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Selecting Ventilation Fan Capacity for University Classroom Based on Empirical Data

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Abstract

This paper presents a guideline for selecting ventilation fan based on empirical data. The research project was undertaken in a university classroom of 64 square meters. In a two-hour experiment, carbon dioxide levels exceeded 1600 ppm when not using any ventilation system. Subsequently, the carbon dioxide levels increased approximately at a rate of 11.49 ppm per minute for 15 students sitting in the room. The carbon dioxide levels within the tested classroom exceeded 1000 ppm after the 42^{nd} minute. When students left the room, CO_2 decreased approximately at a rate of 3.67 ppm per minute. Straight-line functions were used to model the increasing and decreasing behaviour of CO_2 concentration in the classroom. An example of how to select an appropriate ventilation fan capacity is shown as an approximation guideline.

Keywords

Carbon dioxide; Classroom; Indoor air quality; Ventilation

1. Introduction

Ventilation rates have significant impacts on building energy and indoor air quality (Persily, 2016). Good indoor air quality promotes occupant health, comfort and workplace productivity (Cheong & Chong, 2001). Thermal comfort in classrooms is an important requirement to promote students' efficiency and reduce health symptoms (Stazi, Naspi, Ulpiani, & Di Perna, 2017). Indoor carbon dioxide concentrations can be used to measure building ventilation and indoor air quality (Persily & de Jonge, 2017). As ventilation to supply fresh air in an air-conditioned office consumes a considerable portion of energy, while higher ventilation rates result in less dilution, high ventilation rates can have a huge impact on both energy costs and comfort (Wong & Mui, 2008), (Prill, 2000). Higher indoor air quality initiatives result in a nonlinear increasing trend in annual thermal energy consumption (Wong & Mui, 2008). While low ventilation rates consume less energy, they may result in poor indoor air quality (Wang, Xie, Liu, & Xu, 2016). Indoor air quality is associated with student learning ability. Good air quality in classrooms enhance both children' levels of concentration and teacher productivity (Clements-Croome, Awbi, Bakó-Biró, Kochhar, & Williams, 2008). High levels of CO_2 have been shown to have an effect on pupils' learning ability (Griffiths & Eftekhari, 2008). Levels of carbon dioxide can increase by up to 4800 ppm during the first two hours of a classroom in a not well-ventilated classroom (Heudorf, Neitzert, & Spark, 2009). It has been established that mechanical ventilation systems are able to ensure the highest outdoor air supply rates in classrooms, independent of the season

(Gao, Wargocki, & Wang, 2014). Installing an air exchange fan can reduce indoor CO_2 concentration by up to 10.4% (Kang, Tseng, Wang, Shih, & Nguyen, 2016). Ventilation rates represent a critical parameter related to building energy bills and health and comfort of occupants (Batterman, 2017). Poor ventilation potentially causes excessive humidity and the accumulation of gas or chemical exposure (Bernstein et al., 2008). (Wargocki and Silva, 2015) studied impacts of manually window opening to reduce CO_2 level in school classroom. CO_2 sensors were provided as visual indicator in classrooms for teachers and students to react by opening windows. They found that energy usage increases in winter and cooling requirements reduces in summer due to such operation. Overall indoor air pollution exposures attribute to their health since most Europeans spend more than 90% of their time indoors (Arvanitis et al. 2010). People spend most of their time in confined spaces and thus are exposed to high extent to chemicals accumulated indoor (Kotzias & Pilidis, 2017). Indoor air pollution has a high correlation to outdoor air source (Sabazioti, Galinos, Missia, Kalimeri, Tolis, & Bartzis, 2017). Strong emission sources affect indoor environment in buildings (Sakellaris, Tolis, Saraga, & Bartzis, 2017). In order to design and manage appropriate ventilation systems, the effects of increasing and decreasing rates of CO_2 need to be studied. It is useful to know the carbon dioxide generation rates of students in a classroom. (Persily and de Jonge, 2017) studied CO_2 generation rates for building occupants based on human metabolism and exercise physiology. Several methods can be used to estimate and model CO_2. (Lawrence and Braun, 2007) suggested a methodology for estimating CO_2 using field measurements and developed a CO_2 schedule to manage demand-controlled ventilation in small commercial buildings. (Lu, Knuutila, Viljanen, & Lu, 2010) introduced a method of estimating occupant CO_2 generation rates from measurements in mechanically ventilated buildings. (Jiang, Masood, Soh, & Li, 2016) used realtime CO_2 measurements as an estimator tool for CO_2 levels. (Bartlett, Martinez, & Bert, 2004) used numerical method to estimate CO_2 concentration in natural ventilation elementary school classrooms. They found that CO_2 were generated at a rate 404 mg/min per child and air quality in such classroom was lower than recommended air standard. In addition, Weekly et al. developed partial and ordinary differential equations for modeling and estimating CO_2 in a conference room setting (Weekly, Bekiaris-Liberis, Jin, & Bayen, 2015). However, none of the above studies considered either increasing or decreasing rates of CO_2 levels in a classroom environment in hot and humid climate liked Thailand and modeling them in a function of carbon dioxide versus time. This paper aims at modeling CO_2 behavior and suggesting a method for designing ventilation fan capacity in classroom.

