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Specific Indoor Environmental Quality Parameters in College Computer Classrooms

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ABSTRACT: The indoor environmental quality parameters, including temperature, relative humidity, air velocity, particulate matter concentration, illumination level, sound level, carbon dioxide concentration and ventilation rate in two computer classrooms and one general classroom were evaluated. Analytical results reveal average carbon dioxide concentration in the three classrooms during daytime classes was 785"1681 ppm. These values exceeded the exposure limits for indoor air quality suggested by the Environmental Protection Administration of the Republic of China, Taiwan (ROCEPA). The particulate matter concentration in the general classroom was 0.087 mg/m^3, which exceeded the indoor air quality exposure limit for Type-1 venues recommended by the ROCEPA. Illumination level in the two computer classrooms was 386 and 176 Lux; these values are far lower than the illumination level for school classrooms suggested by Ministry of Education, Taiwan. Indoor sound levels in the three classrooms during non-class (51.4"61.9 dB(A) and class times (61.0"73.6 dBA exceeded the limit recommended by the Ministry of Education, Japan. The ventilation rates for the three classrooms were 0.41"0.65 h^{-1}; such low ventilation rates were likely responsible for the very high indoor carbon dioxide concentrations in the three classrooms during class periods. These analytical results indicate schools should examine the efficacy of air-conditioning equipment in classrooms, particularly computer classrooms. Schools should also pay attention to ventilation rates and sound levels. Due to the poor ventilation rates in computer classrooms, this study suggests that problems arisen from the accumulation of specific toxicants dispersed by computer equipment, such as polybrominated diphenyl ethers, need further investigations.

Key words: Indoor environmental quality, Ventilation rate, Indoor air quality

INTRODUCTION

Indoor air pollution has become a worldwide public health issue in the last few decades. Some studies have investigated indoor air quality (IAQ) in residences, offices, schools, shopping malls, restaurants, temples, and other indoor environments. Their analytical results showed that inadequate ventilation results in elevated total bacteria counts, carbon dioxide (CO_2) concentrations (>1000 ppm) and indoor particulate matter (PM_{10}) concentrations exceeding those outdoors (Lee, *et al.*, 2002a; Lee, *et al.*, 2002b; Lee, *et al.*, 2001; Li, *et al.*, 2001). Indoor building materials, smoking, and interior construction increase formaldehyde concentrations (Lee, *et al.*, 2002a; Wu, *et al.*, 2003). Interior decorations, smoking, and the use of industrial solvents result

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in highly concentrated volatile organic compounds (VOCs) (Lee, *et al.*, 2002a; Lee, *et al.*, 2002b).

Total polycyclic aromatic hydrocarbons (PAHs) concentrations in temples have been measured at more than 10 times higher than those in the atmosphere, and similar to PAH concentrations at street intersections (Lin, *et al.*, 2002). In recent years, the issue of indoor environmental quality (IEQ) for schools and educational institutions has been widely discussed (Chiang, *et al.*, 2001; Corgnati, *et al.*, 2007; Grimsrud, *et al.*, 2006; Shendell, *et al.*, 2004a; Shendell, *et al.*, 2004c; Tortolero, *et al.*, 2002; van Dijken, *et al.*, 2006; Zhang, *et al.*, 2006).

