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ชื่อโครงการ พลวัตของระดับความเข้มข้นของคาร์บอนไดออกไซด์: การตรวจวัด และการจำลองในห้องเรียนของมหาวิทยาลัย

ชื่อนิสิต นางสาวสุพิชญาย์ สุขประเสริฐ

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Dynamics of Carbon Dioxide Concentrations: Measurements and Simulation of a University Classroom

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Faculty of Science, Chulalongkorn University

Dynamics of Carbon Dioxide Concentrations:

Measurements and Simulation of a University Classroom

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บทคัดย่อ

ความเข้มข้นของก๊าซคาร์บอนไดออกไซด์ในห้องเรียนของโรงเรียนและมหาวิทยาลัยมีแนวโน้มสะสมตัวอยู่ในระดับที่สูง ซึ่งส่งผลต่อภาวะความสบายของมนุษย์ จึงมีการพัฒนาแบบจำลองที่สามารถจำลองพลวัตของระดับความเข้มข้นของก๊าซคาร์บอนไดออกไซด์เพื่อใช้ในการจัดการระดับความเข้มข้นดังกล่าวให้เหมาะสม ในงานวิจัยนี้ได้ทำการประเมินผลแบบจำลอง 2 แบบ ได้แก่ แบบจำลองของ Teleszewski & Gładyszewska-Fiedoruk และ CIBSE AM 10 ด้วยวิธีการแทนค่าตัวแปรแบบเรียลไทม์และแบบที่กำหนดไว้คงที่ โดยใช้ข้อมูลจากการตรวจวัดทุก ๆ 1 นาที ในห้องเรียนของตึกวิทยาศาสตร์ทั่วไป คณะวิทยาศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย โดยแบบจำลองที่มีประสิทธิภาพดีที่สุดจะถูกนำมาใช้จำลองเพื่อหาจำนวนผู้ใช้ห้องเรียนที่เหมาะสมในช่วงเวลาที่กำหนด จากผลการศึกษา พบว่า แบบจำลองของ Teleszewski & Gładyszewska-Fiedoruk และ CIBSE AM 10 มีประสิทธิภาพดีเมื่อแทนค่าตัวแปร แบบเรียลไทม์ (R^2 = 0.9965 ± 0.0028, 0.9912 ± 0.0072 ตามลำดับ) ในขณะที่การแทนค่าตัวแปรแบบที่กำหนดไว้คงที่มีประสิทธิภาพที่ต่ำมาก (R^2 = -2.7768 ± 5.2673, -20.9980 ± 22.4243 ตามลำดับ) อย่างไรก็ตาม การแทนค่าแบบเรียลไทม์นั้นมีข้อจำกัด เนื่องจากการตรวจวัดระดับความเข้มข้นของก๊าซคาร์บอนไดออกไซด์ทุก ๆ นาทีเป็นเรื่องที่ยุ่งยากในทางปฏิบัติ ดังนั้นการแทนค่าตัวแปรแบบที่กำหนดไว้คงที่ จะถูกนำมาใช้ในการจำลองร่วมกับแบบจำลองของ Teleszewski & Gładyszewska-Fiedoruk ซึ่งให้ประสิทธิภาพที่ดีกว่าแบบจำลองของ CIBSE AM 10 ในการแทนค่าตัวแปรทั้งสองแบบ โดยถูกนำมาปรับปรุงให้มีประสิทธิภาพดียิ่งขึ้นด้วยการวิเคราะห์ความคลาดเคลื่อนจากการจำลอซึ่งแบบจำลองที่ได้จากการปรับปรุงสามารถให้ประสิทธิภาพดีที่สุดที่ 60 นาที (R^2 = 0.7547 ± 0.1631) จากผลการจำลอง พบว่า หากไม่มีการระบายอากาศก่อนเริ่มเรียน ห้องเรียนจะสามารถรองรับผู้ใช้ห้องได้ไม่เกิน 18 คน สำหรับเมื่อมีการเรียนการสอนไปแล้ว 60 นาทีก่อนจะพักเบรก แต่จำนวนนี้สามารถเพิ่มขึ้นได้เมื่อมีการระบายอากาศก่อนใช้ห้องเรียน

คำสำคัญ: ความเข้มข้นของก๊าซคาร์บอนไดออกไซด์; การจำลอง; ห้องเรียน; จำนวนผู้ใช้ห้อง; การระบายอากาศ

Project Title Dynamics of Carbon Dioxide Concentrations: Measurements and Simulation of a University Classroom

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ABSTRACT

Indoor CO_2 concentrations in classrooms in a school or a university tend to be in a high range which affects student's cognitive performance. Several models for simulating the dynamics of CO_2 concentrations are developed to optimize the concentrations in the classroom. This study aimed to thoroughly evaluate two simplified modeling choices for numerical simulation of CO_2 concentrations in the classroom, including Teleszewski & Gładyszewska-Fiedoruk's model and CIBSE AM 10 model. In this study, the real-time input method and fixed input method were both evaluated using the measured data at one-minute intervals from the selected classroom in the General Science Building, Faculty of Science, Chulalongkorn University, Thailand, during January to February 2020. The best performing model was then used to suggest suitable numbers of occupants for certain time spent in the classroom. The Teleszewski & Gładyszewska-Fiedoruk's model and CIBSE AM 10 model perform well when employing the real-time input method (R^2 = 0.9965 ± 0.0028, 0.9912 ± 0.0072 respectively) while being unreliable with the fixed input method (R^2 = -2.7768 ± 5.2673, -20.9980 ± 22.4243 respectively). However, the real-time input method is not practical since the process to measure the CO_2 concentration every minute is tedious. Hence, the fixed input method is leveraged for simulation with the Teleszewski & Gładyszewska-Fiedoruk's model which yields better performance than the CIBSE AM 10 model in both input methods. Moreover, the model could be further improved based upon residual modeling which resulted in the best predictive performance at 60 minutes (R^2 = 0.7547 ± 0.1631). The simulations suggest that the classroom should contain no more than to support a 60-minute study before taking a break when assumed no air ventilation before the class. A suitable number of occupants could be raised if the air ventilation is performed before the class begins.

Keywords: CO_2 concentrations; simulation; classroom; occupants; ventilation

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CHAPTER I

INTRODUCTION

1.1 Background and rationale

People spent large part of their life indoors, according to the National Human Activity Pattern Survey (NHAPS), Americans, on average, spend about 90 percent of their time indoors, where the concentrations of some pollutants are often 2 to 5 times higher than outdoor concentrations (Klepeis, et al., 2001). Carbon dioxide (CO_2) is the pollutant that the concentration in occupied indoor spaces are normally higher than outdoor, since the main source of it came from the by-product of biological respiration. High CO_2 concentrations over 10000 ppm can cause both in acute health affect (headache, confusion, anxiety, drowsiness, and stupor), chronic health affect (asymptomatic) (Porter, Kaplan, & Albert, 2011) and can lead to death when it is up to 70000 ppm (NIOSH, 1976). However, indoor CO_2 concentrations never reach to this level. CO_2 concentration below these levels is not considered a health risk but is a surrogate for human comfort. Therefore, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) has provided a guideline for comfort acceptability of CO_2 concentrations which is about 700 ppm above outdoor air levels.

Generally, CO_2 concentrations in outdoor air range from 300-500 ppm (ASHRAE, 2016). Thus, the range of CO_2 concentrations, according to ASHRAE, should be around 1000 to 1200 ppm but concentrations of CO_2 inside buildings such as office, school, university are higher than outdoor concentration and exceed these values. Unlike office buildings, CO_2 concentrations in classrooms in school or university tend to be in a very high range because they normally have large number of people spent time in (Mui & Wong, 2007).

CO_2 concentrations in classroom are likely to fluctuate according to the change of the number of occupations. The study in changes of CO_2 concentration in hybrid ventilated classroom in UK is shown that CO_2 concentrations rapidly increase in the beginning of the classes since students, lecturers and other occupants entered the classroom and it was increase throughout the duration of the classes as long as the number of occupants are stable (2714 ppm in maximum daily average) (Greene, Eftekhari, Clements-Croome, & Georgiou, 2012). Similarly, the study in the classroom in UK which equipped with trickle ventilators is shown that CO_2 concentrations increase above 1400 ppm for the first 15 min and up to 2700 ppm when all the windows are shut. On the other hand, the CO_2 level slowly decrease when occupants left the room and rapidly decrease when promote natural ventilation (Griffiths & Eftekhari, 2008). These indicate dynamic of CO_2 concentration in classrooms.

The understanding of the dynamic of CO_2 leads to the improvement of the CO_2 model for estimating future CO_2 concentrations in the same purpose for optimization tools for control indoor air quality. There are several factors that affect the dynamic of CO_2 which are brought to model development, such as the volume of the classroom and inadequate ventilation. Teleszewski & Gładyszewska-Fiedoruk (2018) created a CO_2 simplified model. The model was simple since it was created base on experimental results with linear regression equation. Thus, it does not contain some parameters which could affect the dynamic of CO_2 as well, such as the outdoor CO_2 concentrations, flow rates of air. In another study, which more complexity in the model, Irving, S., Ford, B., & Etheridge, D. (2005) has derived CO_2 model from the CO_2 mass balance of indoor CO_2 mainly generated by occupants and outdoor CO_2 via ventilation and infiltration through the building envelope. However, the comparison between these simplified models are not fully defines and the applications of them in classroom management are not concrete.

In order to understand more on using the simplified CO_2 model to estimate dynamics of CO_2 concentrations and provide the factual application of the CO_2 model in classroom management, the present study aimed to compare between two different simplified models and provided insights on model performance and limitations for simulating CO_2 dynamic and suggesting suitable numbers of occupants for certain time spent in a classroom.

1.2 Objectives

1. To measure CO_2 concentrations and air physical parameters in the classroom.
2. To evaluate the selected model for estimating CO_2 concentrations.
3. To suggest suitable numbers of occupants for certain time spent in a classroom.

1.3 Expected Outcomes

1. The measured indoor and outdoor CO_2 concentration and air physical parameters data can be used as valuable information for the Department of Environmental Science, Faculty of Science, Chulalongkorn University; Office of Physical Resources Management, Chulalongkorn University; and Chulalongkorn University in organizing or improving the classes.
2. The comparison of CO_2 concentration predictive models can be used as an example or reference for future study
3. The simulation results of suitable numbers of occupants for certain time spent in a classroom can be used as supportive information for the Department of Environmental Science, Faculty of Science, Chulalongkorn University; Office of Academic Affairs and Educational Management, Faculty of Science, Chulalongkorn University; and Chulalongkorn University in classroom size optimization.

