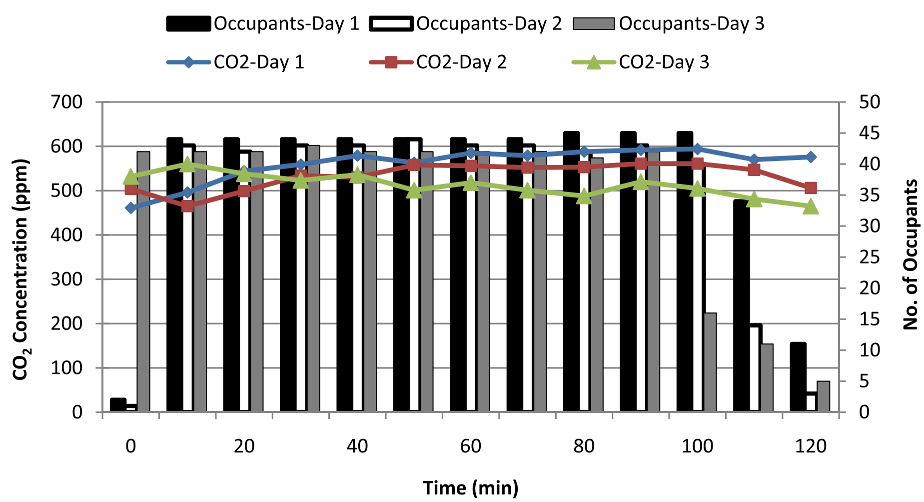

Figure 3 CO_2 concentration and number of occupants with time in Laboratory 2.

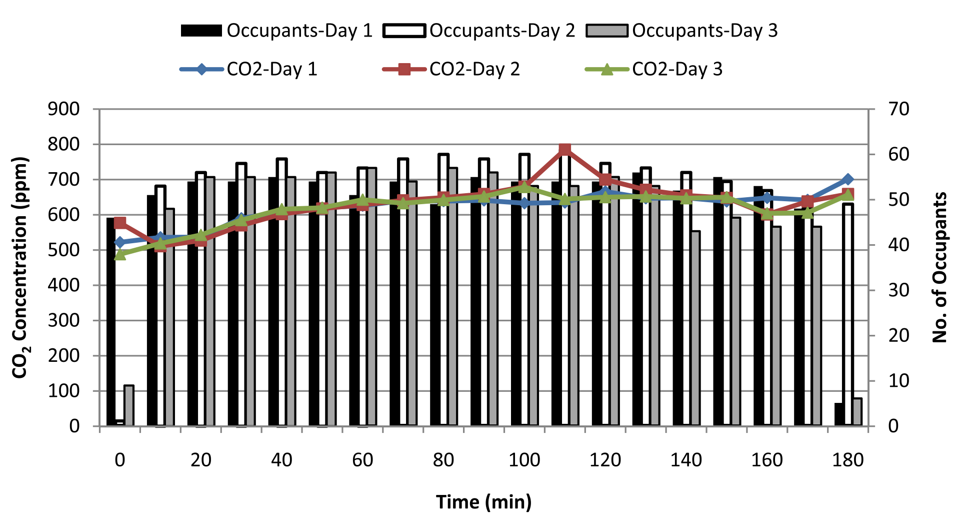

Figure 4 CO_2 concentration and number of occupants with time in Laboratory 3.

Please cite this article in press as: Hussin, M. et al., Air-conditioned university laboratories: Comparing CO$_2$ measurement for centralized and split-unit systems. Journal of King Saud University – Engineering Sciences (2014), http://dx.doi.org/10.1016/j.jksues.2014.08.005

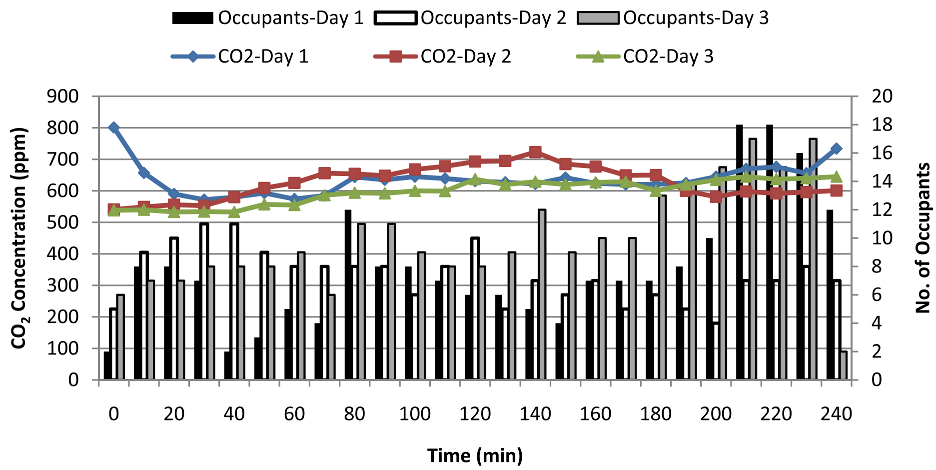

Figure 5 CO_2 concentration and number of occupants with time in Laboratory 4.