The three main IAQ issues for schools are as follows: 1) the exchange rate for fresh outdoor air is insufficient; 2) the indoor relative humidity (RH) is not 30"60%; and, 3) facilities are not equipped with efficient filters (Bayer, 2001). Many studies have applied the guidelines of the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) to determine whether there a facility has an adequate air exchange rate; the indoor CO_2 concentration must be <1000 ppm (Tucker, 1992). However, a study by Shendell et al. (2004b) targeted 22 American public schools and determined that 45% of classrooms studied had short-term indoor CO_2 concentrations >1000 ppm. That study also observed that when a classroom CO_2 concentration was 1000 ppm higher than that outdoors, student annual average daily attendance (ADA) was reduced by 0.5–0.9%. Wargocki and Wyon (2007a) noted that when classroom temperature decreased from 25°C to 20°C, student performance on two numerical and two language-based tests was significantly improved for students aged 10–20. Furthermore, when the outdoor air supply rate was increased from 5.2 to 9.6 L/s per person, student performance on four numerical exercises improved significantly. The students perceived classroom air as fresh when the outdoor air supply rate was increased; the average CO_2 levels declined from 1300 to 900 ppm (Wargocki and Wyon, 2007b). In addition to an inadequate air exchange rate (AER), inadequate humidity levels and inefficient filters increased the concentrations of microorganisms and allergens, and resulted in elevated particulate concentrations. Daisey *et al.* (2003) reported that in Europe and North America, many classrooms were inadequately ventilated, and levels of specific allergens in dust were high enough to cause allergic symptoms in atopic occupants. Ligman (1999) also pointed out that PM_{10} and $PM_{2.5}$ concentrations in American classrooms were higher than those in offices, and indoor particulate concentrations were higher than those outdoors. Although many studies analyzed different indoor locations, indoor environments, and indoor exposure sources (chemical or physical), as well as the IEQ control strategies, few studies have assessed the IEQ of school classrooms such as computer classrooms. Computer classrooms are typically closed indoor spaces with doors and windows are generally closed when the room is in use. Therefore, IEQ issues common in offices would apply to computer classrooms. However, in addition to an indoor location with multiple pollutants, a computer classroom also has a specific source of pollution, i.e. computer-related equipment. The polybrominated diphenyl ethers (PBDEs) dispersed by computer equipment or when mixed with other pollutants can harm student health (Birnbaum and Staskal, 2004). Notably, students use computer classrooms when learning computer skills-related skills and in many courses. The time spent in the computer classroom is typically longer than ever before, especially for students studying information-related courses in vocational schools. Therefore, assessing the potential effects associated with the environment in computer classrooms on student health is important.

This study was planned just prior to Dec. 30, 2005, when the Environmental Protection Administration of the Republic of China, Taiwan (ROCEPA), announced its IAQ recommendations (ROCEPA, 2005). This study received a grant from the National Science Council of the Republic of China, Taiwan, and began experiments on Aug. 1, 2006. The exposure characteristics of PBDEs inside and outside computer classrooms and the IEQ of classrooms were monitored using small samples. The primary study aims were to determine student exposure to pollutants in computer classrooms and identify the main factors that can improve the IEQ of computer classrooms. Study results can serve as a reference for improving the quality and safety of indoor learning environments. This study was only concerned with specific IEQ parametersÿtemperature, RH, air velocity, PM_{10} concentration, illumination level, sound level, CO_2 concentration and ventilation rate. The exposure characteristics of PBDEs in computer rooms are discussed in another study.

MATERIALS & METHODS

This study investigated specific IEQ parameters in two computer classrooms (THA and THB) and one general classroom (TH0) in a southern Taiwan college. Table 1 shows comparisons of environmental characteristics and factors affecting IEQ for the three classrooms.This study utilized an indoor pollution evaluation system (Model IES-2000; SIBATA Scientific Technology Ltd., Japan) to measure and record temperature, RH, air velocity, illumination level, sound level, PM_{10} and CO_2 concentrations in the three classrooms. Six samplers with Teflon tubes were distributed throughout the classrooms for concurrent multiple sampling. The height of the sampling tube was 1.2"1.5 m, which is near the human breathing zone. Exposure concentrations are averaged levels from the six samplers distributed in each room.