CHAPTER II

LITERATURE REVIEW

2.1 CO_2 in classroom

CO_2 is a chemical compound composed of one carbon and two oxygen atoms. It is colorless, odorless and tasteless gas and non-flammable gas that is heavier than air (NIOSH, 1993). It is a product of completed carbon combustion and the by-product of biological respiration. ASHRAE states that CO_2 concentrations in acceptable outdoor air typically range from 300-500 ppm. High outdoor CO_2 concentrations can be an indicator of combustion and/or other contaminant sources (ASHRAE, 2017) whereas CO_2 generated from the by-product of biological respiration tends to associate more with indoor CO_2 concentrations. CO_2 increases in buildings with higher occupant densities, indicating high biological respiration, and is removed from buildings based on outdoor air ventilation rates.

Moreover, indoor CO_2 concentrations also associated with room ventilation. High CO_2 levels may indicate a problem with inadequate outdoor air ventilation rates (OSHA, 2011). The CO_2 levels can vary from the different types of ventilation in room. Ventilation can divide into three main types include natural, mechanical and hybrid (mixed mode) ventilation. Natural ventilation uses natural forces such as winds and thermal buoyancy force due to indoor and outdoor air density differences drive outdoor air through the room. The room must include windows, doors, solar chimneys, wind towers or trickle ventilators. This natural ventilation of buildings depends on climate, building design and human behavior. Mechanical ventilation uses mechanical machine such as exhaust fan to move the air. Fans can either be installed directly in windows or walls, or installed in air ducts for supplying air into, or exhausting air from, a room. Hybrid (mixed mode) ventilation has both natural and mechanical ventilation in the room. It uses mechanical ventilation when the natural ventilation flow rate is too low (Atkinson, 2009).

Classroom can have different types of ventilation system. In naturally ventilated classroom, the CO_2 levels seem to be in the high range when all the building envelopes are closed. The study of CO_2 levels in naturally ventilated classrooms with air conditioning system of semi-government university of Islamabad, Pakistan has shown that mean indoor CO_2 levels in the classrooms that switched on air condition and closed all the windows (985.9-1545.9 ppm in average, 6249 ppm in maximum) are much higher than the classrooms that switched off air condition and open all the windows (620-833.7 ppm, 2444 ppm in maximum). However, the reason that CO_2 reach at very high level, besides inadequate ventilation, is because classroom has large occupation density (Asif, Zeeshan, & Jahanzaib, 2018). Moreover, it might cause from the small volume of the classroom. According to the study in changes of CO_2 concentration in classroom equipped with stack ventilation in Poland, researchers found a close linear relationship between number of students per volume of the classroom (n/m^3) and increase of CO_2 concentration ($R^2 = 0.8301$). In addition, the result has shown that the CO_2 concentrations increases throughout the duration of the classes when using only stack ventilation system and it can up to 2300 ppm. On the other hand, CO_2 concentrations can drop about 25 percent when allow opening windows for 30 to 60 min (Teleszewski & Gładyszewska-Fiedoruk, 2018). The similar result was also found in the study in the classroom in UK which equipped with trickle ventilators that CO_2 level can rapidly increase above 1400 ppm for the first 15 min and up to 2700 ppm when all the windows are shut. The researchers suggest that the classroom required more than just trickle ventilation in order to maintain CO_2 levels below the recommendation level such as ventilation by opening window which can reduce the CO_2 concentration by 1000 ppm in 10 min (Griffiths & Eftekhari, 2008).

The mechanically ventilated classroom is similar to hybrid ventilated classroom, if all the building envelopes are closed and classroom mostly design to have the windows all around in order to reduce energy consumption. Thus, we will easily find the hybrid ventilated classroom more than mechanically ventilated classroom. Researchers in UK have studied in changes of CO_2 concentration in hybrid ventilated classroom. The studied classroom includes the existing mechanical ventilation with vents opened and windows closed, and the results are similar to naturally ventilated classroom. They found that CO_2 level rapidly increase in the beginning of the classes since students, lecturers and other occupants entered the classroom and it was increase throughout the duration of the classes (2714 in maximum daily average). The drop of CO_2 was found when student open the windows during a break (Greene, Eftekhari, Clements-Croome, & Georgiou, 2012). However, switching off the mechanical ventilation resulted in higher CO_2 levels than switching on the mechanical ventilation according to the study in hybrid ventilated classroom in Poland. The discussions are the similar to naturally ventilated classrooms that it also resulted from the fact that during the measurement there were large number of people in the room and the present students took very active part in the lecture (Cichowicz, Sabiniak, & Wielgosińsk, 2015).

2.2 CO_2 exposure effects

2.3.1 Biologic effects of exposure

CO_2 is produced by intracellular metabolism in the mitochondria. The blood pH decreases (acidity increases) as CO_2 accumulates in the blood. Therefore, CO_2 is removed from the human body for maintaining the acid–base balance in the blood. If the lungs cannot remove enough of the CO_2, the respiratory acidosis occurs. Respiratory acidosis can be acute or chronic; the chronic form is asymptomatic, but the acute, or worsening, causes headache, confusion, anxiety, drowsiness, and stupor. Slowly developing, stable respiratory acidosis may be well tolerated, but could result in memory loss, sleep disturbances, excessive daytime sleepiness, and personality changes. Respiratory acidosis occurs when exposure to a CO_2 concentration of 10,000 ppm for at least 30 min in a healthy adult with a moderate physical load (Porter, Kaplan, & Albert, 2011). However, since CO_2 is an asphyxiant gas, exposure of humans at very high concentrations can cause to death. According to the National Institute for Occupational Safety and Health (NIOSH), exposure to 7 percent of CO_2 (70,000 ppm) with 20.9 percent of Oxygen for 5 minute can cause to death while exposure to concentrations ranging from 17 percent to 30 percent within 1 minute leads to loss of controlled and purposeful activity, unconsciousness, coma, convulsions, and death (NIOSH, 1976).

2.3.2 Effects of low-level exposure to CO_2 in humans

Building-related symptoms (BRSs), commonly called sick building syndrome (SBS), are used to describe situations in which building occupants experience acute health and comfort effects that appear to be linked to time spent in a building, but no specific illness or cause can be identified. The complaints may be localized in a room or zone or may be widespread throughout the building. Indicators of SBS may include, e.g., headache; eye, nose, or throat irritation; dry cough; dry or itchy skin; dizziness and nausea; difficulty in concentrating; fatigue; and sensitivity to odors. (EPA, 1991).

Since the CO_2 levels can be used as a rough indicator of the effectiveness of ventilation (OSHA, 2011) and one of the causes of SBS is inadequate ventilation, high CO_2 levels may indicate a problem with inadequate outdoor air ventilation rates. However, lacking ventilation leads to accumulation of other chemical contaminants and biological contaminants besides CO_2. Therefore, SBS is possibly influenced by other indoor pollutants and to prove the relationship between CO_2 and SBS is very complicated and strength of the evidence is very limited.

2.3.3 Cognitive performance

Researchers in USA have assessed direct effects of increased in CO_2 concentration, within the range of indoor CO_2 concentrations on decision making. They have scheduled 22 participants to exposed CO_2 at 600, 1000, and 2500 ppm in an office-like chamber. Each groups of participants were exposed to each of the three conditions for 150 min per condition. At 1000 ppm, compared with 600 ppm, statistically significant decrements occurred in six of nine scale of decision-making performance. At 2500 ppm, compared with 600 ppm, statistically significant decrements occurred in seven of nine scale of decision-making performance (Satish, et al, 2012). Moreover, according to a study of exposure to normal CO_2 (830 ppm) and high CO_2 (2700 ppm) on cognitive performance of 31 volunteer in a small naturally ventilated office in UK, the absence of an expected learning effect in two cognitive performance test can occur after only short duration exposures (60 min) to the higher CO_2 conditions. However, participants who had lacking sleep appeared more susceptible to the effects of the increased CO_2 (Snow, et al., 2019). In another study, in a university building in Saudi Arabia, 499 of adult female students which 99 percent of them slept for more than 7 hours during the nights before the experiment were tested under nine different exposure conditions combining temperatures (20°C, 23°C and 25°C) and CO_2 levels (600 ppm, 1000 ppm and 1800 ppm) and performed a cognitive test. The result has shown that, at 1000 ppm and 1800 ppm, compared with 600 ppm, statistically significant decrements occurred in performance of all tasks in all exposure conditions anyway (Jaber, Dejan, & Marcella, 2017).

2.3 Indoor CO_2 standards and guidelines

2.3.1 International standard

The National Institute for Occupational Safety and Health (NIOSH) has established a Permissible Exposure Limit (PEL) for CO_2 of 5000 ppm averaged over an 8-hour workday (time-weighted average or TWA.) and a Short-Term Exposure Limit (STEL) for CO_2 of 30000 ppm (NIOSH 2010). However, in most buildings, CO_2 concentrations almost never rise to these levels. CO_2 concentration below 5000 ppm is not considered a health risk but is a surrogate for human comfort. Therefore, American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) has provided a guideline for comfort acceptability of CO_2 concentrations which is about 700 ppm above outdoor air levels (ASHRAE, 2016).

2.3.2 Thailand standard

In Thailand, there is a draft regulation of Department of Health, Ministry of Public Health on the residential indoor air quality standard which is not legally enforced. The acceptable guideline value for CO_2 given in the standard is 1000 ppm averaged over an 8-hour workday or total time people spent indoor (MOPH, 2016).

2.4 CO_2 measurements

2.4.1 Instrument for the CO_2 measurements

CO_2 can be measured with either a direct reading meter or a detector tube kit. The relative occupancy, air damper settings, and weather should be noted for each period of CO_2 testing (EPA, 1991).

Direct-reading meters: Direct-reading meters estimate air concentrations through one of several detection principles. The most common principles for CO_2 sensors are infrared gas sensors NDIR and chemical gas sensors. A non-dispersive infrared sensor (NDIR sensor) is a portable sensor, with measuring principle based on gas absorption of radiation at a known wavelength. The key components are an infrared source, a measuring chamber, a wavelength filter, and an infrared detector (Figure 2.1). Any CO_2 molecules present inside of the measuring chamber will only absorb a specific wavelength of the light given off by the infrared source. The filter allows only the wavelength of 4.3 µm to pass through it. The light intensity that is received by the detector is then proportional to the number of given CO_2 molecules inside the chamber (Mendes, et al., 2015).

