Healthy Buildings 2017 Europe
July 2-5, 2017, Lublin, Poland

Paper ID XXXX ISBN: XXX-XX-XXXX-XXX-X

Does Control of Indoor CO_2 Levels Negatively Impact IAQ?

Neil Glover[1], Richard McElligott[1], Chris Muller[2,*], David Bennett[2], and Peter Fish[3]

[1] Future Decisions, Yateley, Hampshire, U.K, University of Reading, Berkshire U.K.
[2] Purafil, Inc., Doraville, Georgia, U.S.A.
[3] Prisma Services Ltd., Holmewood, Chesterfield, U.K.

[*]*Corresponding email:* cmuller@purafil.com

SUMMARY

Carbon dioxide (CO_2) monitoring has long been used as a surrogate indicator of indoor air quality (IAQ). However, with the advent of affordable multi-gas sensor technologies, this is a flawed and counterproductive approach in that low CO_2 levels do not necessarily equate to good IAQ. A common misrepresentation of ASHRAE Standard 62.1: *Ventilation for Acceptable Indoor Air Quality* is that a target level of ~1,000 ppm of CO_2 indicates acceptable IAQ. However, many believe this has detracted from addressing true causes of poor IAQ and ASHRAE even acknowledges such by removing the discussion of CO_2 from normative sections of the standard. Still, this has not kept CO_2 out of the public eye with recent reports of productivity loss associated with higher levels. This information, along with current EU/UK building regulations detailing ventilation system designs, have led to a requirement for CO_2 concentrations not to exceed ~1,200 ppm indoors, which again leads to an assumption by design engineers that the now mandated CO_2 measurement and abatement systems equate to better IAQ, and by proxy improved productivity. Applying a design approach to lower internal CO_2 levels by increasing the intake rate of "fresh" outdoor air actually reduces IAQ in many locations. Within the built environment, outdoor air brings with it elevated levels of a range of pollutants including particulate matter (PM), nitrogen dioxide (NO_2), and ozone (O_3). Thus, higher ventilation rates increase indoor pollutant levels with a concurrent decline in IAQ. Results of investigations will be presented that show how energy saving strategies combined with pollution from motor vehicles can lead to the introduction and build-up of these pollutants within buildings resulting in significantly poorer IAQ within buildings.

KEYWORDS

Air cleaning, air pollution, ASHRAE Standard 62.1, carbon dioxide, indoor air quality

1 INTRODUCTION

Various national bodies such as the Department for Education in the UK have set standards for CO_2 levels in buildings in its own right – in this case stipulating a maximum average value of CO_2 of 1,500 ppm (EFA, 2014). Current EU/UK building regulations, and specifically Part F: Ventilation (DCLG, 2015), implies that CO_2 concentrations should not exceed ~1,200 ppm indoors. The current trend of CO_2 management in buildings and by association its proxy for good IAQ is pushing building control philosophies to lower internal levels by increasing the intake rate of “fresh” outdoor air.

Carbon dioxide (CO_2) has been used as a surrogate indicator of indoor air quality (IAQ) for decades even though the direct connection between CO_2 levels and IAQ in buildings remains debatable. First introduced in 1981 by the American Society of Heating, Refrigerating, and Air-conditioning Engineers in its Standard 62.1: Ventilation for Acceptable Indoor Air Quality (ASHRAE, 2016), a target level of 1,000 parts-per-million (ppm) was used as an indication of acceptable IAQ. Being at or below this level did not guarantee good IAQ, and in fact, many believed it detracted from true causes of poor IAQ to the point that the current version of Standard 62.1 does not consider CO_2 as a contaminant of concern with regards to IAQ and no longer discusses CO_2 in the normative sections of the standard. However, this has not kept CO_2 monitoring out of the public eye.

Because no direct health effects could be identified for CO_2 levels below ~2,500 ppm in commercial buildings, attention turned towards worker productivity and student learning metrics. For instance, several recent studies have suggested a link between “elevated” CO_2 levels in schools and decreases in standardized test scores. However, the current drive for buildings to lower CO_2 levels and its continued use as a proxy indicator for IAQ is both flawed and counterproductive for the maintenance of good IAQ.

