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EXAMINING CO₂ LEVELS IN SCHOOL CLASSROOMS

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SUMMARY

High CO₂ levels in school classrooms continue to be a concern. As a result we reviewed the mass-balance model of ventilation. We identified several factors by fitting the model to the data. The review allowed CO₂ build up, ventilation rates and exhalation rates to be examined in real (on-site) measured conditions.

We discuss the theoretical model of the growth and decay of CO₂ concentration in a space and how it relates to the data through the parameters of the model, providing an understanding of the drivers of CO₂ concentration and some validation of the theory by the data. Results from our measurements of Australian school classrooms are similar to other parts of the world, indicating CO₂ levels, ventilation rates and air temperatures do not comply with the standards.

INTRODUCTION

This paper utilizes the results of the MABEL (Mobile Architecture and Built Environment Laboratory) facility project, which measured several school classrooms for their CO₂, comfort index and temperature stratification levels (Luther and Atkinson, 2012). These Australian results confirm what has been discovered elsewhere internationally, that school classrooms frequently suffer poor indoor air quality, ventilation and comfort control. In an effort to remedy these problems, as found in our evidence-based study, this paper begins first by understanding the build up and decay of CO₂ in the provided cases.

A broad range of studies shows that ventilation rates in schools are inadequate (Mendel and Heath, 2005). What is controversial is the number of air changes required to ventilate classrooms to achieve acceptable levels of CO₂ and pollutants. Perhaps the causes of this are the various units and methods of determining ventilation air change rates as well as a misinterpretation of the standards. The ASHRAE Standard 62.1-2004 (ASHRAE 2004) recommends a minimum of 8L/sec per person for classrooms. Depending on classroom size, and volume this amount could typically result in between 3-5 ACH per classroom (Daisey et al. 2003 and Becker et al. 2007).

Achieving energy efficiency stands in opposition to controlling classroom air humidity, temperature and ventilation. Studies indicate improved student performance for elevated ventilation rates and reduced air temperatures in classrooms in summer (Wargocki and Wyon, 2006). These studies also observed CO₂ levels and found substantial reductions using ventilation rates of 6.5 and 9.5L/s/person, yielding 900ppm and 780ppm respectively. Other
researchers confirm that rates of 7 – 10 L/s/person are required to reduce TVOC’s and other pollutants (Fischer and Bayer, 2003 and Daisey, et al., 2003). Further studies confirm that air quality symptoms increased at a ventilation rate below 10L/s/person (Seppanen et al., 1999). Our review suggests that more accurate calculations accounting for the number of people, their activity and the room volume as well as the air change rate, can be performed.

The above work of others and our measurement studies of several Australian school classrooms prompted several questions. What is a reasonable respiratory (CO₂ generation) rate for a typical student? How does the air change rate affect the CO₂ levels over time? What influence does room volume have on the level of CO₂ for a given condition? In search of answers to these questions we began to review the fundamental mass-balance equations.

**METHODOLOGY**

We present the theoretical model of CO₂ concentration in detail so as to clarify the roles of the quantities involved. The general solution shows the relationships between the key parameters.

**Ventilation Standards and Theoretical Model**

Previous work suggests that the first step in designing for ventilation is to calculate the ventilation requirements with respect to the acceptable indoor air quality. Various national and international standards exist, which give guidance on required fresh air design rates, but the sources offer inconsistent advice. However, all agree that schoolrooms, due to the number of occupants, require more dilution air than adult occupants in a similar space. The range of values suggested in the standards is from 6.25 to 15L/s/person (AS 1668.2-2002 and EN 13779 2007).

In order to determine what a ventilation rate should be for a particular case the parameters involved in causing high CO₂ levels must be understood first. We are interested in understanding how CO₂ concentration changes in a confined space. This change occurs at any instant at rates determined by the ventilation rate and the number of occupants in a known volume. Given a volume, CO₂ enters it at a rate determined by the outdoor CO₂ concentration, $C_{ext}$, and leaves it at a rate determined by the indoor CO₂ concentration at time $t$, $C(t)$. In addition, people add CO₂ to the air in the room at rates estimated from physical measurements (Figure 1).