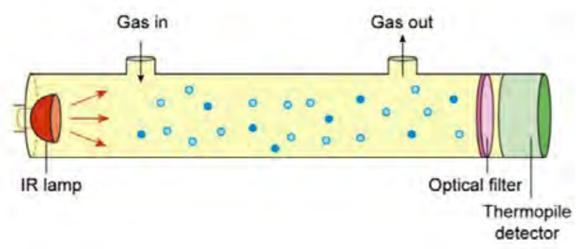


Figure 2.1 Sketch of the Non-Dispersive Infra-Red (NDIR) carbon dioxide (CO_2) sensor structure (Mendes, et al., 2015).

A chemical gas sensor is a device that transforms chemical information into an electrically useful signal. The key components are a transducer and a sensing layer. The chemical gas sensor starts working when gas molecules encounter the sensing layer and cause a potential difference that is converted into an electrical signal (Stojanovska, Calisir, Ozturk, & Kilic, 2019). Based on this electrical signal the concentration of the gas can be estimated.

Detector tube kit: Detector tube kits generally include a hand pump and glass tubes filled with chemical reagents that produced a color change when exposed to the gas. The hand pump draws a known volume of air into a chemically treated tube intended to react with certain contaminants. The length of color stain resulting in the tube correlates to chemical concentration. The point where the reaction stops is read off against graduated markings on the tube. The concept is similar to other colorimetric methods such as pH paper for measuring acids and bases.

2.4.2 Measurement locations

CO_2 measurements for ventilation should be collected away from any source that could directly influence the reading (e.g., hold the sampling device away from exhaled breath). As with many other measurements of indoor air conditions, it is advisable to take one or more readings in "control" locations to serve as baselines for comparison. Readings from outdoors and from areas in which there are no apparent Indoor air quality (IAQ) problems are frequently used as controls. Outdoor samples should be taken near the outdoor air intake.

2.4.3 Measurement periods

Measurements taken to evaluate the adequacy of ventilation should be made when concentrations are expected to peak. It may be helpful to compare measurements taken at different times of day. If the occupant population is fairly stable during normal business hours, CO_2 levels will typically rise during the morning, fall during the lunch period, then rise again, reaching a peak in mid-afternoon. In this case, sampling in the mid- to late-afternoon is recommended. Other sampling times may be necessary for different occupancy schedules (EPA, 1991).

2.5 Related research

Teleszewski & Gładyszewska-Fiedoruk (2018) studied changes of CO_2 in classrooms equipped with stack ventilation systems in Poland and created a simplified model for estimating CO_2 levels. In all classrooms, a linear increase in the concentration of CO_2 was observed. They found that the concentration of CO_2 in the classroom increases throughout the duration of the classes and the rate of increase of increment depends mostly on the volume of the classroom and the number of students. Based on the results of measurements that were performed, they created the model as a function of time, depending on the volume of the classroom and the number of students (Eq. (2.1)).

$$a_{CO_2} = B\gamma t + a_{CO_2,t=0} \tag{2.1}$$

where a_{CO_2} is indoor concentrations of CO_2 (ppm), t is the study time (min), γ = n/V where n is the number of occupants, V is the volume of classroom (m^3), B = 180 is a constant factor (m^3 ppm/person min), and $a_{CO_2,t=0}$ is the indoor concentration of CO_2 at time 0 (ppm).

The average error in all the measurements is equal to 5%. Since the experiments were conducted in a small classroom and the model was created base on experimental data. Therefore, it can be used only in the classrooms with volume from about 200 to 420 m^3.

Krawczyk, Rodero, Gładyszewska-Fiedoruk, & Gajewski (2016) studied changes of CO_2 in the school buildings located in two different climates: Poland and Spain and developed a model for estimating CO_2 concentrations. The proposed model (Eq. (2.2)) has derived from the CO_2 mass balance equation and base on the fact that the condition of temperature and pressure can have an influence on the CO_2 concentration and time.

$$C_{CO_2in} = \frac{T_{in}}{P_{in}(1+ACHt)}[C_{CO_2in_{t=0}} \frac{P_{in(t=0)}}{T_{in(t=0)}} + \left(gN\frac{R}{\mu_{CO_2}V} + C_{CO_2out}\frac{P_{out}}{T_{out}}ACH\right)t] \tag{2.2}$$

Where C_{CO_2in} is indoor concentrations of CO_2 (ppm), $C_{CO_2in_{t=0}}$ is the indoor concentration of CO_2 at time 0 (ppm), C_{CO_2out} is the outdoor concentration of CO_2 (ppm), μ_{CO_2} is the molar mass of CO_2, T_{in} is indoor temperature (K), $T_{in(t=0)}$ is indoor temperature at time 0 (K), T_{out} is outdoor temperature (K), P_{in} is indoor air pressure (atm), $P_{in(t=0)}$ is indoor air pressure at time 0 (atm), P_{out} is outdoor air pressure (atm), R is the Gas Ideal Constant (8.314 J / mol·K), ACH is the air change rate, N is the number of occupants, g is CO_2 gains from a person, V is the volume of room (m^3), t is the time interval.

The proposed model divided into two versions: First, initial concentrations was set to be zero. Second, the CO_2 concentration was estimated every 5 min and the result was taken as the initial concentration for the next time range. The model was verified using experimental data and compared with CISBE AM 10 model (Irving, S., Ford, B., & Etheridge, D. 2005) (Eq. (2.3)). The lowest average error was found in the first model which can be successfully used for simulations of CO_2 concentration in classrooms.

$$C_t = C_{ext} + \frac{q_{CO_2} \times 10^6}{Q} - (C_{ext} - C_0 + \frac{q_{CO_2} \times 10^6}{Q})e^{(-\frac{Qt}{V})} \tag{2.3}$$

where C_t is the indoor concentration of CO_2 at time t (ppm), C_{ext} is the outdoor concentration of CO_2 (ppm), C_0 is the indoor concentration of CO_2 at time 0 (ppm), Q is the volume flow rate of air entering the space ($m^3\ s^{-1}$), q_{CO_2} the volumetric indoor emission rate of CO_2 ($m^3\ s^{-1}$), V is the volume of the indoor space (m^3) and t is the interval since t = 0 (s).

Quang, He, Knibbs, Dear, & Morawska (2014) developed a multi-component model that can be used to maximize indoor environmental quality inside mechanically ventilated office buildings, while minimizing energy usage. One of the component models they developed is indoor CO_2 concentration model (Eq. (2.4)). The model was derived from CO_2 mass balance equation which base on the balance of CO_2 generated inside a building, mainly by the building occupants, and that brought from outside the building via ventilation and penetration through the building envelope.

$$C_{CO_2}(t) = \frac{N(t)G(t)}{1.8Q(t)} + C_{ext}(t) \tag{2.4}$$

where: $G(t)$ is CO_2 release by an individual occupant at time t, 0.0052 l/s for and average adult at a normal activity in the office during sitting and writing or reading, Q is the volume flow rate into a space in m^3/s, $N(t)$ is a number of occupants inside the building at time, $C_{ext}(t)$ is concentration of outdoor CO_2 in this time.

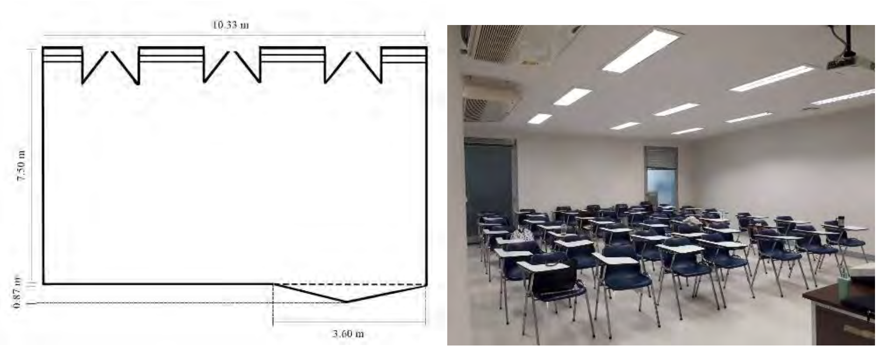
Griffiths & Eftekhari (2008) studied the methods of control in naturally ventilated classroom in United Kingdom with differing conditions of ventilation. The studied classroom had five pairs of upper and lower windows equipped with two trickle ventilation system and the results has shown that the classroom required more than just trickle ventilation in order to maintain CO_2 levels below the recommendation level of 1500 ppm as in UK. Ventilation by opening window for 10 min can reduce the CO_2 concentration by 1000 ppm without compromising thermal comfort. Moreover, they compared the experimental data with a CISBE AM 10 model (Eq. (2.3)) and it matched the experimental data reasonably well but there are a lot of experimental details such as additional class change ventilation from doors, window openings, cleaners and increased metabolic rates that need to be taken into account so a totally accurate simulation would require minute by minute observation.

CHAPTER III

MATERIALS AND METHODS

3.1 Study areas

The measurements are conducted in the building of the Department of Environmental Science of Chulalongkorn University, Bangkok, Thailand, during January and February 2020. The building has four floors and is located close to a roadway. To conduct this experiment, one classroom is chosen. The room is on the third floor and has a balcony at the entrance of the room which is close to the roadway that rarely has a car pass by during study time. It is a naturally ventilated room with air-conditioning system and three doors. Since, there is no windows, the only way of ventilation in the classroom while the classes are in progress is infiltration. Additionally, the room is small (volume ~ 217 m^3) and in a shape as shown in Figure 3.1.



(a) (b)

Figure 3.1 (a) Selected classroom plan and (b) Selected classroom

3.2 Measurements

3.2.1 Instruments and experimental set up

The measurements including indoor and outdoor CO_2 concentration, temperature and relative humidity are conducted using Tenmars ST-501 recorder (Figure 3.2 (a)), a non-dispersive infra-red CO_2 sensor, with the specifications as shown in Table 3.1.

