Chapter 13
Urban Air Quality Management: Detecting and Improving Indoor Ambient Air Quality

T.L. Tan and Gissella B. Lebron

Abstract Current air pollution management and air quality control are primarily focused on outdoor and atmospheric issues. In major cities today with large numbers of shopping malls, offices and public administration centers which act as public spaces, contaminated indoor air could be public health hazards. In Singapore, diagnosing the causes of "sick building syndrome" is as important as treating outdoor pollution as its workforce is increasingly service-oriented and many of whom spend a substantial amount of time working in air-conditioned premises. It is known that indoor air quality (IAQ) can be easily and adversely affected by gas pollutants which are internally generated or infiltrated from external sources. One important and practical example is carbon monoxide (CO) which can be emitted at high concentration levels in an urban structure by burning of tobacco and incense, and by incomplete combustion from gas stoves and fuel engines used in renovation work. In this research, the decay rates of CO concentration (ppm) in air were measured accurately using the Fourier transform infrared spectroscopy in the 2,050–2,230 cm^{-1} wavenumber region. High levels of CO were obtained from sidestream environmental tobacco smoke (ETS). From the modeling of the decay curves of CO concentration with time, the air exchange rates in air change per hour (ACH) were derived for six different ventilation rates. They were found to be from 2.53 to 8.63 ACH. The ventilation rates for CO contained in a chamber were varied using different window areas. Half-lives of the CO decays at six different air exchange rates were also determined and found to decrease from 16.4 to 4.8 min as the air exchange rate increases. The implications of air exchange rate on the decay of indoor CO in ETS were discussed with reference to IAQ in air-conditioned buildings in Singapore, and to IAQ in general urban settings.

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13.1 Introduction

It has been established recently that the design of a building is becoming more important and crucial to the maintenance of good indoor air quality. In buildings where offices are used as air-conditioned workplaces, we are surrounded by artificial lighting, synthetic carpeting, furniture treated with chemicals, and high-tech equipment which can present various types of air quality problem. The World Health Organization has pinpointed that 30% of buildings in general are prone to sick building syndrome problems. Studies have shown that indoor air quality is influenced by two broad categories of building design: the "engineering" characteristics, and "quantitative" information on contamination levels in occupied buildings. The engineering characteristics refer to the information on air ventilation, infiltration standards, humidity, and levels of particles and pollutants in the building. The quantitative information on the building design includes the various monitoring devices and instruments used to measure all aspects of air quality within the building environment. The measurements are then compared to established and accepted standards. Therefore, it is important in the design of a modern building to include the engineering aspects of indoor air quality, and the quantitative information needed to maintain good indoor air.

Since the early 1970s, a considerable effort has been conducted by industrialized countries to measure the concentrations of air pollutants in the outdoor ambient air environment (Godish 2004, McDermott 2004, Yocom et al. 1971). In the United States, air monitoring became obligatory to determine the status of compliance with the National Ambient Air Quality Standards (NAAQs). These standards under the Clean Air Act (CAA) were set up by the US Environmental Protection Agency (U.S. EPA). The main objective of this Act is to improve ambient air quality by reducing emissions of pollutants which are detrimental to human health. The pollutants are listed in CAA as carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), ozone (O_3), particulate matters, hydrocarbons, and lead (Pb) (Brooks and Davis 1992, Yocom and McCarthy 1991). Results of the monitoring of the concentrations of pollutants in outdoor or ambient air over the past 20 years has shown that emission controls have been effective in improving outdoor air quality (Brooks and Davis 1992, Spengler and Soczek 1984). However, a corresponding improvement in the general public health has not been observed in some epidemiological studies (Apte et al. 2000, Fang et al. 2004, Liu et al. 2001, Ohman and Eberly 1998, Seppanen et al. 1999, Smith 2002). One possible reason is that with urbanization, more people spend most of their time indoors where air quality differs from that of outdoors. Indoor pollutants may differ in type and concentration from some outdoor pollutants. For example, concentrations of pollutants such as CO from both outdoor and indoor sources may be higher indoors than outdoors when indoor sources are present (El-Hougeiri and El-Fadel 2004).

It is recognized now that indoor exposure to air pollutants comprises a significant component of total exposure to air pollution. Yocom et al. (1971) in their study of indoor-outdoor air quality in the United States found that the concentrations of CO were higher indoors than that outdoors if gas stoves were used. Indoor-outdoor air quality relationships were further studied by Yocom (1982). El-Hougeiri and El-Fadel (2004) investigated indoor and outdoor air quality at 28 public locations (such as restaurants, recreation areas, sport centres, school classrooms, kitchens, hotels, swimming pools, and movie theatres) in urban areas with proximity to main roads. In their work, the concentrations of CO, NO_2, and total suspended particulate matter (PM) were measured and studied. It is necessary that data be obtained on indoor exposures to pollutants if there is serious concern about the effect of air pollutants on the health of the occupants. The main reason is that most people spend over 90% of their time indoors in developed countries (Burroughs and Hansen 2008). Problems associated with poor indoor air quality caused by excessive pollutants in buildings are generally referred to as the sick building syndrome (SBS). To reduce the adverse health effects of SBS, the use of adequate ventilation has been found to be effective (Lam et al. 2006, Melikov et al. 2005, Seppanen et al. 1999, 2006).