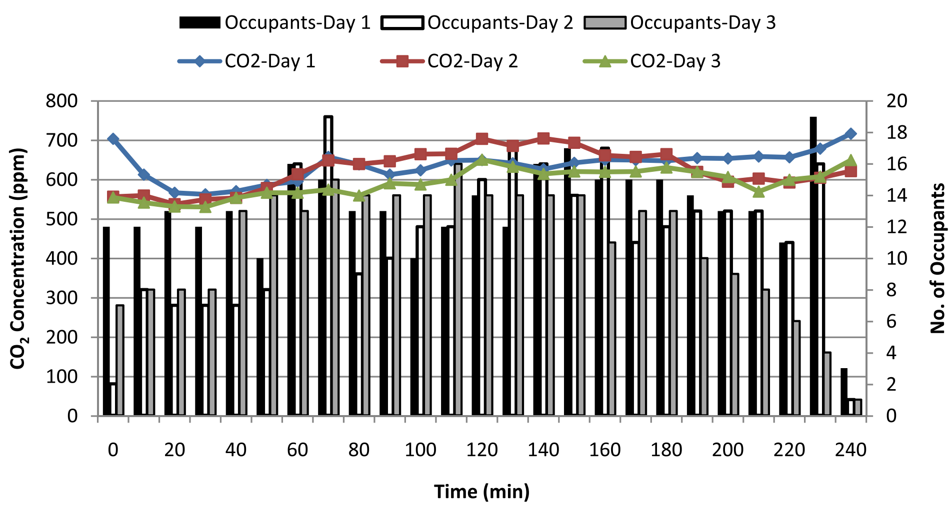

Figure 6 CO_2 concentration and number of occupants with time in Laboratory 5.

Fig. 1a and b show the layout of the workbenches, assessor location, supply air diffusers, and return air grill of the AHU and split unit air conditioning systems used in the laboratories, respectively. The physical measurement was taken 1.5 m above ground level at the center of the laboratories. The number of sampling points was based on the recommendation of the Industry Code of Practice on Indoor Air Quality (2010). The outdoor CO_2 concentration was taken at few points at the internal corridor outside the laboratories.

3. Results and discussion

Figs. 2–6 show the CO_2 concentration and occupant number for laboratories 1–5 of the Engineering Campus, respectively. Fig. 2 shows the CO_2 concentration variation and occupant profiles for a practical class that lasted three hours (180 min). The student number ranged from 50 to 60 throughout the laboratory session. The trend of CO_2 concentration for three readings increased in a 3-hour practical class. The CO_2 concentration was low for the first 30 min of the practical class and increased slowly in time. Based on the three different measurements for three days, the CO_2 concentration in laboratory 1 already exceeded 1000 ppm after 30–60 min of the practical class and slowly increased to 1400 ppm afterward. Experiments on the soldering process of electronic circuits were conducted in this laboratory, which increased the CO_2 concentration. Besides that the supply outdoor grill was closed during the laboratory session. This results in no supply of fresh air which subsequently increased the level of CO_2 concentration in laboratory 1. This value exceeds the 1000 ppm limit set by the Malaysian Code of Practice and ASHRAE guidelines but is still within the 1500 ppm Japan Society for Occupational Health (2004). This high CO_2 concentration indicates poor ventilation and contaminant build-up in the laboratory (Huizenga et al, 2006). Bjorn and Nielsen (2002) declare that CO_2 build-up in classrooms is related to student activity and movement.

CO_2 issues are resolved through a handful of solutions. One solution is to enhance air ventilation systems with the use of extractor fans during practical classes (Ismail et al., 2010). Indoor air needs to be ventilated with sufficient outdoor air to dilute air contaminants and provide students with sufficient oxygen (O_2) for breathing. Ismail et al. (2010) reported that an extractor fan that switches on every 30 min for 5-minute durations can also solve the problem of excess CO_2 in a room.

Please cite this article in press as: Hussin, M. et al., Air-conditioned university laboratories: Comparing CO_2 measurement for centralized and split-unit systems. Journal of King Saud University – Engineering Sciences (2014), http://dx.doi.org/10.1016/j.jksues.2014.08.005