Many currently argue about the need to look at concentrations of a wide range of indoor pollutants, rather than a single proxy value. In most cities, particularly during the day, outdoor air cannot be considered “fresh” but contaminated with elevated levels of a range of pollutants from particulate matter (PM) to chemical pollutants. Increased outdoor air ventilation rates has the result of introducing more and different types of pollutants and as such reduces the IAQ. Initial studies have also shown that due to (off-hours) energy saving strategies, higher levels of motor vehicle pollution are trapped within these buildings. This results in generally poorer IAQ inside the building due to the addition of pollutants with outdoor sources to those with sources inside the building. Finally, quantification of the liabilities of poor IAQ in terms of, for example, health effects, remains an inexact science, albeit an improving one.

2 SOURCES AND TYPES OF OUTDOOR AND INDOOR AIR POLLUTANTS

The World Health Organisation’s air quality guidelines (WHO 2005) gives a detailed analysis of the current toxicological effects of common outdoor and indoor contaminants. Excluding leached pollutants such as VOCs from occupants as well as building materials and furnishings, the typical pollutants encountered indoors (depending on location) are of two types: particulates; PM_{10}, $PM_{2.5}$, and PM_1, and gases; NO, NO_2, O_3, SO_2. CO, and VOCs.

Nitric oxide (NO) is not a toxic pollutant but can be a predecessor of ozone (O_3). Most (97-98%) of the urban population of the EU is exposed to elevated levels of O_3 pollution (EEA 2016) and motor vehicle traffic is estimated to produce 40% of European nitrogen oxide (NOx) emissions (EEA 2014). Motor vehicle emissions are relatively more harmful than from other sources as they occur in areas where people live and work.

For large commercial buildings with standard HVAC systems, indoor pollutants are typically in gaseous form as total particulates are normally only ~20% of outdoor levels. This is not achieved using specialty particulate filters but rather standard bag filters designed for urban dust. A typical profile of PM within an office is shown in Figure 1. The particulate density in micrograms per cubic meter ($\mu g/m^3$) is measured at the ventilation intake to the building, the office space at table height and at the return side of the ventilation system which allows particulate sources to be determined.

The occasional spikes in indoor PM are associated with indoor activity rather than external particulates brought in by the ventilation system. The periods of high particulate counts at the ventilation return are associated with times when the system is off and particulates diffuse back into the return void.

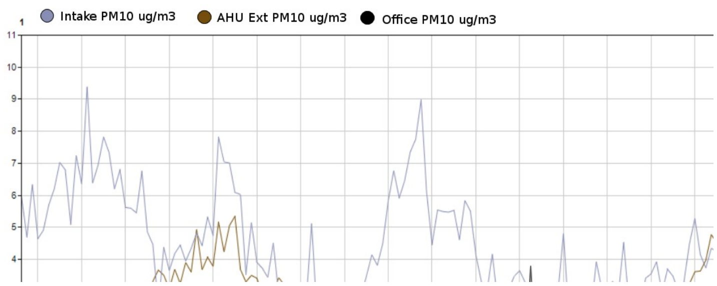

Figure 1. Particulate concentration profile (typ.)

3 AIR QUALITY MONITORING OF OUTDOOR AND INDOOR AIR

There are around 300 Environment Agency (EA) managed monitoring sites in total across the UK which monitor air quality and these are organized into networks to gather a particular kind of information, using a particular method (Defra, 2017). The pollutants measured and methods used depends upon the reason for setting up the network and how the data is used. The number of measurements made has increased dramatically every year for all pollutants (O_3, NO_2, CO, SO_2 and PM_{10}) being monitored and for other UK Strategy pollutants.

For monitoring of indoor air, the quality of sensors and sensor technology have lagged behind requirements. Most provide a “cumulative” IAQ measurement instead of differentiating compounds. Conventional chemical and particulate matter reference monitoring instruments are large and inappropriate for use at multiple sites within buildings. The work done by air monitor manufacturers to develop and authenticate multi-gas and particulate monitoring systems with comparisons to EA reference monitoring stations has resulted in air monitors with verifiable accuracy over long-term trials (“Co-location comparison trials,” 2017).