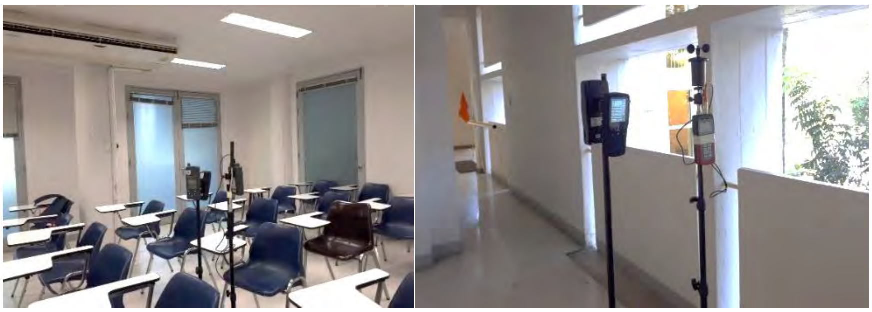
Table 3.1 The specification of all instruments using in the measurements

Tenmars ST-501 recorder	Range	Precision
Concentration of CO_2 (ppm)	0 – 9999	± 75 ppm, ± 8%
Temperature (°C)	0-50	± 1.0 °C
Relative humidity (%)	20-80	± 3%
	<20, >80	± 5%
Hot Wire Tenmars TM-4002	Range	Precision
Air velocity (m/s)	0.01-25.00	± 3%
Digital Anemometer AM-4836C	Range	Precision
Air velocity (m/s)	0.4-45.0	± 3%

(a) (b) (c)

Figure 3.2 (a) Tenmars ST-501 recorder (b) Hot Wire Tenmars TM-4002 and (c) Digital Anemometer AM-4836C

The measurements are performed indoor and outdoor by using two Tenmars ST-501 recorders. One is located 1.2 m above the floor at the center of the room and the another is located at balcony in front of the door (Figure 3.3). Indoor air velocity is measured using a Hot Wire Tenmars TM-4002 (Figure 3.2 (b)) while outdoor air velocity is measured using a Digital Anemometer AM-4836C (Figure 3.2 (c)). The measurement range of the two air velocity meters are shown in Table 3.1.



(a) (b)

Figure 3.3 (a) Experimental set up of indoor instruments and (b) Experimental set up of outdoor instruments

3.3.1 Mathematical models

In the Faculty of science, Chulalongkorn University, classes are usually from 60 to 180 minutes long depend on lecturer and mostly without break between class. The measurements are performed starting from the beginning of the class (01:00 PM) to the end of the class and data are recorded every 1 min. Furthermore, the data analysis is done within the first 120 minutes and the rest of the data are used for supporting the discussion.

3.3 Data analysis

3.3.1 Mathematical models

Two mathematical models are chosen to evaluate in this study. The first model, presented by Teleszewski & Gładyszewska-Fiedoruk (2018) is naive but applicable including only the initial CO_2 concentration, the number of students and the room volume:

$$a_{CO_2} = B\gamma t + a_{CO_2,t=0} \tag{3.1}$$

where a_{CO_2} is indoor concentrations of CO_2 (ppm), t is the study time (min), γ = n/V where n is the number of occupants, V is the volume of classroom (m^3), B = 180 is a constant factor (m^3 ppm/person min), and $a_{CO_2,t=0}$ is the indoor concentration of CO_2 at time 0 (ppm).

The second model, as given in Chartered Institution of Building Services Engineers Application Manual 10 (CISBE AM 10) by Irving, S., Ford, B., & Etheridge, D (2005) and presented in papers Griffiths & Eftekhari (2008) is more complex as the volume flow rate of air, indoor emission rate of CO_2 and outdoor CO_2 concentrations are considered:

$$C_t = C_{ext} + \frac{q_{CO_2} \times 10^6}{Q} - \left(C_{ext} - C_0 + \frac{q_{CO_2} \times 10^6}{Q}\right)e^{\left(-\frac{Qt}{V}\right)} \tag{3.2}$$

where C_t is the indoor concentration of CO_2 at time t (ppm), C_{ext} the outdoor concentration of CO_2 (ppm), C_0 the indoor concentration of CO_2 at time 0 (ppm), Q the volume flow rate of air entering the space ($m^3\ s^{-1}$), q_{CO_2} the volumetric indoor emission rate of CO_2 ($m^3\ s^{-1}$) which can be calculated from the individual average adult CO_2 emission rate (0.0054 l/s) multiplied by number of occupants (n), V the volume of the room (m^3) and t is the time interval (s). When the classroom is unoccupied there is no CO_2 emission from the occupants or q_{CO_2} is equal to zero. Thus, the second model can be rearranged to contribute the following equation:

$$Q = -\frac{V}{t} \times \ln\left(\frac{C_t - C_{ext}}{C_0 - C_{ext}}\right) \tag{3.3}$$

Generally, Q is calculated from the surface of all the openings or vents in the room multiplied by air velocity. Alternatively, the above equation can be used for determining Q as well.

3.3.2 Input method

In this study, two types of input method are investigated including 1-min intervals input method (real-time input method) and fixed input method. The first way is to input the new data every minute according to the frequency of recording to give the output. However, in practice, we do not anticipate using the model with real-time data. Thus, the central basis of this study is fixed input method as a facile usage requirement. This specifies that the value of the input, including number of occupants, indoor concentration of CO_2 at time 0 and outdoor concentration of CO_2 are known and assumed to be constant throughout each time series. Additionally, the maximum number of occupants from each measured time series is chosen as the fixed value of n in Eq. (3.1) and Eq. (3.2).

3.3.3 Evaluation metrics and residual analysis

The two mathematical models are evaluated on measured data. The simulation results are visualized using scatter plot. Coefficient of determination (R^2) (Eq. (3.4)) and Root Mean Square Error (RMSE) (Eq. (3.5)) are employed as the performance metrics.

$$R^2 = 1 - \left(\frac{\sum(y-\hat{y})^2}{\sum(y-\bar{y})^2}\right) \tag{3.4}$$

Where y is the actual value, $\hat{y}$ is the predicted value and $\bar{y}$ is the average of the actual value.

$$RMSE = \sqrt{\frac{1}{n} \times \sum(prediction - actual)^2} \tag{3.5}$$

According to a study basis, the fixed input value is used for the sake of simplicity and practicality, but it might not be accurate when compared with using real-time input value. After evaluation of the two mathematical models, the one with the higher metric score is chosen to improve its precision. The improvement is made by the construction of a residual model in which the outputs are used as a correction factor. Similarly, R^2 and RMSE are considered as the evaluation metrics and the residual plot is also investigated. The proper classroom size and duration of the class are sought after acquiring the highest performance model.

CHAPTER IV

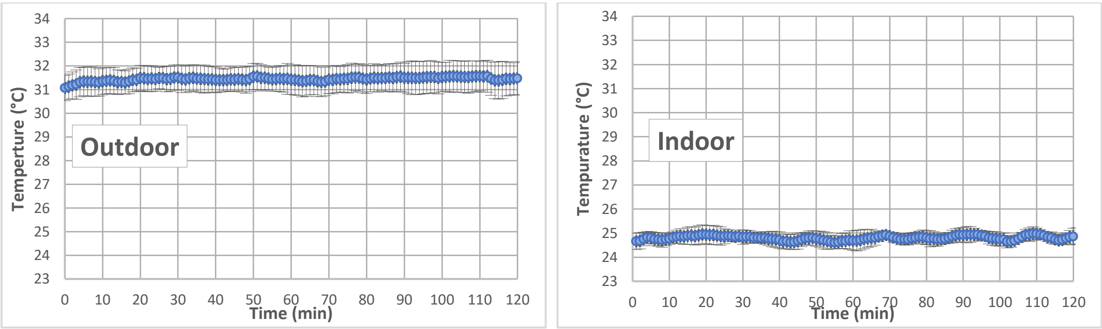
RESULTS AND DISCUSSION

4.1 Summary of outdoor and indoor air physical parameters during measurements

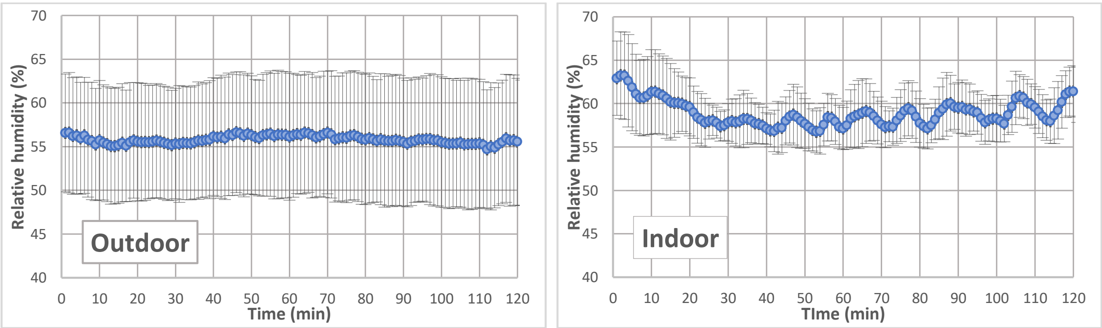
The distributions of temperature and humidity both outdoor and indoor across the dates are impartially stable within a time series of the measurements (Figure 4.1 (a) and (b)), indicating their effects on a given period of time are similar. The results are in correspond with the assumption of the two selected models which assume that the temperature and humidity are negligible.

The range of outdoor air velocity is much higher than the indoor air velocity and the distribution both outdoor and indoor are moderately stable as shown in Figure 4.1 (c). Since the classroom has no windows and the door is always close during studying, the indoor measured data are mainly influenced by air blowing from air conditioner. The distribution outdoor concentration of CO_2 is stable as well while the indoor concentrations of CO_2 increase through time and vary across measurement series (Figure 4.2).