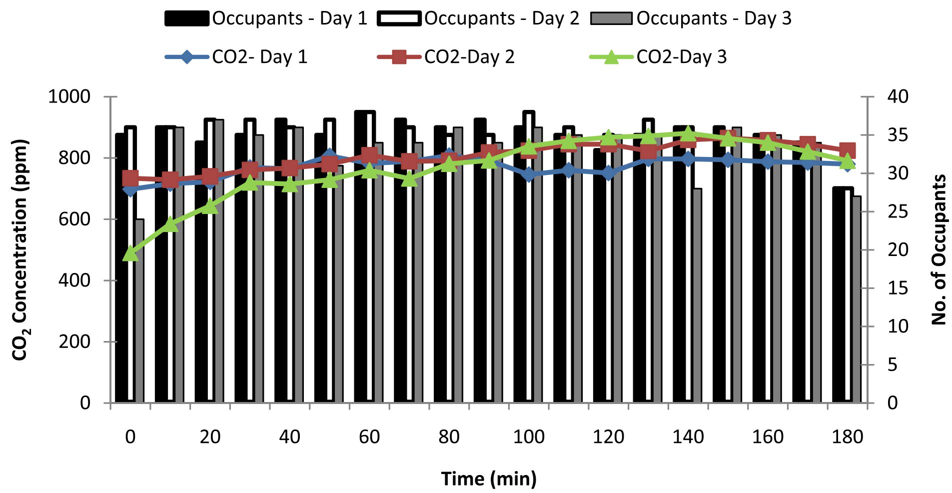

Figure 7 CO_2 concentration and number of occupants with time in Laboratory 6.

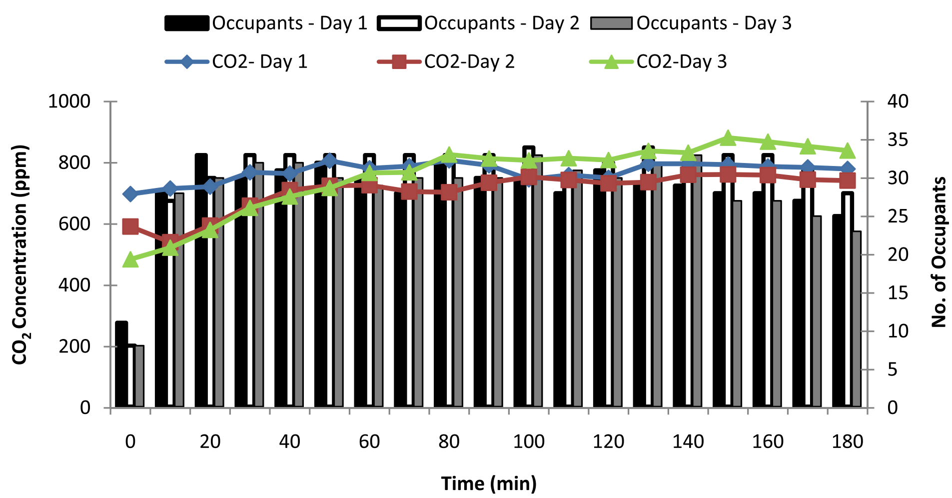

Figure 8 CO_2 concentration and number of occupants with time in Laboratory 7.

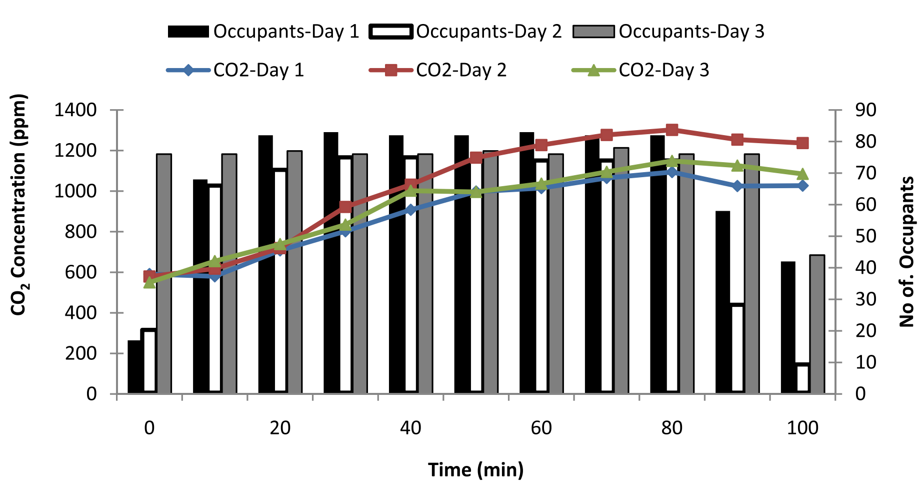

Figure 9 CO_2 concentration and number of occupants with time in Laboratory 8.

Further investigation is necessary for these potential solutions because the increased ventilation also increases the indoor concentration of outdoor-generated pollutants.

Fig. 3 shows that 40–45 students attended the laboratory session. Three readings were taken for three different laboratory sessions for 3 days. CO_2 build-up began when students started