For this study, small sensor pods were used to measure NO, NO_2, NOx, O_3, CO, SO_2, along with PM_1, $PM_{2.5}$, PM_{10} and total particulate carbon (TPC). They were also used to measure local conditions; %RH, temperature, and atmospheric pressure. Their small size along with battery operation and 3G wireless data collection allowed the monitors to be placed within the ventilation systems and office environment without disruption to the building occupants.

4 OUTDOOR AIR QUALITY AND IAQ

The ventilation section of a heating, ventilating and air conditioning (HVAC) system is not only responsible for introducing and distributing “fresh (outdoor) air” but also for maintaining the temperature in the occupied space within a specified temperature range.

The classical approach of ventilation control in large commercial and office buildings is based on time which means that for a specified period, depending on the season, the ventilation system is operated early enough in the day to bring the temperature within the desired range by the start of the working day. As people leave at the end of the day, the ventilation system is shut down, allowing the temperature to depart from this range to save energy. The now mostly empty building relies on diffusion rather than forced ventilation to disperse CO_2 and other pollutants and that have built up during the day. This approach is taken solely to save the considerable amounts of energy expended to control the temperature. The graph shown in Figure 2 below shows the classic timed profile of HVAC systems.

Pressure in the return air duct represented the ON/OFF time for the intake fan. The outdoor pollutant NO_2, associated with early morning traffic, peaks from 6-8 a.m. The internal NO_2 level rises from ventilation start-up at 4 a.m., until it coincides with outdoor NO_2 levels at approximately 7:45 a.m. The peak internal NO_2 level occurs at the start of the day for the office workers, approximately 8:45-9:00 a.m.

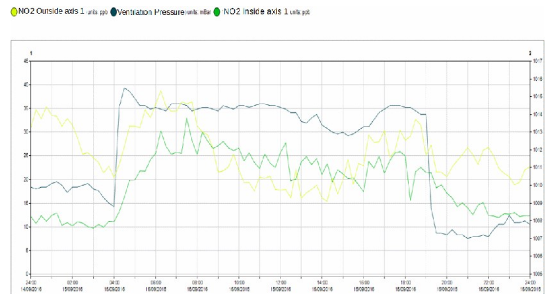

Figure 2. Example of a time-controlled HVAC system (readings were taken in London during British Summer Time (BST).

This NO_2 pollution profile associated with timed ventilation systems is typical of the office buildings surveyed in London, however, most do not absorb the NO_2 as quickly as shown in this profile. The traffic pollution peaks are typically coincident with the HVAC ON & OFF timings making the ingress of early morning pollution inevitable. Due to air transport delays and the inherent buffering effect of large spaces, the early morning pollution is captured and retained across the working day even as the outside levels drop below the internal levels. The daytime pollution is then retained and replenished until the evening peak is captured when the system switches off.

By altering this time controlled HVAC system to a demand controlled system, the intake of outdoor air is limited by need. The greatest need for outdoor air is for dilution of elevated CO_2 levels. In London, a secondary need is to help control the internal temperature by bringing in cooler outdoor air to reduce the cooling load required by modern well insulated office spaces.

The current ventilation requirements for commercial spaces such as offices buildings are set by ASHRAE Standard 62.1-2016. This is based on a nominal outdoor air ventilation rate per person occupying the space. As the number of people occupying the space at any one time is difficult to measure, the UK/EU Building requirements for new buildings have defined a more reasonable value of CO_2 to not exceed ~1,200 ppm indoors (DCLG, 2015). Further, new buildings are required to install CO_2 monitors linked to the operation of the HVAC systems.

The building controls community are well aware of the huge fluctuations in CO_2 that can occur across an office space. For example, poorly ventilated or under-ventilated meeting rooms may see values in excess of the Part F requirement while open office spaces never get close. This and a poor understanding of the effects of external pollution on the internal space has pushed building controls engineers to equate low levels of CO_2 with good IAQ.