2. Research methodology

The study was implemented in one classroom of the King Mongkut's University of Technology North Bangkok. It had a size of 64 square meters, and a ceiling height of 3.5 meters. Fifteen students were present in the room. Initially, two experiments were undertaken involving increasing and decreasing levels of CO_2. Rates of CO_2 concentration in the classroom were recorded by an indoor air quality meter (Kimo AQ 200). Data was modelled using the linear regression method, which is a statistical technique for modelling the relationship between variables (Montgomery, Peck, & Vining, 2012). A straight-line function was selected to represent CO_2 concentration data. Apprehension regarding using slope and y-interception represents the reason for using the straight-line form shown in Equation 1. The slope of a straight-line represents the relative increasing/decreasing rate of CO_2 concentration. The y-interception represents the initial CO_2 level in the room prior to occupancy.

$$y = ax + b \tag{1}$$

where y = carbon dioxide concentration in ppm; x = time in minutes; a = slope of a straight-line or increasing/decreasing rate of CO_2 concentration; and b = y-interception or initial level CO_2 in the room.

The first and second experiments studied the increasing and decreasing of CO_2 as shown in Figure 1 and 2, respectively. Data were gathered on November 9, 2015 during 13:00 to 15:00 for the first experiment in Figure 1. Carbon dioxide levels were recorded for two hours while students were present in the classroom. Nevertheless, actual CO_2 concentration has a single curvature, as shown in Figure 1, and a 2^{nd} degree polynomial function should be used for better correlation than a straight-line function. However, the polynomial can be best employed to estimate figures within the range of the data known. It is not an effective model for making predictions because it tends to create double curvatures later. Therefore, a straight-line function was selected to represent increasing and decreasing rates of CO_2 in this research as an approximation model. In our experiments, two variables were found. Carbon dioxide levels in a classroom are a function of the time that students are present or left the classroom. The CO_2 concentration in Figure 1 can be represented by a straight-line function, as shown in Equation 2. It has a correlation value or R^2 of 0.988. Thus, the increasing rate is 11.49 ppm/minute, as shown in the slope value.

$$y = 11.49x + 427$$

Data for the second experiement were gathered on November 9, 2015 during 15:15 to 17:15 as shown in Figure 2. The decreasing rates of CO_2 concentration can be noticed after students left the classroom without ventilation fans having been operated. Such rates decrease naturally. All doors and windows were not open during the two-hour periods under consideration. A straight-line model for these data sets is shown in Equation 3. It has a correlation value or R^2 of 0.994. CO_2 decreased at a rate of 3.67 ppm/minute. Correlation values of the decreasing rates of CO_2 function is obviously better than the increasing rates of CO_2 function.