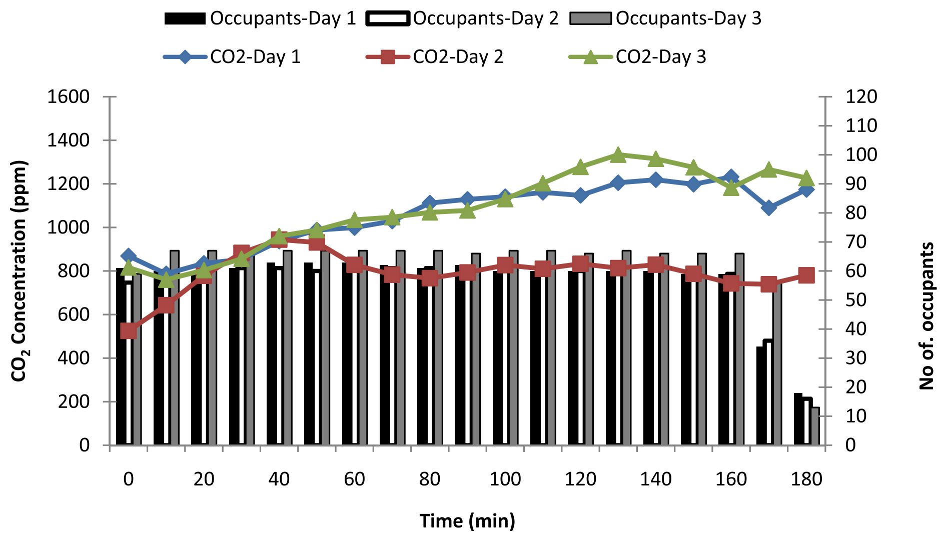

Figure 10 CO_2 concentration and number of occupants with time in Laboratory 9.

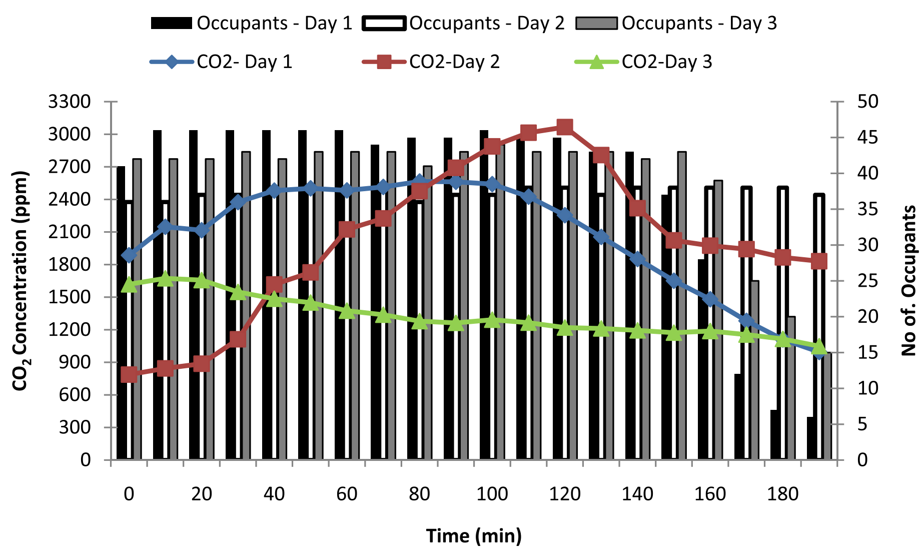

Figure 11 CO_2 concentration and number of occupants with time in Laboratory 10.

occupying the laboratory. The CO_2 concentration increased slowly from 460 ppm to 600 ppm and remained at that level. The CO_2 concentration was generally lower than 1000 ppm.

Fig. 4 shows a consistent CO_2 concentration trend for three different sessions for three days. The CO_2 concentration increased slowly and reached a saturation level of 600–700 ppm. Figs. 5 and 6 show the inconsistent number of occupants throughout the 4-hour laboratory session, which is due to students moving in and out of the laboratory at any time. This inconsistency results in slight fluctuations in CO_2 levels. The CO_2 concentration for these two laboratories slowly increased and remained from 600 ppm to 700 ppm; evidently, the number of occupants in the laboratory did not significantly influence the CO_2 concentration. The high CO_2 concentration at the initial period of the session was due to the delay in starting up the air conditioning system.

Figs. 7–11 show the CO_2 and CO concentrations and number of occupants for laboratories 6–10, respectively. Laboratories 6–10 are located in the main campus. Three readings were collected based on Fig. 7, which shows that the CO_2 concentration is consistent throughout the practical class. The CO_2 concentration remained between 700 ppm and 800 ppm. It was observed to be low during the first 30 min of the practical session on day 3 because of the small number of occupants. The CO_2 concentration then started to increase and remained between 700 ppm and 800 ppm after 30 min of the practical class. Therefore, the CO_2 concentration was generally lower than 1000 ppm. Fig. 8 shows a similar consistent trend in the CO_2 concentration for three different sessions for three days. The CO_2 concentration was low during the first 40 min, then started to build up afterward and remained between 700 ppm and 800 ppm throughout the practical class.

Fig. 9 shows the CO_2 concentration for 3 days of practical classes throughout 100 min. The number of students ranged from 60 to 80 for each session. The CO_2 concentration started to build up from 600 ppm to 1000 ppm within the first 50 min. It reached a saturation level of 1000–1200 ppm until the end of the laboratory sessions.