In the last 15 years, the importance of research on indoor air quality (IAQ) issues in Singapore has been manifested in several studies (Chan 1999, Chan et al. 1995, Ooi et al. 1995, Sekhar et al. 1995, 1999, Tham 1994, Tham et al. 1996). Findings from these studies have guided the setting up of local IAQ guidelines for office premises by the Ministry of the Environment in Singapore (1996). Furthermore, Sekhar et al. (2003) developed an integrated indoor air quality energy audit methodology for Singapore with a purpose of providing an integrated multi-disciplinary model in obtaining measured data concerning different dimensions within the built environment such as ventilation, biological, physical, chemical, and occupant response characteristics. Their research work on five air-conditioned office buildings has led to the development of an indoor pollutant standard index (IPSI), ventilation index, energy index, and building symptom index (BSI). It was found that BSI values have some correlation among them as well as with IAQ and thermal comfort acceptability while there was no significant correlation between BSI and IPSI.

Recently, numerous studies on IAQ have been made on carbon monoxide (CO) because of its severe impact on public health and work performance in urban settings (Godish 2004, Harrison 1998). Statutory safe levels are that the average CO concentration for 8 h exposure must be less than 8.6 ppm (10 $mg.m^{-3}$) and the average CO concentration for 1 h exposure must be less than 26 ppm (30 $mg.m^{-3}$), according to WHO standards (World Health Organization 1999) given in Table 13.1. Concentrations of CO have been measured and studied in indoor parking facilities in France (Glorennec et al. 2008), in Greece (Chaloulakou et al. 2002), in Lebanon (El-Fadel et al. 2001), and in Hong Kong (Wong et al. 2002). Evaluation of IAQ in 10 school buildings in the urban area with major traffic roads in Athens, Greece was made in 2001 (Siskos et al. 2001). In their studies, CO concentration in classrooms was found to be lower than the WHO (1999) standard of 10 mg m^{-3} (8-h average). Determination of CO levels in 384 coffee shops in Ankara, Turkey was also made in 2009 (Tekbas et al. 2009). They found that 34% of the coffee shops had CO levels above the threshold level of 8.6 ppm (8-h average).

Further research on IAQ with measurements on CO concentrations was conducted in air-conditioned buses (Chan 2005) and offices and shops (Liao et al. 1991) in Hong Kong, in heavy traffic streets and tunnel in Santiago, Chile (Rubio

Table 13.1 WHO guideline values for CO (1999)

Pollutant	Annual ambient air concentration (ppm)	Guideline value (ppm)	Exposure time	Toxic effects according to ambient CO concentrations
CO	0.43–6.0 ($0.5–7\ mg/m^3$)	87 ($100\ mg/m^3$) 52 ($60\ mg/m^3$) 26 ($30\ mg/m^3$) 8.6 ($10\ mg/m^3$)	15 min 30 min 1 h 8 h	35 ppm (8-h time-weighted average 200 ppm (maximum limit) 600 ppm (1-h exposure: headache, anxiety, irritability) 2,500 ppm (30-min exposure: loss of consciousness) 4,000 ppm (sudden death)

et al. 2010), in an air-conditioned building in New Delhi, India in 2002 (Prasad et al. 2002), in bathrooms using hot water boilers in Turkey (Tekbas et al. 2001), in indoor karting in Canada in 2005 (Levesques et al. 2005), in burning of joss sticks in London in 2005 (Croxford and Kynigou 2005), in cooking fuels in Pakistan in 2009 (Siddiqui et al. 2009), in commercial aircrafts (Lee et al. 1999), and in a bus terminal (El-Fadel and El-Hougeiri 2003). Emissions of CO from environmental tobacco smoke (ETS) in an indoor environment have serious effect on IAQ (Rickert et al. 1984, Sterling and Mueller 1988, Trout et al. 1998). In 2002, Dingle et al. studied the concentrations of pollutants including CO from ETS and ventilation in 20 social venues in Perth, Western Australia. Other studies on CO emissions from ETS include those of side-stream and second-hand smokes, conducted in 2010 (Daher et al. 2010) and of ETS in restaurants in Finland in 2000 (Hyvarinen et al. 2000).

To improve indoor air quality by reducing air pollutants such as CO in a building, the use of ventilation or air infiltration is the most suitable solution (Meckler 1996, Vitel 2001). Performance in office work was found to improve with higher ventilation rates in a 2006 study (Seppanen et al. 2006) and several sick building syndrome (SBS) symptoms were alleviated when the ventilation rate was increased in a 2004 study (Fang et al. 2004). Moreover, the purpose of ventilation for urban set-ups such as air-conditioned offices and lecture halls is to provide air of a level of quality that is perceived as acceptable (Fang et al. 1998). Since ventilation or air infiltration causes a stable gas at an elevated concentration in the building to be gradually removed from the building, the decay rate of the gas is usually used as a direct measurement technique for ventilation (Brooks and Davis 1992, Meckler 1996, Yocom and McCarthy 1991). The level of ventilation is usually measured in the form of air exchange rate with the unit of air change per hour (ACH). Tracer gases such as SF_6 and CO_2 are commonly used to study air exchange rate. Furthermore, measurements of the decay rate of a gas which is an indoor pollutant would provide useful information on the impact of ventilation on the IAQ of a building.

From a detailed literature review, studies on the impact of ventilation on indoor concentrations of a common pollutant, carbon monoxide (CO) appear to be quite limited. Possible sources of CO in a building can be environmental tobacco smoke

(ETS) from cigarettes, gas stoves and heaters, burning joss-sticks, or even leakage from nearby combustion engines of vehicles into the building (Yocom and McCarthy 1991). When a certain amount of CO is injected into a building whether from indoor or outdoor sources, it can be removed only by exchange with fresh CO-free air. Carbon monoxide is stable and often useful as an indoor tracer for air exchange determinations (Naeher et al. 2001, Yocom and McCarthy 1991). To understand the IAQ of a building, it would be advantageous to know how the concentration of CO changes with time for a certain ventilation or air exchange rate. In view of this, the decay rate of CO would provide information for the time needed for CO concentrations to reach safe levels for a given air exchange rate. Therefore, the objective of this study is to measure the decay of the concentrations of CO over time in an enclosed space with six different window sizes to allow six different values of air exchange rates for a given space. The air exchange rates in ACH would be derived by studying the exponential decay curves of CO concentrations. In this research, the CO concentrations at ppm level were measured using the Fourier transform infrared spectroscopy technique. The infrared technique for measuring the concentration of a gas in air is well established and is known to be sensitive, accurate and reliable (Hanst and Hanst 1994, Salau et al. 2009, Smith 1996).