This study used two methods to assess ventilation rate. First, ventilation rate was measured using a tracer-gas-concentration decay method. An appropriate amount of sulfur hexafluoride (SF_6) gas was injected into the classroom and measured by a computer-controlled multi-gas continuous monitor (Brüel and Kjær 1302e, Naerum, Denmark) (Wu, *et al.*, 2003). The second method (Waring and Siegel, 2007), estimated the ventilation rate for each classroom using the following mass balance equation for CO_2, which assumes a well-mixed space in which the only source of indoor CO_2 was ambient outdoor levels and occupants:
where V is classroom interior volume (m^3), Q is ventilation flow rate (m^3/h), Co and Ci are outdoor and indoor concentrations of CO_2 (mg/m^3), respectively, and E is CO_2 emission rate (mg/h), which is comprised of CO_2 emissions from occupants. Equation (1) was divided by volume,

$$V\frac{dCi}{dt} = QCo - QCi + E \quad (1)$$

V, which we assumed was steady and rearranged to yield the following equation for estimating ventilation rate with a number of air changes per hour (ACH), λ (h^{-1}):

We assume typical human breathing rate is 0.78 m^3/h and 4% of exhaled air is CO_2; thus, a typical human emits 51.9 g CO_2/h. Given the assumptions inherent in Eq. (2), particularly those of complete mixing and steady-state conditions, the λ should be regarded as an approximate estimate of ventilation rate.

Table 1. Classroom data for classes, including interior volume, mean number of occupants, air-conditioner type, number of computers, monitor type, lighting system, and allocation of computers

Classroom	Interior volume (m^3)	Occupants (no.)	Air-conditioner type	Computers (no.)	Monitor type	Lighting system	Allocation of computers
TH0	296	22	window-type	0	None	hanged type T8-fluorescent lamps	without any computers
THA	384	20	water-cooled package/stand-alone ?cycling system?	61	liquid crystal displays (LCD)	T-bar hanging system with mineral-fiber board T8-fluorescent lamps	align with lighting system and the path
THB	595	36	window-type	59	cathode ray tube (CRT)	hanged type T8-fluorescent lamps	align with the path lighting system against the row direction

$$\lambda = \frac{E}{V(Ci - Co)} \qquad (2)$$

Automatic continuous monitoring of each classroom was conducted with and without occupants in the room. Monitoring with occupants present occurred during classes, held approximately from 9:00 am to 5:00 pm. Variation in the number of occupants in a room was minimized. Monitoring without occupants present was performed from 9:00 am to 8:00 am the following day.

Descriptive statistics were calculated for all three classrooms. For each instrument within each site, the minimum, maximum, mean, and standard deviation of temperature, RH, air velocity, PM_{10} concentration, illumination level and sound level were calculated separately. Mann-Whitney nonparametric tests were applied to determine whether temperature, RH, air velocity, PM_{10} concentration, illumination level and sound level measured during classes differed from those measured for empty classrooms.

The nonparametric method was employed to avoid assumptions about the distributions of measured concentrations. One-way analysis of variance (ANOVA) was used to test the hypothesis that no differences in CO_2 concentration exist among study classrooms, including empty and populated classrooms. A value of $p<0.05$ (two-tailed) was considered statistically significant.