The most modern building systems include a measurement of CO_2 within the environmental comfort control strategy. If the measured CO_2 levels within a zone of the building drop below a threshold level, the volume of air to that zone is increased. For the low threshold levels found (600 ppm) this resulted in high volumes of “fresh” air being drawn into all zones of the building during the afternoon working hours. The early morning HVAC start of 5 a.m. is typically associated with the need to cool the space after the evening and night time temperature increases. This high-volume air flow has the effect of capturing the early morning traffic pollution. After the temperature had come into the set range, the volume of outdoor air can be reduced as CO_2 is at near ambient levels as it has not yet had time to increase. This has the effect of reducing the flushing effect and capturing the high morning pollution for a longer period. Higher volumes of outdoor air used in the late afternoon to dilute the higher CO_2 levels bring in a higher level of pollution that accompanies the peak afternoon/evening traffic.

The unintended consequence of this combined timed/temperature/CO_2 threshold strategy is to ensure that the gaseous air pollutant concentrations within space are higher than outside. The potential health effects of higher indoor pollution levels far outweigh the benefits of lower CO_2 levels.

Recent research in the effects of CO_2 have suggested that at levels of 1,000 ppm, statistically significant reduction in intellectual performance can be measured (Satish et al., 2012). Using this as a guide and modifying the control strategy to allow the higher threshold of 800 ppm of CO_2 to dominate the air intake control and the variable speed of the air volume supplied to each zone within the building had significant effects of the pollution levels within the building. These simple changes combined with a learnt profile of the pollution at the air intake and the characteristic building CO_2 profile associated with occupancy allowed the system to significantly change the amount of pollution entering the building, while maintaining CO_2 levels well below required levels. The efficacy of the approach is shown in the graphs below.

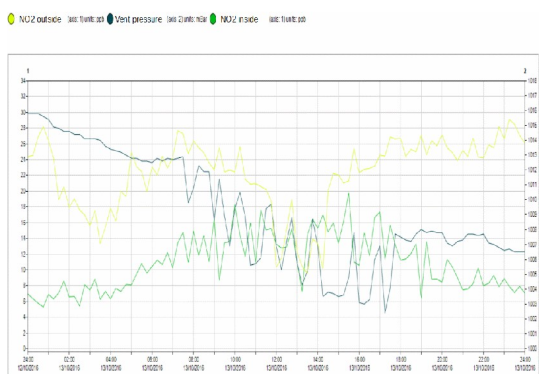

Figure 3. HVAC system ventilation profile

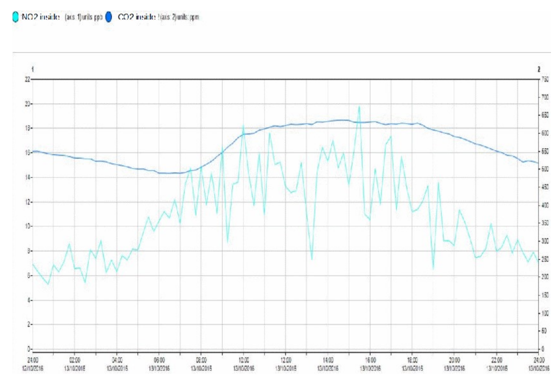

Figure 4. Office space NO_2 and CO_2 levels

The indoor pollution represented by NO_2 in Figure 3 no longer peaks at the start of the working day but meets the lower outdoor NO_2 level just before midday. It tracks the external pollution when the ventilation is at its most active to suppress the internal CO_2 but it has an intermittent effect in the late afternoon as the decreasing number of people results in the suppression of the afternoon/evening traffic related pollution peak. To quantify the pollution reduction, three working days before the control strategy change were compared with three working days after. The external pollution level on each day at each sample interval was considered 100%. The percentage reduction in pollution could then be estimated across the days before and after the control strategy change. Before the change, the pollution was between 9 and 10% greater inside than out for the period from 08:30 to 17:30.