13.2 Methodology

13.2.1 Experimental Method on CO Concentration Measurements

To contain the CO gas from side-stream environmental tobacco smoke, a chamber of 20 cm × 22 cm × 22 cm was constructed. It is made of transparent perspex, and airtight except for two small square open windows on opposite sides of the chamber to allow air infiltration. To allow the infrared beam to pass horizontally through the CO gas sample in the chamber, infrared windows (3-cm diameter) made of CaF_2 were placed at opposite sides of the chamber. A total of six open window sizes were used: 2×2 mm^2, 3×3 mm^2, 4×4 mm^2, 5×5 mm^2, 6×6 mm^2, and 7×7 mm^2. The air exchange rate is expected to increase as the window size increases. Side-stream tobacco smoke from a burning cigarette was injected into the chamber at the start of the experiment through the top cover of the chamber. The temperature of the smoke in the chamber was measured to be 25–27°C and its humidity was maintained at 62–65% during the experiments. These readings were measured using a humidity-temperature meter (model ETHG-912) from Oregon Scientific. The temperature of the ambient air in the room outside the chamber was 25–26°C while the humidity was 60–63%. The air in the chamber and outside it was under atmospheric pressure. A small fan placed at 2 m from one of the windows (inlet window) of the chamber provided a constant air draught of slightly higher pressure compared to that of the other window (outlet). The air speed at the inlet window was found to be less than about 1.5 m/s, using an air velocity meter (Thermo-Anemometer, AZ Instrument 8908). The use of fan was needed to activate a constant but low air infiltration rate into the chamber through the inlet window and out of the outlet window.

The chamber containing the smoke with CO is placed in the sample compartment of the infrared spectrometer. The infrared absorption spectra of the CO gas in the chamber were recorded using the Perkin-Elmer Fourier transform infrared (FTIR) spectrometer of model Spectrum 100 at a resolution of 0.5 cm^{-1} and in the 2,050–2,230 cm^{-1} wavenumber region. This infrared region contained the CO infrared signature (Smith 1996). A spectral run of 2 scans of total scanning time of about 60 s was sufficient in obtaining good signal-to-noise signal for each spectrum. The infrared absorption spectra of CO at different concentrations (ppm) are shown in Fig. 13.1. In the CO spectrum, there are 47 absorption peaks, and the absorbance A of the spectrum is determined by the total area under these peaks,

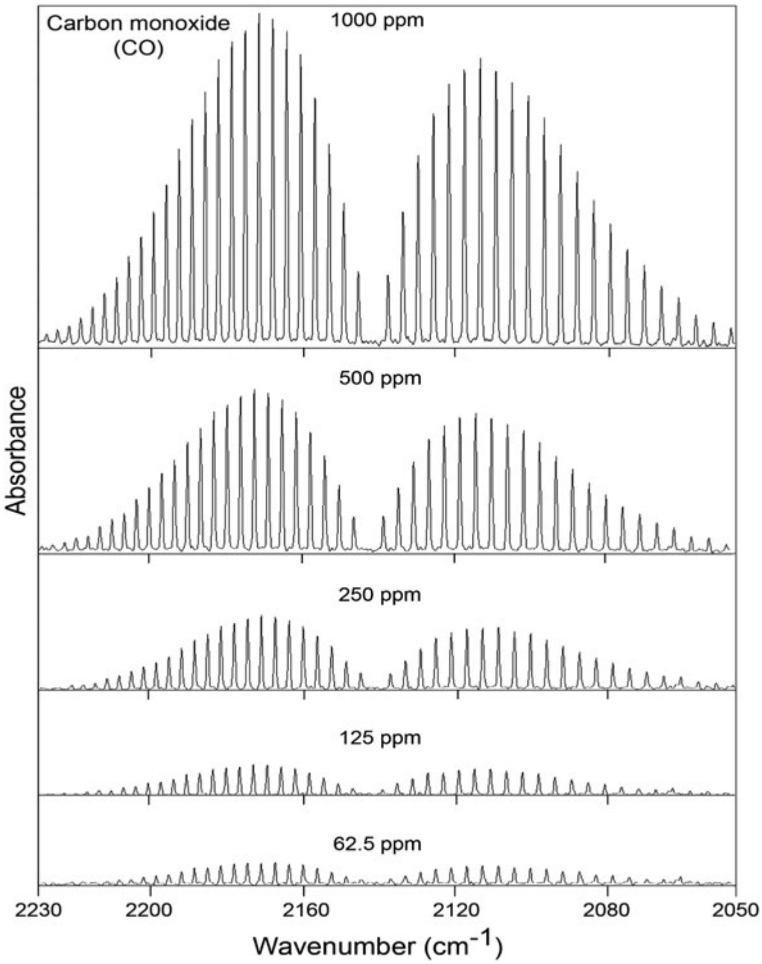

Fig. 13.1 The infrared spectra of CO in the 2,050–2,230 cm^{-1} region at different CO concentrations in ppm

using the SPECTRUM software in the infrared spectrometer. It is known that the absorbance value of the spectrum is directly proportional to the concentration of the absorbing gas (CO) in air (Smith 1996). As shown in Fig. 13.1, the intensities of the absorption peaks decrease (or the values of absorbance decrease) as the concentration of CO decreases from 1,000 to 62.5 ppm.