RESULTS & DISCUSSION

Table 2 lists the monitoring results for IEQ items in the general (TH0) and computer classrooms (THA and THB), and reference standards including measurements of temperature, RH, air velocity, PM_{10} concentration, and illumination and sound levels. The measured carbon monoxide values were not listed as values were lower than instrument detection limits. Measured values for the general classroom TH0 during non-class periods were as follows: temperature, 25.6"27.1^{o}C; RH, 31.1"37.3%; air velocity, 0"0.240 m/s; PM_{10} concentration, 0.043"0.089 mg/m^3; illumination level, 470"580 Lux; and, sound level, 40.0"72.8 dB(A). Measured values for the general classroom TH0 during class periods were as follows: temperature, 28.1"30.2^{o}C; RH, 42.5"51.5%; air velocity, 0"0.240 m/s; PM_{10} concentration, 0.001"0.113 mg/m^3; illumination level, 460"570 Lux; and, sound level, 40.0"94.2 dB(A). The THA computer classroom values during non-class periods were as follows: temperature, 25.0"25.5^{o}C; RH, 57.5"70.5%; air velocity, 0.160"0.270 m/s; PM_{10} concentration, 0"0.004 mg/m^3; illumination level, 340"370 Lux; and, sound level, 50.3"53.9 dB(A). The THA computer classroom values during class periods were as follows: temperature, 20.7"23.7^{o}C; RH, 51.3"74.7%; air velocity, 0.110"0.250 m/s; PM_{10} concentration, 0"0.003 mg/m^3; illumination level, 350"400 Lux; and, sound level, 52.1"74.1 dB(A). The THB computer classroom values during non-class periods were as follows: temperature, 24.8"25.6^{o}C; RH, 31.4"49.7%; air velocity, 0.120"0.340 m/s; PM_{10} concentration, 0"0.019 mg/m^3; illumination level, 190"210 Lux; and, sound level, 60.2"70.6 dB(A). The THB computer classroom values during class periods were as follows: temperature, 25.5"28.6^{o}C; RH, 34.7"43.3%; air velocity, 0.050"0.430 m/s; PM_{10} concentration, 0"0.011 mg/m^3; illumination level, 150"190 Lux; and, sound level, 61.9"79.9 dB(A). Comparisons of IEQ item between class and non-class periods reveals significant differences in all parameters ($p<0.05$), except for RH of the THB classroom ($p=0.163$). During class periods, average temperature (29.3^{o}C) of the TH0 general classroom and the RH (37.9%) of the THB computer classroom did not meet ASHRAE standards. Average PM_{10} concentration (0.087 mg/m^3) of the TH0 general classroom during class did not meet the Type-1 suggested IAQ values of the ROCEPA. Average illumination values of computer classrooms THA (386 Lux) and THB (176 Lux) during class did not meet Ministry of Education, Taiwan, standards. However, indoor air velocities in the three classrooms during non-class and class periods met the Indoor Environmental Institute (IEI) standards, and indoor sound levels exceeded Ministry of Education, Japan, standards (no sound level standards for classrooms in Taiwan).

Fig. 1 presents comparisons of mean indoor CO_2 concentrations in all three classrooms during daytime class periods, daytime non-class periods, and nighttime non-class periods. Measurement

Table 2. Measurement results and reference standards for temperature, RH, air velocity, PM_{10} concentration, illumination level and sound level in the study classrooms during non-class and class periods

Classroom		Temperature (^oC)		RH (%)		Air velocity (m/s)		PM_{10} (mg/m^3)		Illumination (Lux)		Sounds (dB(A))	
		Non-class	Class	Non-class	Class	Non-class	Class	Non-class	Class	Non-class	Class	Non-class	Class
TH0	mean	26.6	29.3	33.8	45.6	0.048	0.088	0.063	0.087	550	531	54.0	73.6
(16 - 28 occupants)	SD	0.4	0.5	1.4	2.4	0.041	0.062	0.013	0.010	25	17	9.9	8.4
	Max	27.1	30.2	37.3	51.5	0.240	0.240	0.089	0.113	580	570	72.8	94.2
	Min	25.6	28.1	31.1	42.5	0.000	0.000	0.043	0.001	470	460	40.0	40.0
THA	mean	25.3	23.0	64.9	65.8	0.206	0.184	0.001	0.000	360	386	51.4	61.0
(17- 23 occupants)	SD	0.1	0.8	4.0	4.8	0.022	0.033	0.001	0.000	3	8	0.6	4.5
	Max	25.5	23.7	70.5	74.7	0.270	0.250	0.004	0.003	370	400	53.9	74.1
	Min	25.0	20.7	57.5	51.3	0.160	0.110	0.000	0.000	340	350	50.3	52.1
THB	mean	25.2	27.0	36.3	37.9	0.239	0.314	0.005	0.001	201	176	61.9	70.5
(32 - 40 occupants)	SD	0.2	0.9	3.7	2.4	0.046	0.082	0.005	0.001	4	6	2.4	4.8
	Max	25.6	28.6	49.7	43.3	0.340	0.430	0.019	0.011	210	190	70.6	79.9
	Min	24.8	25.5	31.4	34.7	0.120	0.050	0.000	0.000	190	150	60.2	61.9
Reference standards		22 - 27[a]		40 - 70[a]		<=0.35[b]		0.06[c], 0.15[d]		>=500[e]		50 (windows closed[f])	