$$y = -3.67x + 1801 \tag{3}$$

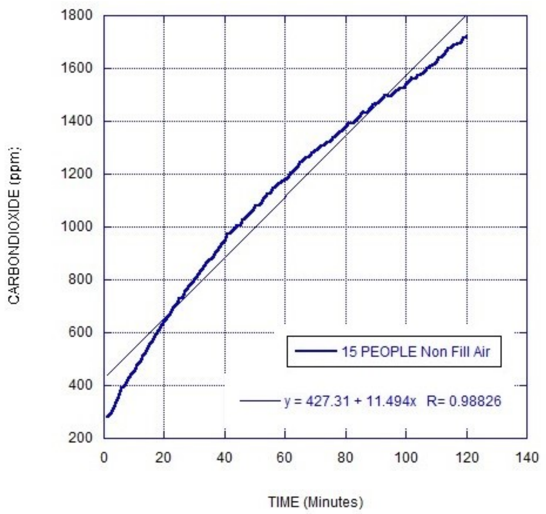

Figure 1. Increasing rates of CO_2 in the experimental room

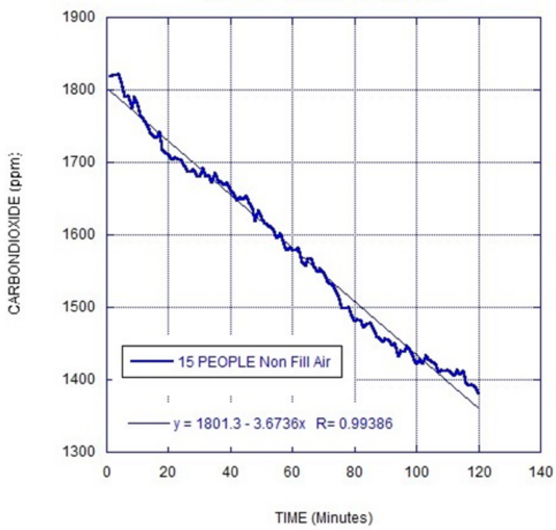

Figure 2. Decreasing rates of CO_2 in the experimental room

With respect to carbon dioxide levels, the Occupational Safety and Health Administration specifies the transitional limit of carbon dioxide in workplace as 5,000 ppm over a time weighted average (OSHA, 2017). A generally satisfactory level for indoor CO_2 concentration is between 1,000-1,200 ppm (ASHRAE, 2014). Therefore, the level of CO_2 used as a threshold in this research is 1,000 ppm, representing generally acceptable indoor air quality. The impact of employing ventilation fans is then studied by encouraging fresh air into the room and reducing CO_2 concentration, as shown in Figure 3. It illustrates the data gained in the third experiment where ventilation fans were operated. The fans were operated manually when CO_2 levels inside the room exceeded 1000 ppm. The ventilation fans supply fresh air at a rate of 362 cfm, or 616 m^3/hr. The actual ventilation rate, which ensures acceptable indoor air quality, is 24.13 cfm/person. This number is higher than that recommended by Thai standards. The minimum ventilation rate required for a classroom in Thailand stands at 15 cfm/person (EIT, 2005). The fresh air supply fan has enough power to disburse CO_2 at a rate under 1,000 ppm. The test duration in Figure 3 is less than 120 minutes due to classes adjourning before time.

From Figure 3, the ability to dissipate CO_2 concentration can be determined by projecting the increasing rate beyond the 64^{th} minutes with Equation 2, and subtracting with actual CO_2 figures for the period between the 64^{th} and 101^{st} minutes. Thus, we arrive at the projection shown in Figure 4. The difference between the values of the two lines shown in the Figure 4 can be modelled as presented in Equation 4. It can estimate a removal rate of CO_2 while ventilation fan is operated. The installed ventilation fans, which have a capacity of 362 cfm, have the ability to remove CO_2 at a rate of approximately 13.4 ppm/minute. By dividing 362 cfm with 13.4 ppm/minute, 27 cubic foot of fresh air is required to remove one ppm of CO_2.

$$y = 13.4x - 0.98 \tag{4}$$

However, ventilation fans serve to channel hot and humid air into rooms since Thailand is subject to a typically hot and humid climate. Electricity consumption increases since air conditioning units work harder and consume more electricity to maintain the room temperature at 25 °C. Energy consumption is 1.28 and 1.91 kWh when ventilation fans are switched off and on, respectively. Through dispersing fresh air into the experiment room, electricity consumption increased by 49%. Thus, minimizing the use of ventilation fans can save energy.