The CO infrared spectra were calibrated in terms of CO concentration in ppm using a Drager X-am 2000 digital detector meter which employs the electrochemical method. The detector has a range of 0–2,000 ppm with a measuring accuracy of less than 2%. Its reaction time is less than 6 s. The Drager meter was placed inside the gas chamber and CO reading (in ppm) was taken during the recording of the infrared absorption spectrum using the Perkin-Elmer spectrometer. The absorbance of the CO spectrum corresponding to the ppm concentration of CO was then measured. The calibration line of absorbance against CO concentration (ppm) from 0 to 1,700 ppm is plotted as shown in Fig. 13.2. The absorbance values ranged from 0 to about 2. The calibration line could be fitted well with the coefficient of determination $R^2 = 0.991$ or correlation coefficient $R = 0.995$. By using the calibration line, the CO concentrations in ppm could be determined from the absorbance values measured from the infrared spectra. The concentration of CO in ambient air in the room outside the gas chamber was 1–3 ppm.

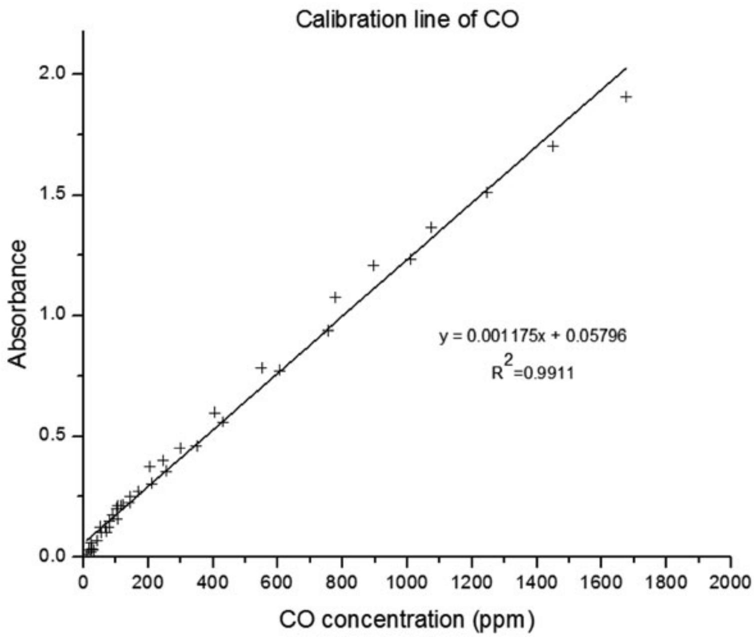

Fig. 13.2 The calibration line of concentration of CO measured in infrared absorbance and in ppm level

In the experiments, for each window size starting from $2 \times 2\ mm^2$, a fixed amount of side-stream environmental tobacco smoke containing CO at 1,000–1,800 ppm was initially injected into the chamber. High levels of CO were used in the experiments because at 600 ppm with 1 h exposure, headache, anxiety, and irritability set in, followed by loss of consciousness at 2,500 ppm (30-min exposure), and sudden death at 4,000 pm (see Table 13.1 for WHO guidelines). The CO gas was allowed to mix well with the air in the chamber for about 5 min. At time $t = 0$, the first infrared absorbance spectrum of CO was taken, and subsequently, the spectra were taken at time intervals of every 80 s. The recording of the spectra and their corresponding time continued until the CO concentration reached a level as low as 30 ppm. These experiments were repeated for 5 other bigger window sizes. From these measurements, the decay rate of CO due to air exchanges for 6 ventilation rates in the chamber can be studied.

13.3 Modelling of Gas Decay Rate

The American Society of Testing Materials (ASTM) standard method for determining air leakage rate by tracer dilution in Annual book of ASTM Standards (1983) describes the protocol for measuring the air exchange rate using the tracer gas decay or dilution method. The air exchange rate I is calculated using the following exponential decay equation (ASTM 1983):

$$C = C_0 e^{-It} \tag{13.1}$$

where C = tracer gas concentration at time t; C_0 = tracer gas concentration at time = 0; I = air exchange rate, and t = time.

This relationship assumes that the loss rate of the initial concentration of tracer gas is proportional to its concentration. By applying natural log on the equation, Eq. (13.1) becomes linear as follows:

$$\ln C = \ln C_0 - It \tag{13.2}$$

If time t is measured in hours (h), the air exchange rate I is expressed in air change per hour (ACH). Values of I can be obtained by plotting the best-fit graph of measured values of C against t or of $\ln C$ against t.

The time taken for the concentration of the gas to decay by half is called the half life T of decay, and it is useful to apply it to estimate the total time needed for the concentration to reach a safe and accepted level. The half-life T of the exponential decay can be calculated using:

$$T = \frac{\ln 2}{I} \tag{13.3}$$

13.4 Results and Discussion

The decay curve of CO concentration (ppm) with time (min) for a window of 2 × 2 mm^2 is shown in Fig. 13.3. The starting concentration of CO was about 1,350 ppm which is at a health hazard level (Table 13.1). It decays to a safe level at 35 ppm after about 80 min. The curve could be fitted accurately with an exponential function with $R^2 = 0.995$ to give an air exchange rate $I = 0.04211\ min^{-1}$ in good agreement with the trace gas modeling given by the exponential decay Eq. (13.1). The value of I is multipled by 60 to give 2.53 h^{-1} which is the value in air change per hour (ACH). The I value in ACH is given in Table 13.2. The plot of ln C against time (min) in Fig. 13.4 could be fitted accurately using a straight line which gives $I = 0.04542\ min^{-1}$ applying the natural log Eq. (13.2) with R^2 =0.974. The values of the air exchange rate I determined from the best-fits of exponential decay curve (Fig. 13.3) and of linear ln C-time graph (Fig. 13.4) are in close agreement (within 8%).