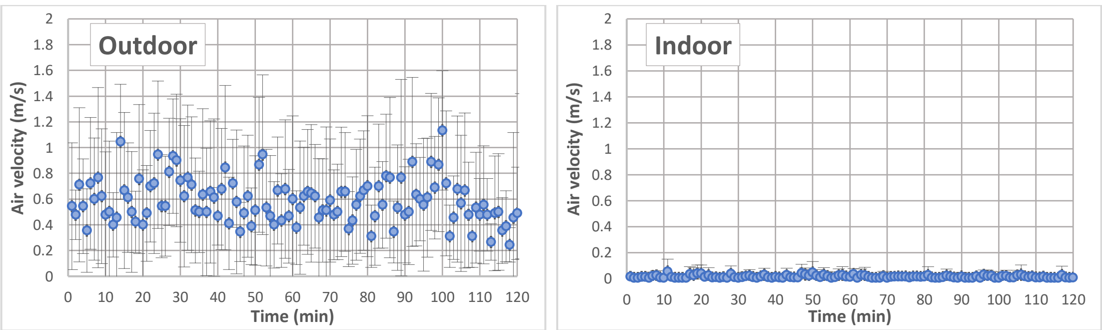
The dynamics of indoor concentration of CO_2 in all measurement series is shown in Figure 4.3. The CO_2 concentrations regularly grow through time approximately in linear and rise above 2000 ppm in 50 to 90 min except measurement series 2 (Figure 4.3 (a)). Since the measurement series 2 holds the large capacity of occupants, the indoor concentration of CO_2 exceeds 2000 ppm in the first 30 min. In contrast, the indoor concentrations of CO_2 of measurement series 5, 6 and 8 never rise to 2000 ppm within the 120 min (Figure 4.3 (b)). Since during measurement the door was open after the 60-minute study in the measurement series 5, the indoor concentrations of CO_2 slightly increase after then. In the measurement series 6 and 8, there is a small break between classes. Thus, the indoor concentrations of CO_2 decrease during the break which makes it below 2000 ppm. However, in all measurement series, the indoor concentrations of CO_2 rapidly exceed the acceptable value which is approximately 1190 ppm (700 ppm above outdoor air level, (ASHARE, 2017)) within the first 10 to 20 minutes. Furthermore, Satish et al. (2012) reported that if the students expose to 1000 ppm of indoor concentration of CO_2 for 150 min, it can reduce their decision-making performance such as ability to use information effectively and development of creative activities as compared to the lower level (600 ppm).



(a)



(b)



(c)

Figure 4.1 (a) Outdoor and indoor air temperature during measurements (b) Outdoor and indoor air relative humidity during measurements (c) Outdoor and indoor air velocity during measurements

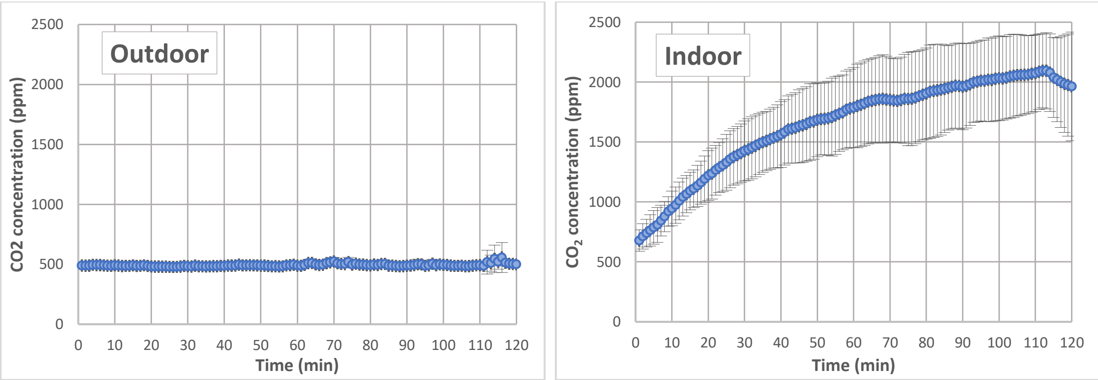
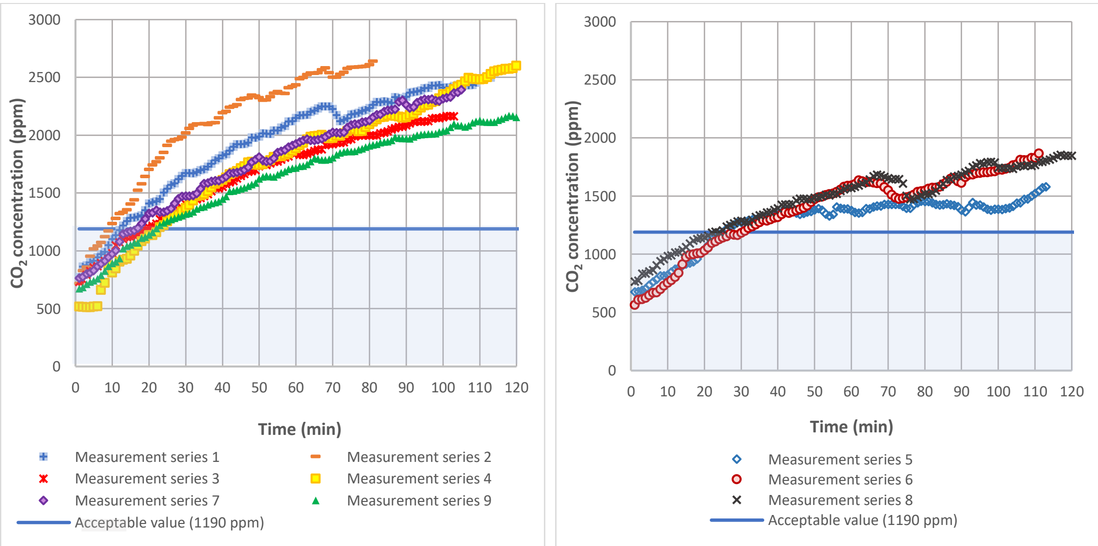


Figure 4.2 Outdoor and indoor concentration of CO_2 during measurements



(a) (b)

Figure 4.3 (a) The indoor concentration of CO_2 of measurement series 1, 2, 3, 4, 7, and 9 with no break and opening door between class. (b) The indoor concentration of CO_2 of measurement series 5, 6, and 8 with break and opening door between class.

In this study, there are 9 measurement series and each one has a different number of occupants and study time as shown in Table 4.1.

Table. 4.1 Summary of measurement series and model fixed input value.

Measurement series	Date	Study time (min)	Number of occupants***	Indoor concentration of CO_2 at time 0 (ppm)***	Outdoor concentration of CO_2 (ppm)***
1	29/01/20	113	27		
2	30/01/20	81	44		
3	05/02/20	120	26		
4	06/02/20	120	32		
5	12/02/20	113	27	686*	490**
6	13/02/20	111	26		
7	19/02/20	105	27		
8	20/02/20	120	29		
9	26/02/20	120	26		

* The average measured value of indoor concentration of CO_2 at 12:59 AM
** The average measured value of outdoor concentration of CO_2 at 12:59 AM
*** fixed input value

4.2 CO_2 model evaluation

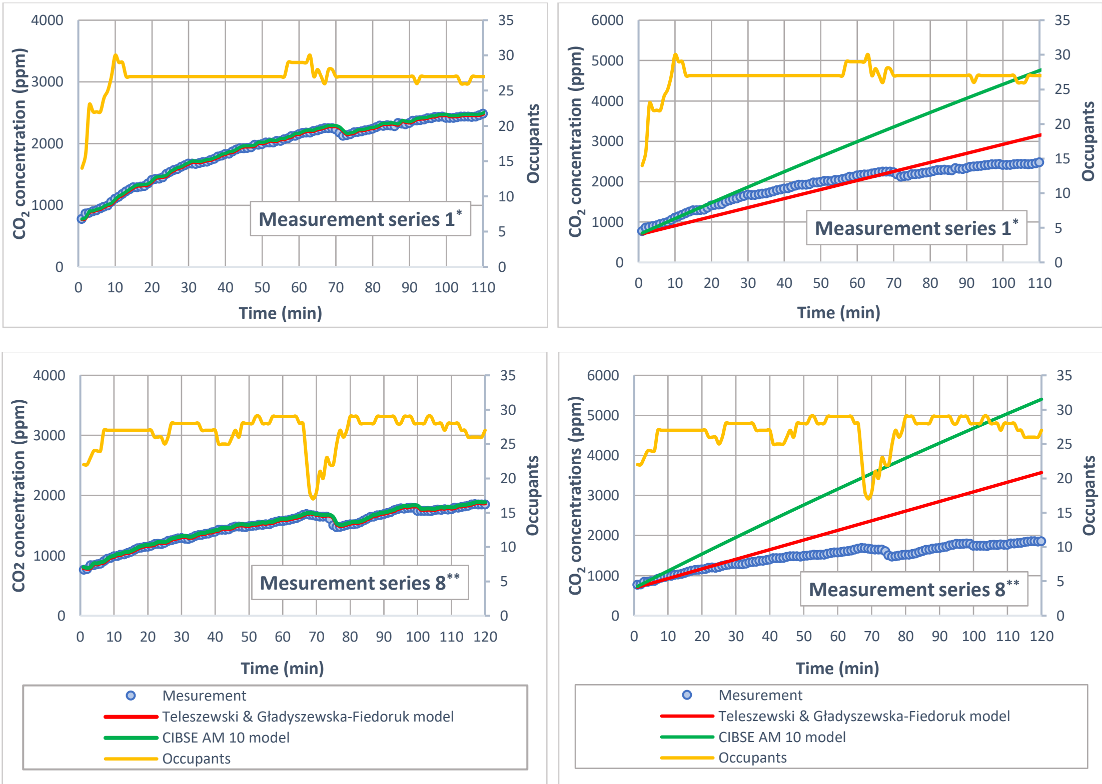
The two selected models are evaluated based on measured data and different ways of model input are also considered. Results of evaluation of the models are presented in Table 4.2. The real-time input method is to input the new measured data every minute. The average R^2 of the Teleszewski & Gładyszewska-Fiedoruk model and the CIBSE AM 10 model with real-time input method are 0.9965 ± 0.0028 and 0.9912 ± 0.0072 respectively. The result of the CIBSE AM 10 model is in corresponds to the result presented in papers Griffiths & Eftekhari (2008). Although the R^2 is not reported in the paper, they disclose that the model matched the measure data rationally well. However, Teleszewski & Gładyszewska-Fiedoruk (2018) record the indoor concentration of CO_2 every 5 min. Thus, it might not be able to compare the study results. Conversely, the fixed input method is simple but unreliable. Since the method is to specify the input value, including number of occupants (maximum value in each day), indoor concentration of CO_2 at time 0 (490 ppm) and outdoor concentration of CO_2 (686 ppm) as shown in Table 4.1, and the two models give all negative R^2. The average R^2 of the Teleszewski & Gładyszewska-Fiedoruk model and the CIBSE AM 10 model with real-time input method are -2.7768 ± 5.2673 and -20.9980 ± 22.4243 respectively. In both real-time input method and fixed input method, the average R^2 of the Teleszewski & Gładyszewska-Fiedoruk model is ways better than the CIBSE AM 10 model.