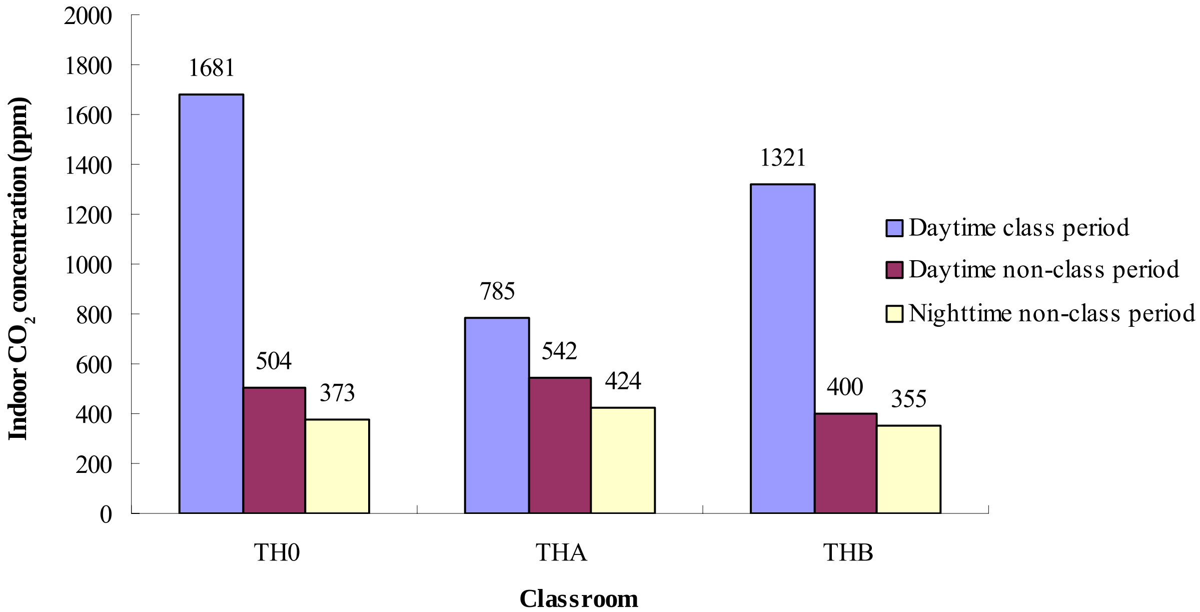

Fig. 1. Arithmetic means of indoor CO_2 concentrations according to classroom category and classes. For each classroom, the difference in indoor CO_2 concentrations according to classes was statistically significant (one-way ANOVA) (*p*<0. 001)

results demonstrate that average indoor CO_2 concentrations in each classroom with three different uses were significantly different ($p<0.05$). The CO_2 concentrations ranked from highest to lowest occurred during daytime class periods, daytime non-class periods, and nighttime non-class periods.