From the other experiments, the decay curves of CO for window sizes of 3 × 3 mm^2, 4 × 4 mm^2, 5 × 5 mm^2, 6 × 6 mm^2, and 7 × 7 mm^2 are shown in Figs. 13.5, 13.6, 13.7, 13.8 and 13.9, respectively. The starting CO concentrations for various window areas ranged from 1,000 to 1,800 ppm. From the exponential decay fits, the corresponding air exchange rates (I) in ACH were obtained as given in Table 13.2. It is found that as the window area increases from 4 to 49 mm^2, the air exchange

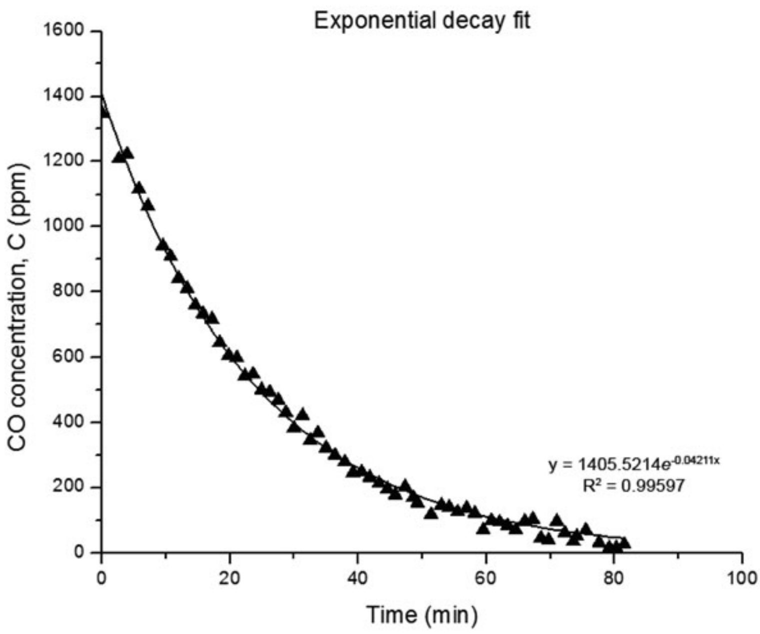

Fig. 13.3 CO decay curve for 2 × 2 mm^2 window

Table 13.2 Values of air exchange rate (ACH) and half-life T (min) obtained from CO decays for different window areas

Window area (mm^2)	Air exchange rate, I (ACH)	Half-life, T (min)
$2 \times 2 = 4$	2.53	16.4
$3 \times 3 = 9$	3.60	11.6
$4 \times 4 = 16$	4.16	10.0
$5 \times 5 = 25$	5.72	7.3
$6 \times 6 = 36$	6.64	6.3
$7 \times 7 = 49$	8.63	4.8

rate increases from 2.53 to 8.63 ACH. The values of half-life T calculated using Eq. (13.3) are also provided in Table 13.2. The value of T decreases from 16.4 to 4.8 min as the window area increases from 4 to 49 mm^2, showing that the decay rate increases as the ventilation rate increases. From the exponential decay curves, it can be observed that as the window area increases, the air exchange rate (I) increases, and therefore the time needed for CO to reach the safe exposure level at 52 ppm (30-min average exposure time) becomes shorter. Table 13.1 gives the CO guidelines for concentration values provided by WHO (1999) for health safety and toxic effect of CO.

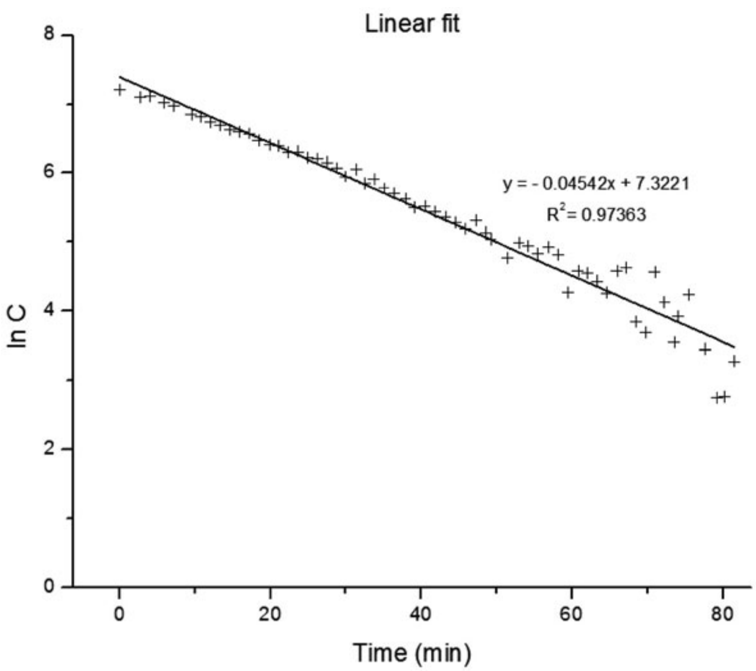

Fig. 13.4 Natural log graph of CO concentration, ln C against time for 2×2 mm^2 window