However, it is obviously seen that the R^2 of the two models with real-time input method are virtually perfect which is approximately 0.99 while the models with fixed input value are given negative R^2, indicating building prediction with fixed input method is much worse than real-time input method. Generally, the lowest R^2 is equal to zero and it returns to the assumption that is the model simulation is not better than using the mean of measured data. However, if the model simulation is worse than using the mean, R^2 will be negative. One possible way to receive a negative R^2 is to force the intercept through a specific point which is using fixed value to construct the model simulation in this study. To gain insight into these, the Teleszewski & Gładyszewska-Fiedoruk model will be the example case explanation. Y-intercept $(a_{CO_2,t=0})$ is settled to be 686 ppm in every prediction series but it is changed through the series in the real-time input method. Thus, the prediction lines of the real-time input are more fit to the actual data than the fixed input method. Furthermore, the slopes in the real-time input method are changes through time resulted in extremely fit between the predicted value and measured data while the slope is again fixed in the fixed input method (Figure 4.4 (a)). Thus, this worsens prediction especially in the day with an unsteady number of occupants and the same reasons have occurred to CIBSE AM 10 model as well.

Table 4.2 Summary of average metrics score for evaluation of indoor concentration of CO_2 model

		Teleszewski & Gładyszewska-Fiedoruk		CIBSE AM 10	
		Real-time input value	Fixed input value	Real-time input value	Fixed input value
R^2	Avg.	0.9965	-2.7768	0.9912	-20.9980
	SD	0.0028	5.2673	0.0072	22.4243
RMSE	Avg.	21.18	561.15	33.86	1582.24
	SD	4.09	220.88	5.77	292.85

The predicted values of the indoor concentration of CO_2 in measurement series 8 which has an unsteady number of occupants through time are much higher than the measured data especially when occupants are fluctuated at 60 to 80 min (Figure 4.4 (b)). At the end of the class, the measured value is 1848 ppm while the predicted values of the Teleszewski & Gładyszewska-Fiedoruk model and CIBSE AM 10 model are 3573 and 5402 ppm respectively. Eventually, the huge error occurs while the results of measurement series 1 are adverse. The stable number of occupants are allowed the fixed input method to be accepted since the measured data are truly constant.



(a) (b)

Figure 4.4 (a) Predicted value of indoor concentration of CO_2 from real-time input method versus measured data in measurement series 1 and 8. (b) Predicted value of indoor concentration of CO_2 from fixed input method versus measured data in measurement series 1 and 8.

* The day with an unsteady number of occupants.
** The day with a steady number of occupants.

Since, the real-time input method allows slope and intercept to be changed. Thus, besides R^2, the average RMSE of the real-time input method is low indicating less error while the fixed input method is extremely high. The average RMSE of the Teleszewski & Gładyszewska-Fiedoruk model with real-time input value and fixed input value are 21.18 ± 4.09and 561.15 ± 220.88 respectively while the CIBSE AM 10 model are shown the higher error with average RMSE 33.86 ± 5.77 and 1582.24 ± 292.85 for real-time input value and fixed input value respectively. The RMSE results are significantly different between the two settings. The Teleszewski & Gładyszewska-Fiedoruk model yields better performance especially when the fixed input value scheme is employed. In this study, the individual CO_2 emission rate is an average value for the adult which is 0.0054 l/s. However, it could be changed during studying as class activities and other related factors change. Since the constant indoor emission rate of CO_2 is considered in CIBSE AM 10 model, the model can provide worse prediction. It is found that the CIBSE AM 10 model produces more error compared to Teleszewski

& Gładyszewska-Fiedoruk model in both real-time input method and fixed input method. Together with the fact that the term of indoor emission rate of CO_2 is also depending on the number of occupants which is forced to be stable in the fixed input method, the method is prone to error.

According to the results, the predicted values of the two models with fixed input method are close to the measured data at the beginning as shown in (Figure 4.4). Therefore, R^2 and RMSE are used to search for the highest performance of the two models working time as well. The results show that Teleszewski & Gładyszewska-Fiedoruk model can perform well within 45 min ($R^2 = 0.74 \pm 0.18$) before the metric is reduced to 0.54 ± 0.51, 0.05 ± 1.18 and -1.06 ± 2.61 when the operating time exceeds 60 min, 75 min and 90 min respectively. In comparison, CIBSE AM 10 model produces all negative R^2. The model performs poorly since the first 15 min ($R^2 = -2.46 \pm 3.35$). Similarly, the RMSE of the two models is low at the beginning of the prediction and it increases through duration of time since the slope and y-intercept are fixed. Additionally, the RMSE of the Teleszewski & Gładyszewska-Fiedoruk model is lower than the CIBSE AM 10 model in every predict time duration (Table 4.3).

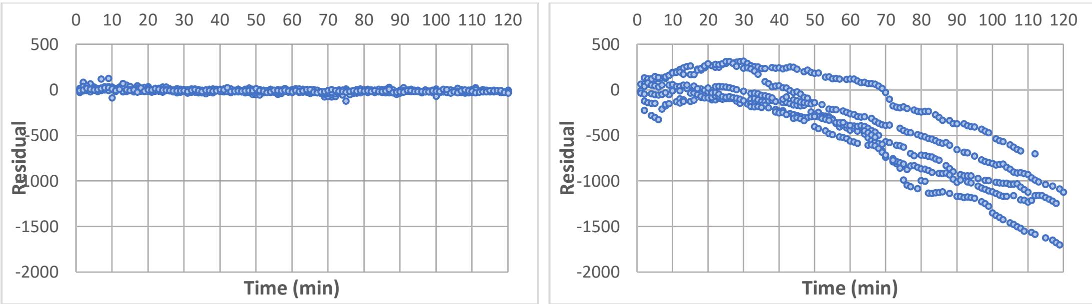
Table 4.3 Summary of metrics score for evaluation of indoor concentration of CO_2 model at different predict time duration.

Time (min)	Teleszewski & Gładyszewska-Fiedoruk				CIBSE AM 10			
	R^2		RMSE		R^2		RMSE	
	Avg.	SD	Avg.	SD	Avg.	SD	Avg.	SD
15	0.27	0.50	110.32	56.47	-2.46	3.35	164.53	104.51
30	0.73	0.21	121.01	67.97	-1.21	1.72	299.59	115.04
45	0.74	0.18	137.94	56.26	-2.65	2.77	497.44	137.53
60	0.54	0.51	185.85	74.91	-4.90	4.53	725.69	188.57
75	0.05	1.18	273.07	114.04	-8.17	7.27	975.13	243.48
90	-1.06	2.61	373.29	168.61	-13.74	13.29	1171.40	234.56
105	-2.34	4.48	489.98	204.47	-19.35	19.90	1415.32	262.50

Undoubtedly, it is evident that the Teleszewski & Gładyszewska-Fiedoruk model has higher performance than CIBSE AM 10 model and the fixed input method has shown greater error of the predicted value than real-time input method. Despite unreliable, the fixed method is taken as we know less of input data in practice. Thus, the Teleszewski & Gładyszewska-Fiedoruk model with fixed input method is chosen to be improved based on the residual value.

4.3 Residual analysis and modelling

To improve the Teleszewski & Gładyszewska-Fiedoruk model, residual analysis is employed. According to the results, residual plot of real-time input method is randomly dispersed around the horizontal axis (Figure 4.5 (a)). Conversely, the one with fixed input method is obviously lived in pattern (Figure 4.5 (b)). Thus, only the residual plot is investigated in the residual analysis.



(a) (b)

Figure 4.5 (a) The residual plot of a 6 random measurement series with the real-time input method. (b) The residual plot of a 6 random measurement series with the fixed input method.

The residual model is built and evaluated based on the residuals of 6 random measurement series. Since the distribution of residuals plot is in linear pattern (Figure 4.5 (b)) and time is the only one variable which varies, a simple linear regression is calculated to predict residual based upon time. Results of the simple linear regression indicated that there is a collective effect between time and residual, (F (1, 530) = 1387.13, $p < 0.001$, $R^2 = 0.72$). The predictor is examined further and indicated that time ($t = -37.24$, $p = 0.001$) is significant predictor in the model (Table 4.4). The result of model evaluation is shown in Table 4.5. The R^2 and RMSE equal to 0.70 and 256.27 respectively.

$$Correction\ factor = (-12.068 \times t) + 306.1 \tag{4.1}$$

Where t is the study time (min) and the output of the residual model is called correction factor.

Table 4.4 Simple linear regression analysis summary for time predicting residual

Variable	*B*	*SE B*	β	*t*	*p*
(Constant)	306.100	0.324		14.530	.000**
Time	-12.068	21.067	-0.851	-37.244	.000**

Note: $R^2 = 0.72$
** $p < .01$

Table 4.5 Summary of average metrics score for evaluation of indoor concentration of CO_2 model

	Residual model
R^2	0.70
RMSE	256.27

The residual is the difference between the observed value of the dependent variable (y) and the predicted value (ŷ) (Eq. (4.2)). Thus, the new predicted value of the indoor concentration of CO_2 ($a_{CO_2,new}$) can calculate from Eq. (4.3).

$$\text{Residaul} = \text{y} - \hat{\text{y}} \tag{4.2}$$

$$a_{CO_2,new} = a_{CO_2} + correction\ factor \tag{4.3}$$

The evaluation of applying the residual model with the Teleszewski & Gładyszewska-Fiedoruk model is achieved based on 3 random measurement series (3, 5 and 7) (Table 4.6). The correction factor tends to be positively improved the model since the average R^2 before the improvement is negative (-4.70 ± 8.48) while the latest one with correction factor is positive (0.07 ± 1.26). Imperfectly, the new R^2 approaches to zero, since the door of the classroom was opened during studying. Thus, the trend of indoor concentration of CO_2 in measurement series 5 has remained constant at 60 min and continues onward while the predicted values are continually increased (Figure 4.6). In the result of the undesirable situation, the great negative R^2 in both models without correction and with correction are found and might not indicate the actual performance of the model. In contrast, the trends of indoor concentration of CO_2 measurement series 3 and 5 are regularly grown and the model can work properly. Therefore, the R^2 of these measurement series is quite high which are equal to 0.81 and 0.78 in measurement series 3 and 7 respectively. However, the correction factor can reduce the huge error of the prediction since the average RMSE of the model with correction is two times less than the model with no correction.