Please cite this article in press as: Hussin, M. et al., Air-conditioned university laboratories: Comparing CO_2 measurement for centralized and split-unit systems. Journal of King Saud University – Engineering Sciences (2014), http://dx.doi.org/10.1016/j.jksues.2014.08.005

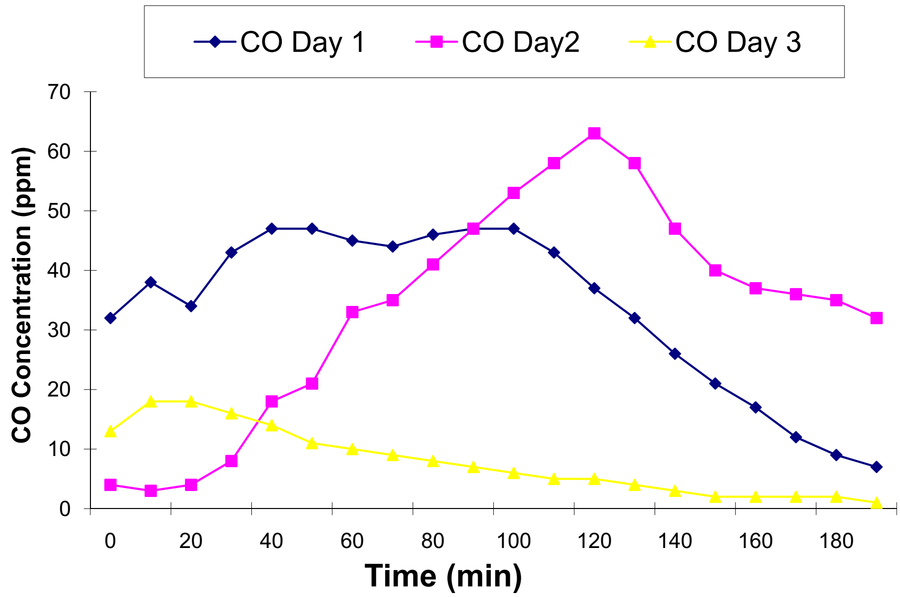

Figure 12 CO concentration with time in Laboratory 10.

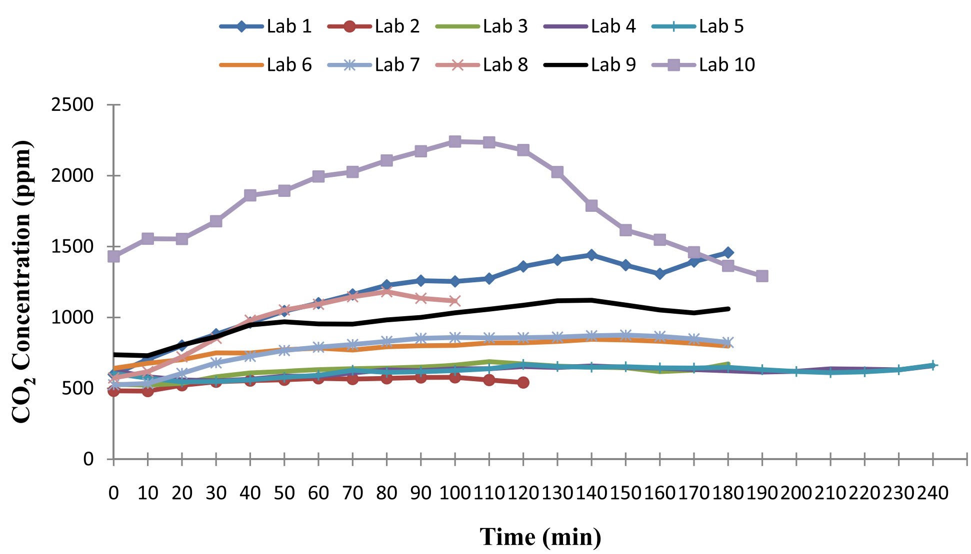

Figure 13 Average of CO_2 concentration with time for the 10 laboratories in the Engineering and Main Campuses.

Fig. 10 shows the CO_2 concentration for three measurements throughout 180 min of practical classes. Measurements for days 1 and 3 were taken in the morning, whereas measurements for day 2 were taken in the afternoon. The number of students ranged from 55 to 65 for each session. The CO_2 concentration for days 1 and 3 at the initial stage of the classes ranged from 800 ppm to 875 ppm. It started to build up to 1400 ppm after 130 min since the classes started and reached saturation level until the end of the practical classes. The CO_2 concentration for day 2 at the initial stage of the class was at 500 ppm. It started to build up to 900 ppm after 40 min of the practical class and reduced to 750 ppm and 800 ppm until the end of the practical classes. This is because the students opened few windows during the practical classes which resulted to the movement of hot air inside the laboratory to the outer building space. The findings indicate that the CO_2 concentrations for days 1 and 3 exceeded 1000 ppm.

Fig. 11 shows the CO_2 concentration for three different days of practical classes for 180 min. The number of students that attended the classes ranged from 30 to 45. Days 1 and 2 showed high CO_2 concentrations of 2400–3000 ppm, respectively. The CO_2 concentrations reduced after 100 min and 120 min of the practical class as the number of students reduced. Day 3 showed a consistent CO_2 concentration of 1200–1500 ppm. Students were conducting experiments using Bunsen burners on days 1 and 2, which increased the CO_2 concentration. According to the IAQ guidelines of the Illinois Department of Public Health, the standard of 1000 ppm is

Please cite this article in press as: Hussin, M. et al., Air-conditioned university laboratories: Comparing CO2 measurement for centralized and split-unit systems. Journal of King Saud University – Engineering Sciences (2014), http://dx.doi.org/10.1016/j.jksues.2014.08.005

Table 2 Average indoor CO_2 concentration (with and without practical class) in comparison with outdoor CO_2 concentration for the 10 laboratories.