The CO_2 levels in the open office area peaked at 16:15 at 610 ppm and held until about 18:30. The control strategy change increased the CO_2 levels in the open office area, rising faster during the morning to the peak of 640 ppm which held from 12:00 to 19:30 as shown in Figure 4. This slight increase is due to the threshold CO_2 in other smaller monitored spaces controlling the outdoor air ventilation rate. The pollution levels after the strategy change are between 69% and 71% of the external levels over the 8:30 to 17:30 period. This 30% drop below external levels in London is typically enough to bring the inside space below legally required air quality levels.

Indirect versus direct control of air pollutants

The examples described above illustrate how air quality can be affected, both positively and negatively, using basic ventilation control strategies to vary when and the amount of outdoor ventilation air is being introduced into a building and distributed throughout the occupied space by the HVAC system. However, in locations such as London where outdoor pollutant levels exceed regional / national air quality standards, the indirect control of indoor pollution by varying the amount of outdoor ventilation air and/or the use of transfer air to control CO_2 levels does not always have the desired effect. The data presented here shows that although CO_2 guidelines are being met, IAQ can still suffer due to the introduction of outdoor air pollutants – especially during those periods of elevated pollutant levels, i.e., morning and afternoon rush hours (with the emphasis on “hours”).

In these locations, consideration should be made for the direct control of pollutants using enhanced air cleaning. This being air cleaning for $PM_{2.5}$ not currently provided for with the standard HVAC filters employed in most buildings and for chemical contaminants such as NO_2, O_3, and SO_2 using gas-phase air filtration. This latter form of air cleaning is available in delivery systems that include combination particulate / chemical filters that can replace existing pleated dust filters, flat panel extruded carbon composites, and/or bulk-fill modular filters to provide the level of filtration necessary to allow the use of whatever quantity of outdoor air may be deemed necessary to provide for IAQ and energy conservation.

5. CONSIDERATIONS FOR ENERGY SAVINGS

Ventilation, IAQ, and energy conservation

The relationship between the amount of outdoor ventilation air required to provide acceptable IAQ in a building and the amount of energy required to temper this air is in one respect relatively straightforward and in another quite complex. The basic premise is to use outdoor air to dilute those airborne pollutants whose primary sources are inside the building to levels that would not cause adverse health effects to building occupants. However, if ambient levels of outdoor pollutants are above regional or national guidelines, one would merely be substituting one group of pollutants – those with indoor sources – with pollutants whose primary sources are outside the building. For urban environments, this means pollutants found in motor vehicle exhaust, mainly NO_2, SO_2, and PM (which includes diesel particulate matter or DPM). In fact, motor vehicles contribute more than half of the CO and NOx, and almost a quarter of the hydrocarbons emitted into the air.

Bringing in large quantities of outdoor ventilation air, regardless of air quality, can present a significant energy penalty whether discussing either cooling or heating loads in a building. The amount of energy saved by adopting this demand led approach is difficult to quantify even though the self-heating load of the building remains constant. The building used for this study does not have a recirculating air system but uses fan coil units to cool locally recirculated air to meet the desired temperature. For periods when no outdoor air is being used, these less efficient units take the cooling load normally supplied by the main plant. However, when the air outside is significantly colder than inside it is typically heated to less than 10 degrees below the desired temperature. This allows slow cooling of the space without disrupting the thermal comfort of the occupants. Thus, this heating and the reduction in main fan intake and exhaust requirements must be balanced with the increased reliance on the local fan coil units. The reduced usage of the main air intake and exhaust fans is of the order of 50% which in extremes of temperature will equate to significant energy savings but in milder weather the inefficiencies of these units may lead to increased energy usage. The overall energy usage in mild periods is low so a marginal increase will only have a very small effect on energy use.

6 DISCUSSION AND CONCLUSIONS

National ambient air quality standards (NAAQS) and monitoring requirements are established by the EU but are implemented at the local level. The NAAQS are based on risk factors versus actual epidemiology and in contrast, the WHO guidelines for indoor air quality are more health-based but currently only have guidelines for nine contaminants due to the level of effort required to characterize individual chemical species. Even with these air quality standards in place, many still argue that there are no safe levels of pollution.