Table 4.6 Summary of average metrics score for evaluation of the Teleszewski & Gładyszewska-Fiedoruk model without correction and with correction

Measurement series	Model with no correction		Model with correction	
	R^2	RMSE	R^2	RMSE
3	-0.26	464.66	0.81	179.40
5*	-14.48	880.67	-1.39	346.05
7	0.63	278.64	0.78	217.26
Average of all series ± SD	-4.70 ± 8.48	541.32 ± 308.25	0.07 ± 1.26	247.57 ± 87.36

* The door of classroom was opened during studying at 60 min and continue onward.

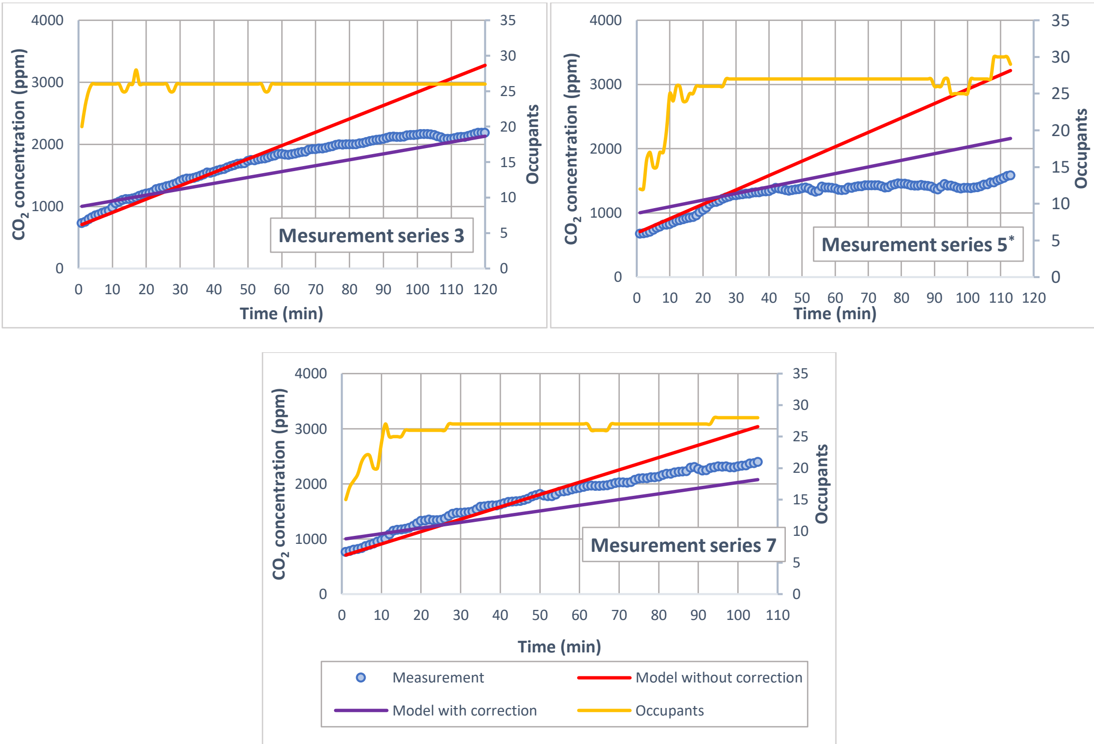


Figure 4.6 Predicted value of indoor concentration of CO_2 from Teleszewski & Gładyszewska-Fiedoruk model with and without correction versus measured data in 3 random measurement series (3, 5 and 7).

* The door of classroom was opened during studying at 60 min and continue onward.

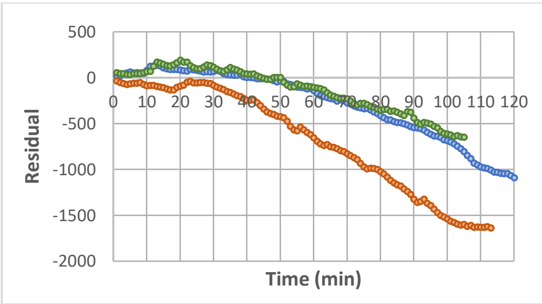
To entirely compare with the original, the ability of prediction in different time duration is also evaluated (Table 4.7). The ability in prediction of the model without correction is over at 45 min before the R^2 is reduced from 0.82 ± 0.15 to 0.49 ± 0.76. Positively, the model with correction can predict up to 60 min with R^2 equal to 0.75 ± 0.16 and it is nearly accepted when continuing the prediction until 75 min (R^2 = 0.62 ± 0.27). Since measurement series 5 is also considered, the same reason as mentioned in the previous result is explained why it might not show the highest performance of actual time duration of the model. The RMSE of the model with correction at 15 min and 30 is 202.48 ± 70.15 and 162.19 ± 51.49 respectively which is approximately two times higher than the RMSE of the model without correction. It seems not to correspond to R^2, since the trend of residual plot is not perfectly arranged in linear. It is low in the first 10 min and risen after that as shown in Figure 4.5 (b). Referring to the residual trend, it is made y-intercept of the residual model being over than the actual. Stated differently, the correction factors are overestimated for the first 10 min. Thus, the RMSE is floated high at the beginning and slightly increased while the RMSE scores of the model without correction are extremely increased for a longer prediction.

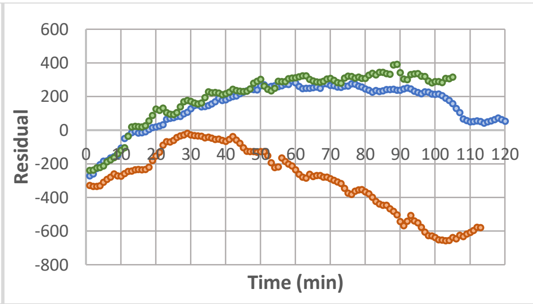
Table 4.7 Summary of average metrics score for evaluation of the Teleszewski & Gładyszewska-Fiedoruk model without correction and with correction at different predict time duration.

Time (min)	Model without correction				Model with correction			
	R^2		RMSE		R^2		RMSE	
	Avg.	SD	Avg.	SD	Avg.	SD	Avg.	SD.
15	0.43	0.25	82.72	7.80	0.87	0.16	202.48	70.15
30	0.80	0.05	93.00	21.27	0.86	0.17	162.19	51.49
45	0.82	0.15	104.93	34.86	0.84	0.15	165.53	19.64
60	0.49	0.76	151.02	114.78	0.75	0.16	187.90	12.05
75	-0.25	1.93	235.57	178.85	0.62	0.27	211.04	13.42
90	-1.49	3.85	340.92	234.26	0.42	0.53	237.68	26.50
105	-3.61	7.12	466.36	286.30	0.08	1.10	265.53	61.00

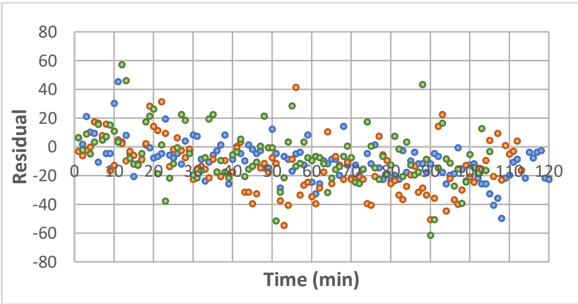
It is obviously seen that the residual plot of the model with correction is still in pattern especially when compared to the real-time input method (Figure 4.7). Since the Teleszewski & Gładyszewska-Fiedoruk model is also constructed based on simple linear regression and the residual plot shows non-random dispersion with fixed input method, the linear residual model cannot improve the residual trend. Theoretically, if the points in a residual plot are non-randomly dispersed around the horizontal axis, a linear regression model is not appropriate for the data. To clarify, we try to improve the linear original model which shows non-random residual plot with another linear model (residual model). In results of the improvement, the outputs of the model are still in linear which provides same residual plot pattern but less error. Thus, the proportion of residual is much smaller than the model without correction.

However, it cannot entirely conclude that the linear residual model is not appropriate to use as a tool to improve the original model. It might have some features that could add into the model and yield better performance. The non-linear models can alternatively use to improve the Teleszewski & Gładyszewska-Fiedoruk model as well but it might not simple as a linear model.





(a) (b)



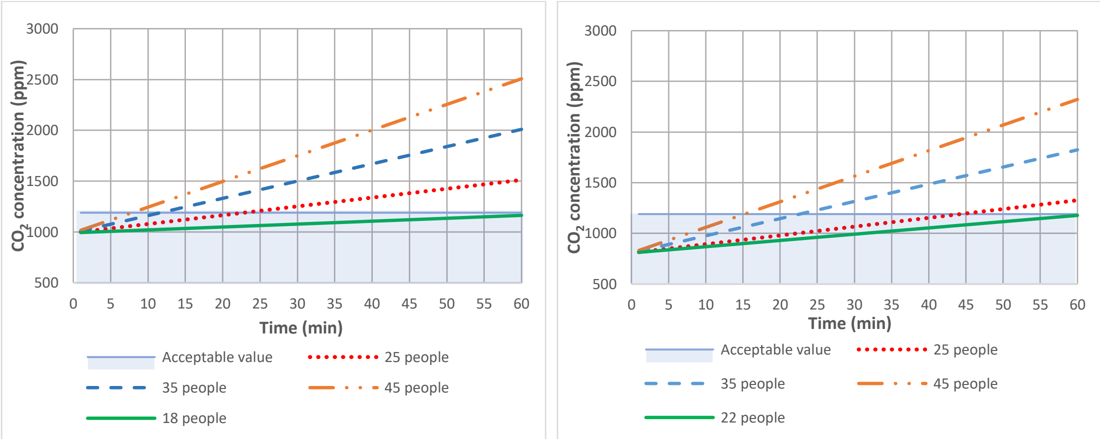
(c)

Figure 4.7 (a) The residual plot of a 3 random measurement series with the fixed input method without correction. (b) The residual plot of a 3 random measurement series with the fixed input method with correction. (c) The residual plot of a 3 random measurement series with the real-time input method.