Lab	Average indoor CO_2 concentration (w/o practical class) (ppm)	Average indoor CO_2 concentration (with practical class) (ppm)	Average outdoor CO_2 concentration (ppm)
1	500	1158	638
2	504	547	552
3	450	623	554
4	540	620	558
5	550	618	558
6	469	775	664
7	495	769	733
8	437	952	877
9	502	978	740
10	590	1801	948

not applicable to buildings with CO_2 sources other than exhaled breath; under this condition, the Occupational Safety and Health Administration (OSHA) standard for CO_2 should be used. The OSHA standard is an 8-hour time-weighted average of 5000 ppm with a short-term 15-minute average limit of 30,000 ppm. The CO_2 concentration in this laboratory was higher than 1000 ppm but still within the recommended WHO threshold limit value of 5000 ppm, which is a safe value for healthy adults in an 8-hour work day (WHO Report, 1990).

Carbon monoxide (CO) concentration was detected by the multi-sensor instrument in days 1 and 2. CO is a combustion product, and its presence indicates an infiltration issue in the indoor environment. Fig. 12 summarizes the CO measurement results and found that the CO concentration did not comply with the CO concentration limit of 10 ppm set by WHO (2010) and the Malaysian Code of Practice (DOSH, 2010). CO exposure at levels as low as 35 ppm causes mild fatigue. CO concentration that exceeds 10 ppm is associated with SBS symptoms, such as dizziness, fatigue, and headaches (Samet, 1993).

Fig. 13 shows the average CO_2 concentrations with time of the 10 laboratories for easy comparison. Laboratory 1 in the Engineering Campus showed the highest average of CO_2 concentration with build-up of CO_2 concentration being more than 1000. The monitored CO_2 concentration for laboratory 1 ranged between 600 ppm and 1480 ppm. The average measured CO_2 concentrations for laboratories 2–5 fell within the acceptable range of 500–750 ppm.

Laboratory 10 in the Main Campus showed the highest CO_2 concentration, which is due to the nature of the experiment. Fig. 12 shows CO presence in the laboratory because of the use of Bunsen burners, which is the main source of indoor CO. The other laboratories showed consistent CO_2 concentrations that range from 700 ppm to 1000 ppm after 50 min of the practical classes. Seppanen et al. (1999) reported that half of the 22 studies on SBS symptoms in office buildings found that increased indoor CO_2 levels were positively associated with a statistically significant increase in one or more prevalent SBS symptoms.

Table 2 compares the average indoor (with and without practical classes) and outdoor CO_2 concentrations. Data are averaged from the three readings taken from three different days. The CO_2 concentrations decreased during unoccupied periods and increased during occupied periods for all cases. This trend agrees with the findings of Zain Ahmed et al. (2004) on their study of CO and CO_2 concentrations in naturally ventilated houses in Malaysia. The average outdoor CO_2 concentration was higher than the indoor CO_2 concentration without a practical class. The activities of laboratory

Table 3 Design installation of air conditioning system for the 10 laboratories.

Lab	Area (ft^2)	Design air capacity[a] (cfm) (A)	Design max. occupancy[b] (B)	Design outdoor air[c] (cfm) (C)	Design outdoor air/person (cfm) (D = C/B)	Outdoor air/person (*ASHRAE) (cfm)
1	3139	9000	37	1800	48	20
2	2800	8700	33	1740	52	20
3	3139	10,000	37	2000	54	20
4	2080	4500	25	900	36	20
5	1444	3700	17	740	43	20
6	1980	3760	23	–	–	–
7	1980	3760	23	–	–	–
8	4018	9300	47	–	–	–
9	4018	9300	47	–	–	–
10	4048	11,118	48	–	–	–

[a] Based on design documentation.
[b] Based on design documentation provided by Malaysian Economic Planning Unit (EPU), 85 ft^2/person.
[c] Based on 20% of design air capacity.

Table 4 Comparison between actual performance and design performance of air conditioning system for the 10 laboratories.

Lab	Effective volume (ft^3)	Design air capacity	Actual max. occupancy (E)	Design outdoor air (cfm) (F)	Actual outdoor air/person (cfm) (G = F/E)	Outdoor air change rate[a] (ACH)
1	26,681	9000	60	1800	30	4.05
2	23,800	8700	45	1740	38	3.73
3	26,681	10,000	60	2000	33	4.49
4	17,600	4500	18	900	50	3.06
5	12,274	3700	19	740	39	3.62
6	16,830	3760	35	–	–	–
7	16,830	3760	29	–	–	–
8	34,153	9300	67	–	–	–
9	34,153	9300	59	–	–	–
10	51,612	11,118	38	–	–	–

[a] Based on design outdoor air divided by effective volume of respective laboratory.

occupants during the practical class obviously increased the indoor CO_2 concentration. Indoor concentrations were more elevated than outdoor concentrations mostly because of the building occupants.