It has been shown how various ventilation strategies can also prove to be detrimental with regards to achieving and maintaining acceptable IAQ. Assuming that harmful pollutants can be managed through indirect control using dilution with outdoor air and keeping CO_2 levels below specified limits is an incorrect assumption.

The CO_2 levels observed in this study did not exceed the 1,000 ppm ASHRAE guideline level, the 1,200 ppm limit suggested in Part F of the Building Code, nor the 1,500 limit set for schools. For the most part CO_2 levels remained below 800 ppm, even during periods of maximum occupancy. Previous studies of schools (Lamping, 2007) using significantly reduced outdoor air ventilation rates along with direct control of pollutants through enhanced air cleaning with recirculation showed similar CO_2 levels to what was observed in this study. Further, it was observed that the use of medical inhalers by students was reduced as much as 50% in schools using this ventilation strategy, an indication of improved air quality.

In England, it is estimated that 15% of people have asthma, and the UK has the highest prevalence of asthma symptoms in the world (Howieson, 2005). However, there are currently no regulations for IAQ nor regulatory levels for indoor contaminants in the UK. Part F of the building code looks to consolidate energy efficiency, requiring further ventilation designs to be incorporated within today's tightly sealed buildings. And although this has been an encouraging step, the fall-back position remains to use CO_2 as a proxy for IAQ, with acceptable levels generally established using ASHRAE guidelines and/or standards. Current work is being done within ASHRAE Technical Committees and Resource Groups to develop a list of indicator compounds with specific relevance to IAQ and incorporate this list into the current Standard 62.1 for guidance when evaluating indoor environments and perceived IAQ.

With the requirement to provide buildings that present a healthy and productive environment for building occupants, the continued use of CO_2 as a proxy to gauge IAQ can prove counterproductive to these goals. It has been shown here that bringing in large quantities of "fresh" (outdoor) air in areas that do not meet current air quality standards for one or more criteria pollutant will serve to increase the indoor levels of these pollutants and which could prove to be harmful to occupants. Given this, one must carefully balance the use of CO_2 as a surrogate for acceptable IAQ against the ability to accurately monitor and directly control pollutants known to have harmful effects at concentrations much lower than any threshold limit for CO_2. Consideration must be given to relegate CO_2 monitoring for the more appropriate use of demand controlled ventilation – with air cleaning as indicated – for the maintenance of acceptable IAQ and as part of an energy conservation strategy.

7 REFERENCES

ASHRAE. 2016. *ANSI/ASHRAE Standard 62.1-2016,* Ventilation for Acceptable Indoor Air Quality. Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

"Co-location comparison trials." (2017). Retrieved from http://www.aqmesh.com/performance/co-location-comparison-trials/.

DCLG. 2015. Approved Document F, F1 Means of Ventilation. London: Department for Communities and Local Government.

Defra. 2017. Monitoring Networks. London: Department for Environment Food & Rural Affairs. Retrieved from: https://uk-air.defra.gov.uk/networks/.

EEA. 2014. Sector share of nitrogen oxides emissions. Copenhagen: European Environment Agency. Retrieved from http://www.eea.europa.eu/data-and-maps/daviz/sector-share-of-nitrogen-oxides-emissions#tab-chart_1.

EEA. 2016. Air quality in Europe – 2016 report. Copenhagen: European Environment Agency.

EFA. 2014. Building Bulletin 101: ventilation for school buildings. Coventry: Education Funding Agency.

Howieson, s. 2005. *Housing and Asthma*. London: Spon Press.

Lamping, G.A. 2007. "Applying the IAQ Procedure to Reduce Ventilation Requirements in Schools," *ASHRAE Transactions*, 2007 Annual Meeting, Long Beach, CA, Volume 113 Part 2.

Satish U., Mendell M.J., Shekhar K., Hotchi T., Sullivan D., Streufert S., & Fisk, W.J. 2012. Is CO2 an indoor pollutant? Direct effects of Low-to-moderate CO2 concentrations on human decision-making performance. *Environmental Health Perspectives*, 120(12), 1671.

WHO. 2005. Air Quality Guidelines - Global Update 2005. Copenhagen: World Health Organization.