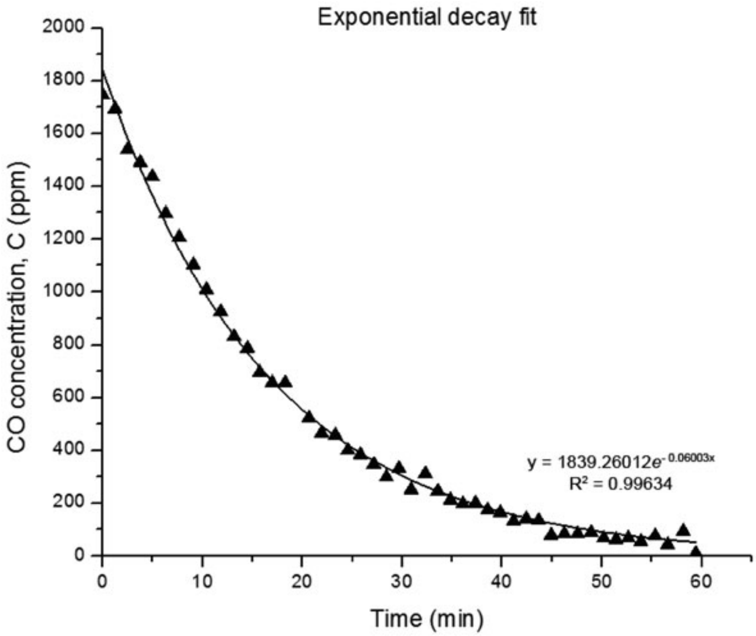

Fig. 13.5 CO decay curve for 3 × 3 mm^2 window

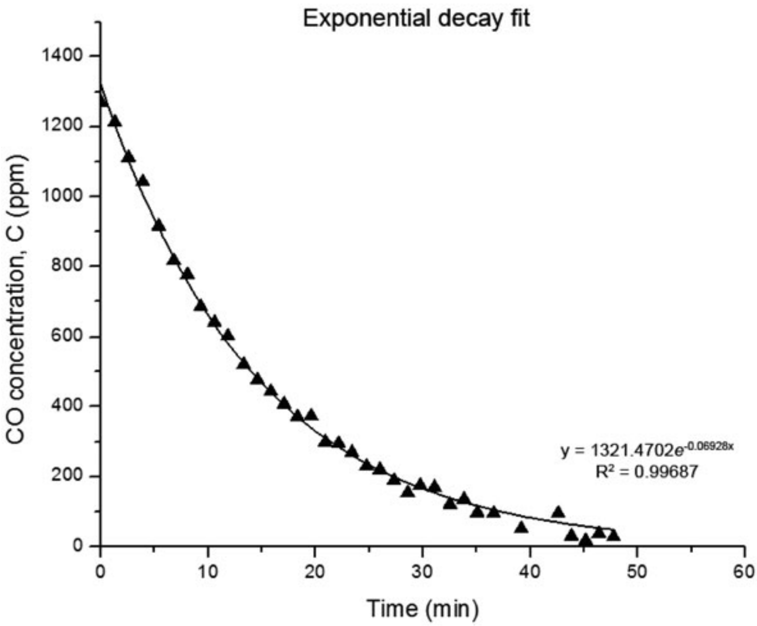

Fig. 13.6 CO decay curve for 4 × 4 mm^2 window

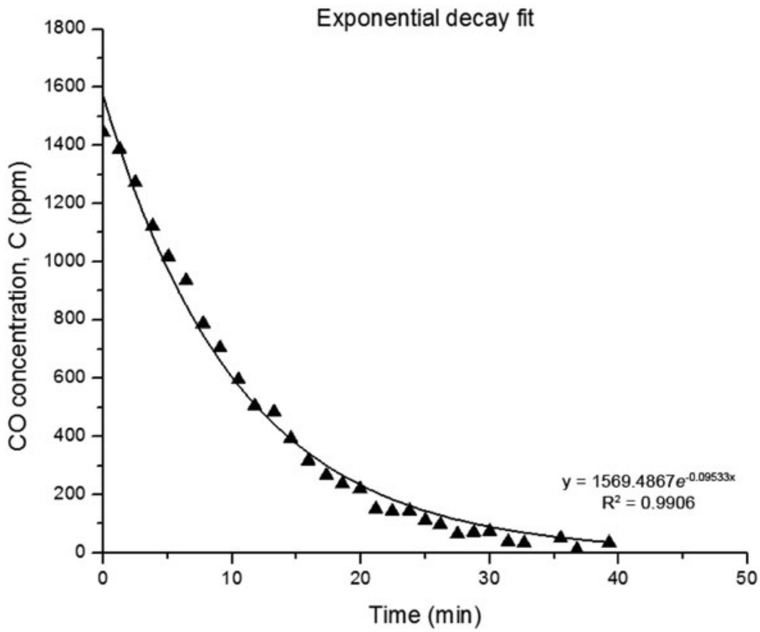

Fig. 13.7 CO decay curve for 5 × 5 mm^2 window

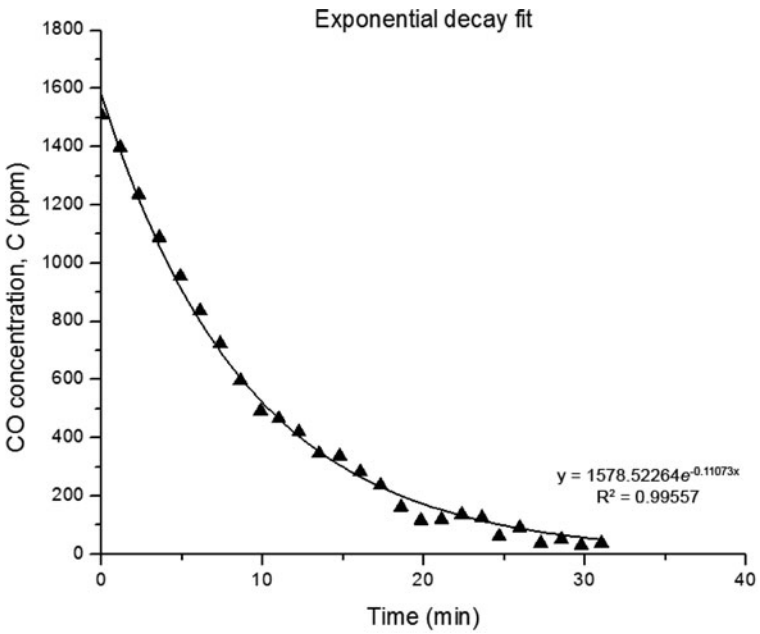

Fig. 13.8 CO decay curve for 6 × 6 mm^2 window

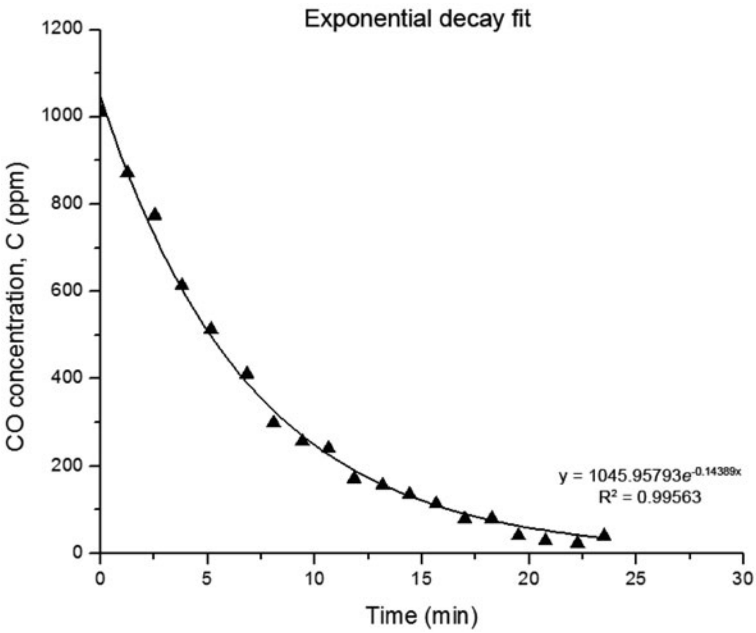

Fig. 13.9 CO decay curve for 7 × 7 mm^2 window

The application of the decay rate of gas concentration to measure the ventilation or air exchange rate has been well tested. For example, in an interesting study (Colls 2002), the particle concentration in a kitchen was artificially increased by burning some toast. Then the ventilation rate was set at a high constant level using an extractor fan, and the concentration of the particles was measured by an optical particle counter. The counter was able to measure particle size distributions as 1-min averages. It was found that the particle concentration increases to a sharp peak when the toast was burning. After the burning, the particle concentration was found to decay exponentially. The natural log fit of the concentration with time gave a straight line gave a gradient of 0.12 min^{-1} or 7 ACH. Using the values of floor area and volume, the deposition velocity for the particles was derived (Colls 2002). In another study (Naeher et al. 2001), CO was used as a tracer for assessing exposures to particulate matter in wood and gas cook stoves used in homes of highland Guatemala. The decay rates of high level of CO concentration produced by incomplete combustion were monitored so that exposure concentration and time to inhalable particles could be studied. In this work, we have used CO from side-stream environmental tobacco smoke (ETS) obtained from burning cigarettes of a popular brand. Therefore, the findings from the CO decay rates at various