![Figure 1. Carbon dioxide flows in a confined space](image-url)
This is summarized in Equation (1) in which the rate of adding CO₂ less the rate of exhausting CO₂ causes the concentration of CO₂ in the volume to change. This equation expresses the mass balance, the balance of CO₂ entering and leaving the volume at some instant, \( t \):

\[
V \frac{dC(t)}{dt} = G + QC_{\text{ext}} - QC(t)
\]  

(1)

where

- \( V \) = space volume in m
- \( C(t) \) = indoor CO₂ concentration in ppm(v)
- \( C_{\text{ext}} \) = outdoor, or ambient, CO₂ concentration in ppm(v)
- \( t \) = time in s
- \( G \) = indoor CO₂ generation rate in mL/s for a fixed number of occupants
- \( Q \) = space ventilation rate in m³/s
- \( \frac{dc(t)}{dt} \) = the rate of increase in the CO₂ concentration in ppm(v)/s

The rate of increase of CO₂ will be zero when \( G + QC_{\text{ext}} = QC(t) \); that is, the CO₂ generated by people balances the CO₂ introduced and removed by ventilation. If this balance is achieved, as it will after a sufficient time, \( C(t) = G/Q + C_{\text{ext}} \). This specific \( C(t) \) is the steady state or final value of CO₂ concentration and we label it \( C_{ss} \).

To allow for the number of people in the room, we define \( g \) and \( N \) in terms of \( G \) as follows:

\[
G = Ng
\]  

(2)

where \( N \) = the number of people in the space, and \( g \) = indoor CO₂ generation rate in mL/s per person. Hence,

\[
C_{ss} = \frac{G}{Q} + C_{\text{ext}} = \frac{Ng}{Q} + C_{\text{ext}}
\]  

(3)

it is always true that \( C_{ss} \geq C_{\text{ext}} \). Hence, \( C(t) \) can never fall below the ambient concentration of CO₂, \( C_{\text{ext}} \).

Quite often, insufficient time is available for \( C(t) \) to reach \( C_{ss} \), and we need to know the transient behaviour of \( C(t) \); that is, how \( C(t) \) changes before settling. Furthermore, it may be that the space is not initially in equilibrium with the environment. The solution to the above Equation (1), satisfying initial and final values, is the exponential equation:

\[
C(t) = (C_{ss} - C_{t0}) \left(1 - e^{-\frac{Qt}{V}}\right) + C_{t0}
\]  

(4)

where \( C_{t0} \) is the actual CO₂ concentration at \( t = 0 \).

\* Note that 1 mL/m³ = 1 ppm(v).

\* We ignore the unrealistic case in which, initially, CO₂ is absent from, or reduced in, the indoor air, as it will eventually rise to the ambient concentration, \( C_{\text{ext}} \), of CO₂.
The air change rate is in fact the quotient \( Q/V \) represented by the symbol \( a \). Its reciprocal, \( \tau = V/Q \) is the time constant of Equation (4). This is the time required to change one air volume in the space considered. It is important to understand that the concentration of CO\(_2\) as time passes is determined by knowing the values of three parameters, its initial concentration, \( C_{t0} \), final concentration, \( C_{ss} \), and the air change rate, \( a \). Of course, these values may change in response to external or internal influences, changing the behaviour of \( C(t) \).

Substituting \( aV \) for \( Q \) and rearranging Equation 3,

\[
\frac{N_g}{V} = a(C_{ss} - C_{ext})
\]

it is clear that the three quantities determining the concentration curve that are on the right of the equation are also related to the quantity \( N_g/V \). This quantity is the rate at which people add to the CO\(_2\) concentration in the space. That is, the number of people in the room, their average CO\(_2\) exhalation rate and, inversely, the room volume combine to offset exfiltration reducing CO\(_2\) concentration to the background value.

An example of modelling various air change rates, by applying the previous equations to a space with a constant CO\(_2\) generation rate and fixed volume is shown in Figure 2. Note that the time-constant, \( \tau = 1/a \), differs for each curve as \( a \) changes, as does the final value, \( C_{ss} \).

If the air change rate, \( a \) is small, the time-constant, \( \tau \), and the final value, \( C_{ss} \), are large. The concentration of CO\(_2\) takes a long time to settle to a large value. On the other hand, if \( a \) is large, the time-constant, \( \tau \), and the final value, \( C_{ss} \), are small, and the concentration settles quickly to a small value, closer to \( C_{ext} \).

![Graph: Theoretical CO\(_2\) Concentration for various Air Change Rates](image)

**Figure 2. CO\(_2\) Concentration for Various Air Change Rates in a Classroom**

**Establishing a Target Value of Classroom CO\(_2\)**

According to the NISTIR 6729 report by Emmerich and Persily (2001), carbon dioxide is not generally considered to be a health problem. A limit for an 8 hour exposure and a 40 hour work week is 5000 ppm(v) and a short 15 min exposure limit is 30,000 ppm(v).
A major driver for investigating CO₂ build up in school classrooms is discomfort, leading to learning difficulties. Several publications by the World Health Organisation (WHO) and ASTM D6245 (2002) recommend an upper limit value of 1000 ppm. Furthermore, studies have been conducted to investigate the Predicted Percentage Dissatisfied (PPD) with CO₂ concentrations indicating that a 25% PPD begins at around 1000 ppm. It must be noted that this figure is concentration above outdoor CO₂ levels, indicating that ~1,400 ppm would be the accepted value at 25% PPD. These findings have also been confirmed in the publications of Olesen (2004).