Table 3 lists indoor and outdoor CO_2 concentrations of all classrooms during class periods, estimated ventilation rates used in this study, and values suggested by the ROCEPA. The average CO_2 concentrations in all classrooms (TH0, 1681 ppm; THA, 785 ppm; THB, 1321 ppm) exceeded recommended exposure limits of Type-1 IAQ standards (600 ppm) recommended by the ROCEPA during daytime classes. Average CO_2 concentrations in the TH0 and THB classrooms (both with relatively poor ventilation rates) were significantly higher than recommended exposure limits of Type-2 IAQ standards (1000 ppm) suggested by the ROCEPA. Furthermore, the TH0 (1.59 h^{-1}), THA (3.93 h^{-1}), and THB (2.12 h^{-1}) ventilation rates (based on CO_2 mass balance) were 3"5 times higher than ventilation rates estimated using the tracer-gas-concentration decay method. These differences resulted from non-steady-state conditions in the three classrooms when the CO_2 mass balance was used.

Analytical results reveal that for both the general and computer classrooms, several IEQ indicators during daytime class did not meet the relevant standards or recommended values (Tables 2 and 3). Temperatures and PM_{10} concentrations were excessively high in the TH0 classroom, RH

Table 3. The indoor and outdoor CO_2 concentrations for the three classrooms during class periods, and estimated ventilation rates and standards suggested by the ROCEPA

Classroom	Indoor CO_2 conc. (ppm)	Outdoor CO_2 conc. (ppm)	Suggested value of the ROCEPA (ppm)	Ventilation rate (h^{-1})	
				CO_2	SF_6
TH0	1681	329	Type I[a]: 600	1.59	0.41
THA	785	402	Type II[b]: 1000	3.93	0.65
THB	1321	496		2.12	0.54

and illumination level were too low in the THB classroom, and illumination level was too low in the THA classroom. The CO_2 concentrations were excessively high in all three classrooms. Moreover, classroom sound levels did not meet the standards of the Ministry of Education, Japan, regardless of whether sound levels were measured during class or non-class periods. The IEQs of classrooms in this study can adversely affect student health and learning performance. Two explanations for experimental results are as follows. First, the low level of illumination in computer classrooms resulted from old and unclean lamps and lanterns with poor collocation. Second, poor IEQ was generally associated with air-conditioning methods, types, and efficacies; for instance, the elevated temperatures in the TH0 general classroom were due to power-saving devices that automatically inactivated air-conditioners several times during the class period; the low RH in the THB computer classroom was secondary to the low re-supply air rate. Indoor sound levels in the three classrooms were too large and resulted from poor air-conditioner operation and noiseful echoing in classrooms. The low ventilation rate of the air-conditioning system was the principal reason for the elevated indoor CO_2 concentrations in classrooms, as evidenced by elevated indoor CO_2 concentrations during daytime class periods and both non-class day and night periods (Fig. 1), which were consistently higher than the recommended Type-1 IAQ exposure limits and ventilation rates for classrooms, which were within 0.65 h^{-1} based on the tracer-gas-concentration decay method (Table 3).

CONCLUSION

Energy efficiency and reducing carbon emissions have become global goals. Windows and doors should be closed when air-conditioning systems are in use during classes to save energy. Some schools have installed power-saving devices that automatically inactivate air-conditioners when the contracted instantaneous electricity consumption will be soon achieved. Although these methods reduce energy consumption, they may result in poor IAQ, which can adversely affect health and learning of both teachers and students. Experimental results suggest that schools should assess the functioning of air-conditioning equipment in classrooms (particularly in computer classrooms), and should determine whether ventilation rates are sufficient and if sound levels are excessive. This study suggests three methods which can save energy, and improve IEQ in classrooms by improving illumination levels and reducing CO_2 concentrations. First, install canopies outside of classroom windows which have adjustable leaves to allow outdoor air and sunshine to enter classrooms. Second, adjust or replace loop power supplies that control which lines or rows of lamps to be turned on/off, as all lamps are occasionally not needed to be turned on for save-energy consideration. Third, rearrange or install lamps and lanterns in appropriate positions and directions. Finally, this study indicates that using carbon-dioxide mass balance to determine ventilation rates may result in errors when indoor CO_2 concentrations do not reach a steady-state condition.

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