air exchange rates would be useful in assessing the exposures to the particulate matter and pollutants found in ETS. Recently, there has been an increased interest in understanding the serious health effects of ETS (Daher et al. 2010, Dingle et al. 2002, Hyvarinen et al. 2000, Rickert et al. 1984, Sterling and Mueller 1988, Trout et al. 1998). This is a useful application of this study, in addition to the assessment of IAQ with respect to CO concentrations in ambient air.

The graph of air exchange rate (I) in ACH against the window area (mm^2) using values from Table 13.2 is plotted as shown in Fig. 13.10. As shown, a proportional relationship is observed: as the window area increases, the air exchange rate increases almost linearly. Using values from Table 13.2, the graph of half-life *T* against the window area (mm^2) is plotted as shown in Fig. 13.11. As the window area increases, the air exchange rate increases resulting in a decreasing half-life or faster decay rate of CO. The trends observed in terms of the effect of window areas on the ventilation rate and decay rate of CO can be used for a better understanding of IAQ issues if CO is the main indoor pollutant.

In a study of five air-conditioned buildings in Singapore (Sekhar et al. 2003), the CO levels were found to be very low ranging from 0.2 to 2.64 ppm which are within the ambient air level allowed for CO by WHO (1999) and Ministry of the Environment, Singapore (1996), as given in Table 13.1. The air exchange rates for the five buildings ranged from 0.34 to 2.60 ACH. The findings that even at low air exchange rate (0.34–0.59 ACH) for one building, the CO concentration still remains low at 0.4–2.4 ppm showed that there were obviously no internal sources of CO such as from environmental tobacco smoke, and the infiltration of CO from external sources into the building was negligible. In their work (Sekhar et al. 2003),