**Estimating CO₂ Generation within a Classroom**

Since we are interested in the removal of CO₂ we need to know at what rate this is being generated. Results presented in Plowman & Smith (2007) and Emmerich & Persily (2001) for an activity level of 1.5 met indicate a CO₂ production level of 0.0065 L/sec, or 390 mL/min. However, it should be noted that these values are for adults and are therefore conservative. Plowman & Smith report a tidal volume range of 6–90 L/min from which a typical tidal volume of 20 L/min might be assumed. The exhaled CO₂ concentration is about 4.5% or 900 mL/min. ASTM D6245 (2002) suggests the CO₂ generation rate of a child with a physical activity level of 1.2 met is 0.0029L/s. For an adult this this is 0.0052 L/s (320 mL/min). In Figure 2, the CO₂ generation rate per student is assumed to be 300mL/m/person, but we intend to investigate this parameter more closely from our measurement data.

**RESULTS AND DISCUSSION**

We studied 24 classrooms in four different schools during a winter period in Victoria Australia (a cool temperate climate) with different building construction types. No classroom had room conditioning during the measurement period. It is clear that CO₂ levels can increase rapidly in a typical occupied non-ventilated room as shown, for example, in Figure 3. Furthermore, the opening of a door copes with this problem easily during a break, indicating that a proper cross-ventilation will reduce CO₂ levels dramatically.

![Figure 3. CO₂ and Humidity Levels in a Single Classroom](image-url)
We need to fit the theoretical model to the data to identify the parameters $a$, $c_{ss}$ and $c_{t0}$ in Equation (4) because the CO$_2$ concentration rarely settles to steady values. Indeed, there is no point in Figure 3 which has reached a steady state. Given these values, we can then determine the factor $Ng/V$, and hence the CO$_2$ exhalation rate, $g$.

The fit of the model to seven points from 9:15 to 10:45 (left ellipse in Figure 3) is shown in Figure 4. From Equation (5), $Ng/V = 2193$ ppm/hour. Assuming a room volume of 250m$^3$ and that there are 22 – 25 people in the room, as recorded, for 25 people, $g = 366$ mL/person/minute.

The fit of the model to the later seven points from 12:00 to 13:30 (right ellipse in Figure 3), is shown in Figure 5. In both cases, the room is closed and the air change rate is 0.62 which is close to 0.60 for the earlier fit. This is a good validation of the model. Hence, $Ng/V = 75$ ppm/hour. However, the number of people recorded is 6 – 20 and the internal partition between this and the adjacent classroom is now open, so the room volume is now 500m$^3$. This yields $g = 104$ mL/person/minute for 6 people, a figure too low which needs further investigation.

CONCLUSIONS

We have reviewed a number of papers which show that ventilation rates in schools are inadequate and that the required air change rate to achieve acceptable levels is controversial. As a result, we have gone back to the theoretical foundations of ventilation. Although this theory is long-standing, insights from it have proved valuable.

We have explored the behaviour of CO$_2$ concentration in a room as a function of time, room volume, the number of people present and their exhalation rate of CO$_2$, the air change rate, the initial concentration of CO$_2$ and its background concentration. As a result, we have fitted the function to the data in a number of cases, of which we have shown two fits from the same
room. This shows a consistency in the value of the air change rates required to fit the model to the data, validating our approach. Having fit the data, we have then been able to estimate the exhalation rate, but this is not as consistent and needs further investigation.

Having made a fit by adjusting the parameters $a$, $C_{ss}$ and $C_{t0}$ in Equation (4) to minimize the mean square error of the theoretical data point to the measured data point, a good estimate of $Ng/V$ and therefore $g$ may be determined since $N$ and $V$ are known.

Re-examining the equations of ventilation theory and fitting measured data have provided important insights. The causes and rates of CO$_2$ generation within a room are better understood. In particular, the rate at which CO$_2$ is exhaled per student in a classroom under typical user conditions can be better identified. Also, the study of air change rates and their influence on CO$_2$ reduction is applicable to HVAC ventilation system design. It is important to recall that this investigation considered non-mechanical, passive ventilation of classrooms. These passive air-change rates could be increased through mechanical means if necessary.

Furthermore, the observation that it takes time to reach a particular CO$_2$ level in the real-world classroom, where nothing remains constant for a long period of time, can mean that active ventilation can be delayed until a threshold concentration is reached, saving energy.

Lastly, since we have a method for investigating ventilation which identifies the relevant parameters from data, we have a model which can be used for prediction. Working in reverse, the variation of concentration of CO$_2$ can be predicted as a function of time, as $N$ and the room conditions change. This work is yet to be reported. We intend to make further findings from our case study measurements, including advice for HVAC design and control.

**REFERENCES**