The average outdoor CO_2 concentration in the Main Campus was higher than in the Engineering Campus because of heavy traffic movement and congested surroundings. The source of CO_2 concentration is activities generated by outdoor combustion (e.g., automobile exhaust from nearby roads or packing areas and construction).

Table 3 shows the design of the air conditioning system installation for the 10 laboratories. Table 4 compares the actual and design performances of the AHU system in laboratories 1–10. The split air conditioning systems in laboratories 6–10 were unable to exhaust room air, inject indoor air, or filter and treat indoor air to the required extent due to their construction. The indoor unit is basically designed to re-circulate indoor air through a filter and evaporator coil and continually cool the air. Therefore, no value was reported for designs of outdoor air, outdoor air/person, actual outdoor air/person, and outdoor air exchange rate.

Based on Tables 3 and 4, the values for design outdoor air/person (Table 3) and actual outdoor air/person (Table 4) are higher than those of the values set by the ASHRAE Standard 62-2007. Table 4 shows that the actual maximum occupancy was higher than the designed maximum occupancy in Table 3. This finding indicates that the fresh air obtained from the air conditioning system adequately ventilated the laboratory. Cheong and Lau (2003) reported the same observation in their study of IAQ audit in an air conditioned building in the tropics.

Based on the results in Table 2, we observe that student activities during practical classes and the number of occupants influence the CO_2 concentration. The types of air conditioning systems and building age do not significantly influence CO_2 concentration. The effectiveness of air conditioning systems (i.e., maintenance, cleaning procedures, and periodic inspection) improves ventilation and increases the air ventilation measurement level supplied in the indoor environment (Irtishad, 2001).

4. Conclusion

We evaluated ten laboratories to analyze the indoor CO_2 levels in mechanically ventilated laboratories and to identify necessary improvements. High CO_2 concentration in laboratories 1 and 10 indicates a minimum laboratory ventilation rate as specified in the codes. CO_2 levels should be reduced to produce laboratory environments that are conducive to learning. The other laboratories had CO_2 concentrations lower than 1000 ppm. The calculation based on the design documentation indicates that the values for design outdoor air/person and actual outdoor air/person for AHU air conditioning systems were higher than the values set by ASHRAE, which indicates that the air conditioning system adequately ventilated the laboratory.

Acknowledgments

The project is sponsored by Universiti Sains Malaysia under a short-term grant (Grant number 304/JPEB/6311008). The support from the Dean and the technical staff of the School of Physics, School of Biological Sciences, School of Pharmaceutical Sciences, School of Materials and Mineral Resources Engineering, the School of Chemical Engineering, and the School of Electric and Electronics is highly appreciated.

References

ASHRAE Standard 62–2007, Ventilation for acceptable indoor air quality. Atlanta: American Society of Heating and Refrigerating and Air-Conditioning Engineers Inc.

Awbi, H.B., Pay, A. 1995. A study of the air quality in classrooms. In: Proceedings Second International Conference on Air Quality, Ventilation and Energy Conversation in Buildings, Montreal, Canada, 9–12 May 1995, pp 93–104.

Bako-Biro, Z., Kochhar, N., Clements-Croome, D., Awbi, H.B., Williams, M. 2007. Ventilation rates in schools and learning performance. In: Proceedings of Clima 2007 WellBeing Indoors, Helsinki 10–14 June 2007.

Bjorn, E., Nielsen, P.V., 2002. Dispersal of exhaled air and personal exposure in displacement ventilated rooms. Indoor Air 12 (3), 147–164.

Bulińska, A., Popioek, Z., Bulińsk, Z., 2014. Experimentally validated CFD analysis on sampling region determination of average indoor carbon dioxide concentration in occupied space. Build. Environ. 72, 319–331.

Carlsson, H., Nilsson, U., Stman, C., 2000. Video display units: an emission source of the contact allergenic flame retardant triphenyl phosphate in the indoor environment. Environ. Sci. Technol. 34, 3885–3889.

Cheong, K.W.D., Lau, H.Y.T., 2003. Development and application of an indoor air quality audit to an air-conditioned tertiary institutional building in the tropics. Build. Environ. 38, 605–616.

Daisey, J.M., Angell, W.J., Apte, M.G., 2003. Indoor air quality, ventilation and health symptoms in schools: an analysis of existing information. Indoor Air 13, 53–64.

DiBerardinis, L., Greenley, P., Labosky, M., 2009. Laboratory air change: what is all the hot air about? J. Chem. Health Saf. 16 (5), 7–13.

Farhad, M., 2009. Effect of reducing ventilation rate on indoor air quality and energy cost in laboratories. J. Chem. Health Saf. 16 (5), 20–26.

Hu, H.P., Zhang, Y.P., Wang, X.K., Little, J.C., 2007. An analytical mass transfer model for predicting VOC emissions from multi-layered building materials with convective surfaces on both sides. Int. J. Heat Mass Transfer 50 (11–12), 2069–2077.