4.4 Indoor concentration of CO_2 simulation and suitable numbers of occupants for certain time spent in a classroom

The simulations are conducted to suitable numbers of occupants for certain time spent in a classroom. If we do not change the duration of a classes (3 hours), the simplest way is to give students a break which reduces the indoor concentration of CO_2. Although the frequency of taking break is in one place between 30 to 90 min (Barnes, 2020, Cirillo, 2018, Dantz, Edgar, & Dement, 1994), the indoor concentration of CO_2 in the experiment exceeds the acceptable value within the first hour. Additionally, the performance of the students begins to progressively decline when continually study for the 50 min duration (Ariga & Lleras, 2011). Thus, the simulation of indoor concentration of CO_2 is employed based on the frequency of taking break every 60 min.

The first simulation is construct based on the same input data as used in the model evaluation ($a_{CO_2,t=0}$ = 686 ppm, C_{ext} = 490 ppm). To make a distinct comparison, the proper number of occupants and the range in the past (25, 35 and 45 people) are observed. The results are shown in Figure 4.8 (a). According to (ASHRAE, 2017), the acceptable value of indoor concentration of CO_2 is 1190 ppm (700 ppm above the outdoor concentration of CO_2 level). If the acceptable value is concerned and the classroom physical is not change, the number of occupants must be less than 18 people to support the 60 min study duration. In contrast, the classes with 25, 35, and 45 people rapidly exceed the acceptable value in 23, 12 and 4 minutes respectively.

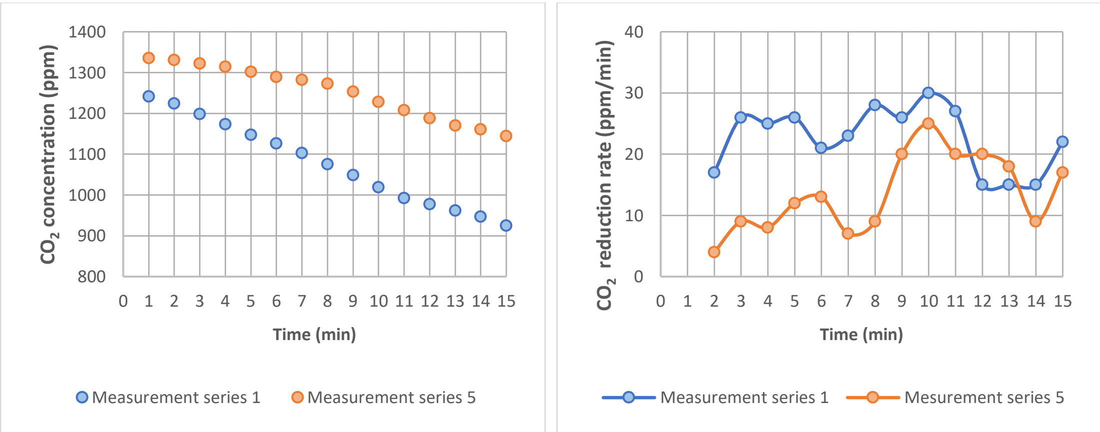


(a) (b)

Figure 4.8 (a) Simulation of indoor concentration of CO_2 where $a_{CO_2,t=0}$ = 686 ppm (b) Simulation of indoor concentration of CO_2 where $a_{CO_2,t=0}$ = 500 ppm

However, there is one simple way to optimize the indoor concentration of CO_2 which is opening door before classes. It can reduce the initial indoor concentration of CO_2 which allows expanding the duration of time before meeting the acceptable value. The simulation in Figure 4.8 (b) shows if the door is opened before classes and the indoor concentration of CO_2 at time 0 is reduced to 500 ppm. The duration of time can expand to 45, 23 and 16 min in the classroom which contains 25, 35, and 45 people respectively. Furthermore, this initial indoor concentration of CO_2 level can acceptably allow occupants to stay inside the classroom up to 22 people. According to the (Griffiths & Eftekhari, 2008), ventilation by opening window for 10 min can reduce the indoor concentration of CO_2 by 1000 ppm without compromising thermal comfort while the (Teleszewski & Gładyszewska-Fiedoruk, 2018) takes 30 min to reduce 25 percent of the indoor concentration of CO_2 by opening windows. However, the selected classroom in this experiment does not contain any windows. The only way to ventilate the classroom is opening door. Additionally, the classroom is equipped with air-conditioning system and it always employs during classes. Thus, opening door might affect energy consumption. There are two ways to ventilate the selected classroom. The first way is to clear the occupants in the classroom and keep the door closed in order to not affect the amount of energy consumption. The reduction of indoor concentration of CO_2 are observed after the class is over. According to the empirical results (Figure 4.9), if all occupants are cleared, indoor concentration of CO_2 is reduced by the ratio of 18 ppm/min. After leveraging this strategy approximately 28 minutes, indoor concentration of CO_2 drops and reaches the level at the starting point (686 ppm).

Since the ventilation method takes an extensive time period and needs a lot of occupants' cooperation, the method is not practical. Secondly, the ventilation can be done by opening the doors while the air conditioners are turned off. Since the door is opened, the second ventilation method reduces indoor concentration of CO_2 expressively and yields more effectiveness.



(a) (b)

Figure 4.9 (a) Reduction of indoor CO_2 concentration from measurement series 1 and 5 (b) Reduction rate per minute of indoor CO_2 concentration from measurement series 1 and 5

Apart from these mentioned strategies, one can install the mechanical ventilation system in the classroom, then the number of occupants and the break period are neglectable. According to (ASHRAE, 2017), the outdoor airflow required in the breathing zone of the occupied space (V_{bz}) can be calculated from the following equation:

$$V_{bz} = R_p \times P_z + R_a \times A_z \qquad (4.4)$$

Where A_z is a zone floor area, the net occupiable floor area of the ventilation zone, ft^2 (m^2), P_z is a zone population, the number of people in the ventilation zone during typical usage, R_p is a outdoor airflow rate required per person (minimum R_p for lecture classroom = 7.5 cfm/person or 3.8 L/ s·person) and R_a is a outdoor airflow rate required per unit area (minimum R_a for lecture classroom = 0.06 cfm/ft^2 or 0.3 L/s·m^2)

Breathing zone is the region within an occupied space between planes 3 and 72 in. (75 and 1800 mm) above the floor and more than 2 ft (600 mm) from the walls or fixed air-conditioning equipment (Figure 4.10). The outdoor airflow from the above equation is specific to the breathing zone since the air should be supply to the occupied zone not to the area without occupants.

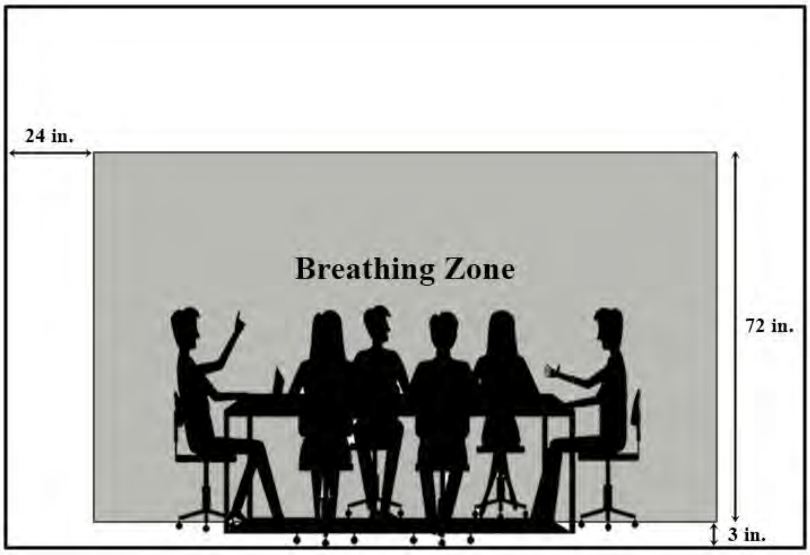


Figure 4.10 Breathing zone (ASHRAE, 2017)

The actual breathing zone outdoor air flow of the maximum capacity of the selected classroom (45 people) is 29 cfm or 14 l/s while the minimum value required is 389 cfm or 184 l/s. It indicates that the ventilation system is needed for outdoor air supplying. In Thailand, outdoor air normally has high temperature. Thus, to optimize the energy consumption, installing the supply system, i.e. fresh air supply fan, or energy and heat recovery ventilators (ERV / HRV) is the proper solution (Zemitis & Borodinecs, 2019).

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This study has conducted the 9-measurement series that have a different number of occupants and study time. The measured data reveal that, the distributions of temperature and humidity both outdoor and indoor across the dates are moderately stable within a time series of the measurements which correspond with the assumption of the two selected models. The distributions of outdoor and indoor air velocity and outdoor concentration of CO_2 are stable as well. Conversely, the indoor concentrations of CO_2 increase through time and are different across the measurement series. The results show that the concentration exceeds the acceptable value within the first 10 to 20 minute.

The comparison of CO_2 concentration predictive models shows that the Teleszewski & Gładyszewska-Fiedoruk model yields better performance than the CIBSE AM 10 model in both real-time input method and fixed input method. Although the fixed input method excessively produces unreliable prediction compared to the real-time input method, the method is more practical. Thus, the Teleszewski & Gładyszewska-Fiedoruk model is chosen to be enhanced with the fixed input method which performs based upon the residual modeling. The residual model is constructed and applies to the Teleszewski & Gładyszewska-Fiedoruk model as a correction factor. The results show that the residual model can suitably enhance the original model with the fixed input method. It produces the positive R^2 while the one without correction factor gives negative R^2. However, it should be noted that the model cannot perform properly when the room is ventilated.

To suggest the suitable numbers of occupants for certain time spent in the classroom, the simulations of indoor concentration of CO_2 are conducted based on the frequency of 60-minute break using the model with correction. The results show that if there is no ventilation before class, the maximum capacity of occupants that allow being in the classroom is no more than 18 people while ventilation before classes can stay up to 22 people. The duration of the break depends on the door opening. It must take at least 28 minutes break if the air conditioner is turned on, the door is closed, and all the occupants are cleared. However, the time can be shortened by turning off the air conditioner and opening the door. Additionally, the ventilation system can be alternatively installed, then the number of occupants and the frequency of break are negligible.

5.2 Recommendations

Future study may pay more attention to cognitive performance effect due to the high level of CO_2 because this will benefit the selection process of the suitable number of occupants in a classroom. One can easily incorporate the CO_2 simulation modeling with his/her study of cognitive performance. Furthermore, in case of mechanical ventilation system, the energy consumption should be identified precisely in order to find the best solution for classroom ventilation.

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