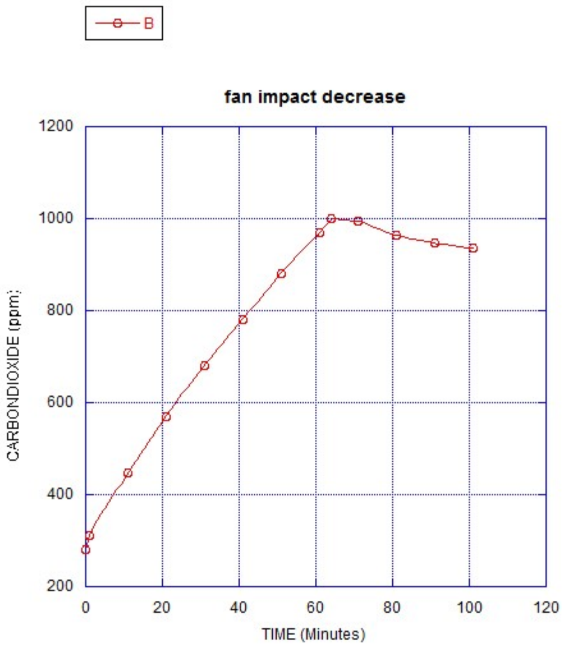

Figure 3. Operating a ventilation fan at a threshold of 1000 ppm

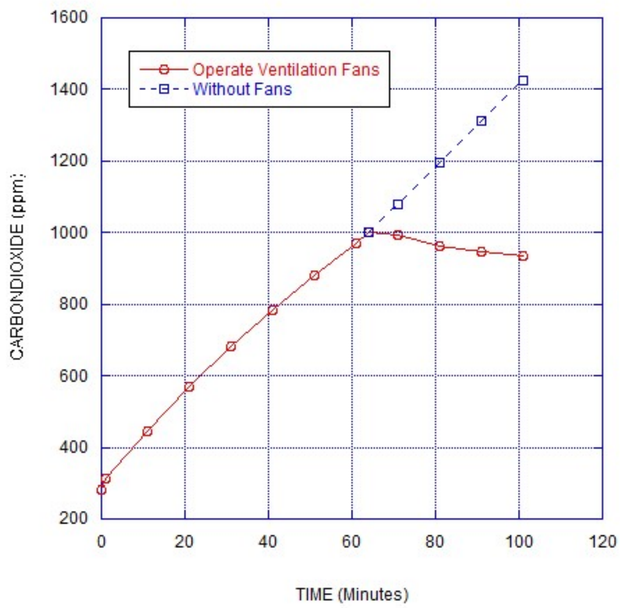

Figure 4. Using Equation 2 to project increasing rate of CO_2 to determine the ability to dissipate CO_2 by installed ventilation fan.

3. Scenarios in operating ventilation fans

To maintain desirable indoor air quality, ventilation fans should be operated in rooms crowded with people. In this section, we will consider two scenarios concerned with the operation of a ventilation fan. The first scenario mimics situations when CO_2 sensors are set to operate ventilating fans at 1000 ppm, as shown in Figure 5. Equation 2 was used to generate CO_2 in both scenarios. Meanwhile, the ability to remove CO_2 by fans as represented in Figure 3 is used to simulate the CO_2 concentration behaviors when operating ventilation fans. The total fan operating time is 54 minutes and the maximum CO_2 found is 1015 ppm.

Second, the alleviation of CO_2 concentration is studied after students having left the classroom. Two methods were considered involving alleviation under natural conditions and alleviation using ventilation fans, as shown in Figure 6. During the first 120 minutes, classes were full with 15 students studying for two hours. Subsequently, students left the classroom. In Figure 6, the top line represents the situation where CO_2 decreases naturally at a rate of 3.67 ppm per minute as determined from Equation 3. It is obvious that CO_2 cannot be removed to a satisfy level at 1000 ppm within one hour. The other line represents the situation where the ventilation fan was operating and students left the room for one hour. CO_2 concentration reduced at the combined rates of 3.67 and 13.4 ppm per minute as determined from Equations 3 and 4, respectively. When using the latter method indoor air quality quickly improves. CO_2 concentration diminishes by 1029 ppm in one hour. Since most classrooms in Thailand are vacant during lunch period from 12:00-13:00, schools should be strongly encouraged to operate ventilation fans during this period in order to restore air freshness in the classroom.

4. Selecting ventilation fan size

This section gives a guideline in selecting the appropriate size of ventilation fan based on developed models. The question under consideration concerns if 25 students are attending a class in a 64 square meter room, what is the appropriate capacity of a ventilation fan in cfm. The first step involves calculating the CO_2 emission of 25 students. Based on our data, CO_2 increases at a rate 11.49 ppm/minute for 15 students or 0.76 ppm/person/minute.

Therefore, the CO_2 emission rate for 25 students should be 19.15 ppm/minute, as shown in Table 1. From earlier results, it is suggested that approximately 27 cubic feet of fresh air would be required to remove one ppm of CO_2. Therefore, a ventilation fan capacity of 517 cfm is appropriate for this size of room and number of students. This number is higher than recommended by EIT (2005) and (ASHRAE, 2007) at 375 cfm and 187.5 cfm, respectively. Furthermore, the fan might be controlled by CO_2 sensor setting a threshold at 1000 ppm to turn the fan on and off at 800 ppm. Such operation could minimize energy consumption from air condition unit.