Huizenga, Abbaszadeh, Zagreus, Arens, 2006. Air quality and Thermal comfort in office buildings: results of a large indoor environmental quality survey. In: Proceeding of Healthy Building, vol. 3, pp. 393–397.

Industry Code of Practice on Indoor Air Quality 2010, Department of Occupational Safety and Health Malaysia, ISBN: 983-2014-51-4.

Irtishad, 2001. Effectiveness of HVAC duct cleaning procedures in improving indoor air quality. Environ. Monit. Assess. 72, 265–276.

Ismail, A.R., Singh, S., Goh, C.N., 2010. Thermal comfort in a closed air conditional ICT laboratory at Ungku Omar Polytechnic Malaysia. In: National Conference in Mechanical Engineering Research and Postgraduate Students (1st NCMER 2010), 26–27 May 2010, FKM Conference Hall, UMP, Kuantan, Pahang, Malaysia, pp. 555–563.

Japan Society for Occupational Health, 2004. Recommendation of occupational exposure limits, 2004–2005. J. Occup. Health 46, 329–344.

Lee, S.C., Chang, M., 1999. Indoor air quality investigations at five classrooms. Indoor Air 9, 134–138.

Ng, Lisa C., Amy Musser, Persily, Andrew K., Emmeric, Steven J., 2012. Indoor air quality analyses of commercial reference buildings. Build. Environ. 58, 179–187.

Makowski, M., Ohlmeyer, M., 2006. Comparison of a small and a large environmental test chamber for measuring VOC emissions from OSB made of Scots pine (*Pinus sylvestris* L.). Holz Roh-Werkst 64 (6), 469–472.

Nabinger, S.J., Persily, A.K., Dols, W.S., 1994. A study of ventilation and carbon dioxide in an office building. ASHRAE Trans. 100 (2), 1264–1273.

Prill R., 2000. Why Measure Carbon Dioxide Inside Buildings? Washington State University Extension Energy Program, WSU-EEP07-003, pp. 1–3.

Rackes, A., Waring, M.S., 2014. Using multiobjective optimizations to discover dynamic building ventilation strategies that can improve indoor air quality and reduce energy use. Energy Building 75, 272–280.

Report, 1990. Global Environment Monitoring System. Air Quality in Selected Urban areas. WHO offset Publication, Geneva.

Righi, E., Aggazzotti, G., Fantuzzi, G., Ciccarese, V., Predieri, G., 2002. Air quality and well-being perception in subjects attending university libraries in Modena (Italy). Sci. Total Environ. 286 (1–3), 41–50.

Samet, J.M. 1993. Indoor air pollution: a public health perspective. In: Proceedings of the 6th International Conference on Indoor Air Quality. Helsink: International Conference of Indoor Air Quality 1. pp. 3–12.

Seppanen, O.A., Fisk, W.J., 2004. Summary of human responses to ventilation. Indoor Air 14, 102–118.

Seppanen, O.A., Fisk, W.J., Mendell, M.J., 1999. Association of ventilation rates and CO_2 concentrations with health and other responses in commercial and institutional buildings. Indoor Air 9, 226–252.

Singhvi, R., Turpin, R., Kalnicky, D.J., Patel, J., 2001. Comparison of field and laboratory methods for monitoring metallic mercury vapor in indoor air. J. Hazard. Mater. 83, 1–10.

Siskos, P.A., Bouba, K.E., Stroubou, A.P., 2001. Determination of selected pollutants and measurement of physical parameters for the evaluation of indoor air quality in school building in Athens, Greece. Indoor Built Environ. 10 (3–4), 185–192.

Sulaiman, Z., Mohamed, M., 2011. Indoor air quality and sick building syndrome study at two selected libraries in Johor Bharu, Malaysia. Environ. Asia 4 (1), 67–74.

Watson A.F.R. 2013. Indoor Air Quality in Industrial Nations, Reference Module in Earth Systems and Environmental Sciences.

Xu, Y., Little, J.C., 2006. Predicting emissions of SVOCs from polymeric materials and their interaction with airbone particles. Environ. Sci. Technol. 40, 456–461.

Xu, Y., Zhang, Y.P., 2004. A general model for analyzing single surface VOC emission characteristics from building materials and its application. Atmos. Environ. 38 (1), 113–119.

Yau, Y.H., Chew, B.T., Saifullah, A.Z.A., 2012. Studies on the indoor air quality of Pharmaceutical Laboratories in Malaysia. Int. J. Sustainable Built Environ. 1 (1), 110–124.

Yrieix, C., Dulaurent, A., Laffargue, C., Maupetit, F., Pacary, T., Uhde, E., 2010. Characterization of VOC and formaldehyde emissions from a wood based panel: results from an inter-laboratory comparison. Chemosphere 79 (4), 414–419.

Zain Ahmed, A., Abdul Rahman, S. & Sharani, S., 2004. CO and CO_2 concentrations in naturally ventilated houses in Malaysia. In: The 21st Conference on Passive and Low Energy Architecture, 19–22 September 2004, Netherlands.