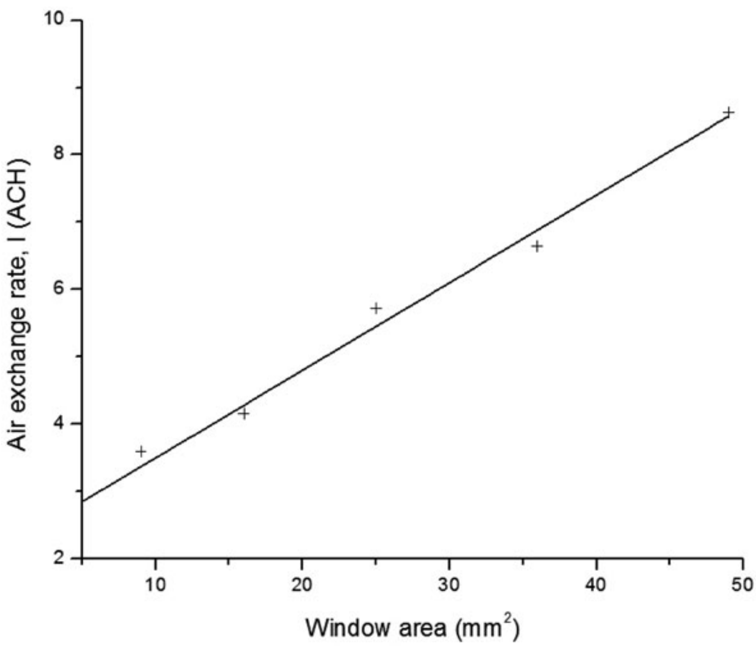

Fig. 13.10 The graph of air exchange rate (ACH) against window area (mm^2) for CO decays

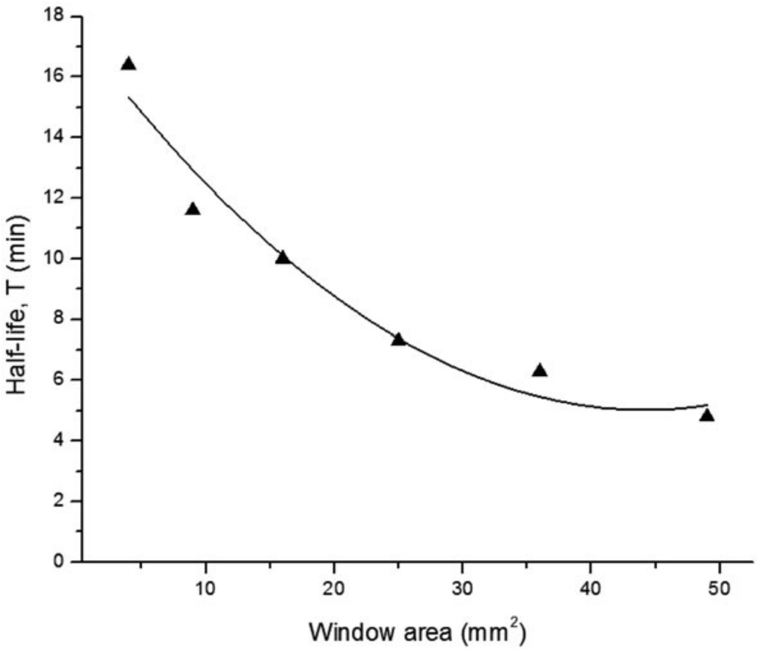

Fig. 13.11 The graph of half-life *T* (h) against window area (mm^2) for CO decays

the building with highest air exchange rate of 1.00–2.60 ACH was found to have the lowest maximum CO concentration of 1.23 ppm. This observation shows that higher air exchange rate reduces the concentration of CO even at very low levels in air-conditioned building. In agreement, the present results though at high levels of CO show that as air exchange rates increase, CO concentration decreases to a safe level in a shorter time. For example at air exchange rate of 2.53 ACH, the CO concentration level at a dangerous level of 1,400 ppm can be reduced to a safe level of 52 ppm (30-min exposure time) given in Table 13.2 within the time of 70 min, as shown in Fig. 13.3. The half-life of CO decay at 2.53 ACH was found to be 16.4 min, which is longer than 11.6 min at 3.60 ACH, as given in Table 13.2. From this work, it is found that as the air exchange rate increases, the half-life of CO decay decreases, showing that the CO concentration reaches a safe level in a shorter time (Table 13.2). The findings indicate that high air exchange rate not only keeps CO concentration at a low acceptable level, but also reduces elevated levels of CO in the building to safe levels, according to WHO guidelines (Table 13.1) in a shorter time.

From the results of this work, high ventilation rate (more than the usual 1 ACH) is needed to reduce the risk of CO toxic effect within the exposure of less than 1 h for high initial CO concentration (1,000–1,800 ppm). In a study (Tekbas et al. 2001), CO levels above 50 ppm (range of 54–300 ppm) were determined in 12 homes, out of 197 homes assessed, which used water boilers in the bathrooms running on liquid petroleum gas. Poor ventilation in these homes was observed. It was also mentioned that in a typical home air exchange rates would be expected to be near 1 ACH for the reduction of maximum CO concentration and also to increase decay rate for homes with internal sources of CO such as burning of joss or incense sticks (Croxford and Kynigou 2005). It was observed (El-Fadel et al. 2001) that the inadequacy of ventilation rates were often associated with high energy costs in an indoor environment, and the cost-benefit analysis was usually evaluated in terms of potential health impacts and decreased productivity. From practical observation (El-Fadel et al. 2001), typical ventilation rates of 5–10 ACH were commonly used to control IAQ if CO is selected as an indicator. These high rates are in good agreement with 2.53–8.63 ACH found in this work.

13.5 Conclusion

In managing urban air quality, the assessment of indoor air quality becomes a necessity as more people spend more time in an indoor environment. Since CO is an important indoor gas pollutant which can seriously affect IAQ, the decay rates of CO concentration for six different ventilation rates by using different window areas were measured and analyzed. Air exchange rates of 2.53–8.63 ACH and half-lives of 16.4–4.8 min were obtained from the decay of CO from ETS using high initial concentration of 1,000–1,800 ppm. The Fourier transform infrared technique was used to accurately measure the CO concentration in a gas chamber. The results would provide a better understanding of how the IAQ can be assessed if CO is of paramount concern.

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