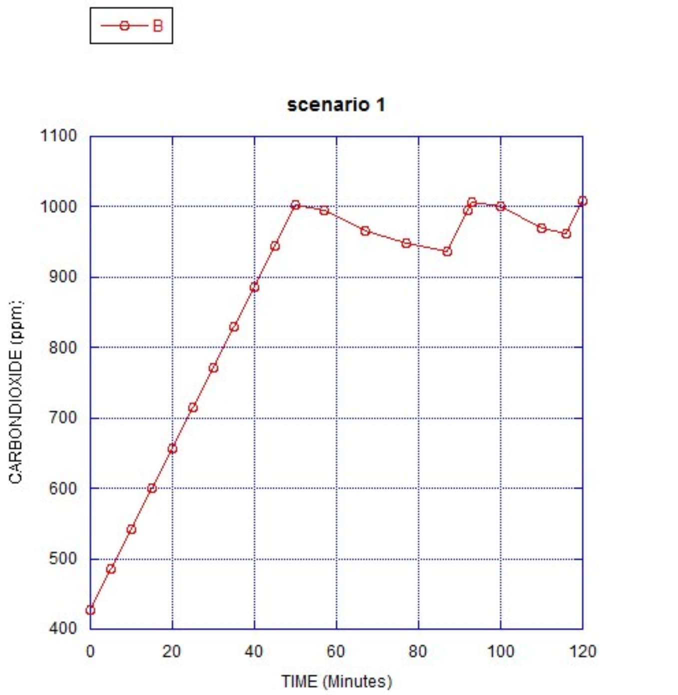

Figure 5. Simulating an operation of a ventilation fan at a threshold of 1000 ppm.

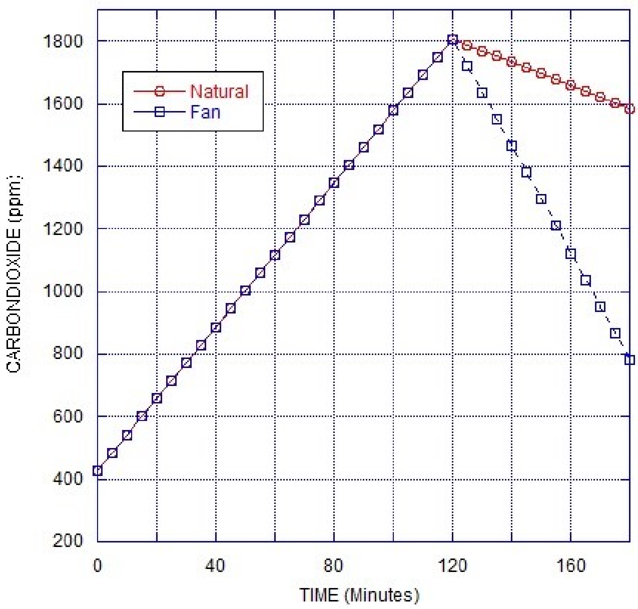

Figure 6. Effects of CO_2 removal by natural means and using ventilation fan after students have left a classroom

Table 1. Example in selecting the size of ventilation fans

Input		
Number of Students	25	persons
Size of Room	64	sq.m.
Process		
Rate of CO_2 Generated By Students		
At a Rate of 0.76 ppm/person/minute	19.15	ppm/min
Result		
Required Size of Fans to Maintain		
1000 ppm based on 27 cf/ppm	517	Cfm

5. Conclusion

This research outlines details of preliminary models for estimating and predicting CO_2 concentration in classrooms. An example case study is presented. However, there are many limitations regarding the models since they are developed in terms of a classroom of 64 square meters with 15 students in attendance. More research could be undertaken to develop more versatile models encompassing different situations such as different size of rooms, ventilation fan capacities, and number of students. In our experiment, CO_2 increases at a rate 11.49 ppm/minute with 15 students, or 0.76 ppm/person/minute. It decreases naturally at a rate of 3.67 ppm per minute after students have left the classroom. This rate also depends on the nature of openings to the room. Guidelines for selecting the size of ventilation fans to reduce CO_2 concentration in classrooms have been suggested. The operation of mechanical ventilation may be required during vacant periods before students enter their next class in order to ensure acceptable indoor air quality for students. This research demonstrates how to develop a model for estimating CO_2 values in a classroom from an empirical study. An increasing rate of CO_2 due to students being present in the classroom were found at 0.76 ppm/person/minute. By using a ventilation fan, CO_2 level in room reduces. From our study, a 27 cubic foot of fresh air is required in order to remove one ppm of CO_2. As a result, building designers can use this number as a guideline in selecting ventilation fan capacity.

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