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Predicting building ventilation performance in the era of an indoor air crisis

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Editorial

Background

Coronavirus disease 2019 (COVID-19) is caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), which is continuing to evolve. Vaccination alone has not completely controlled the COVID-19 pandemic, and infection with SARS-CoV-2—particularly with the omicron variant—continues to threaten human health and life and thus negatively affect economies worldwide.

Furthermore, the 3-year-long COVID-19 pandemic has revealed that there is a global indoor-air crisis (Li et al. 2021). The role of surface touch in SARS-CoV-2 transmission has been recognized as insignificant, but nearly all transmission occurs indoors. However, the airborne transmission route was only recognized by leading health authorities in late 2020, almost a year since the first reported infection. Following the dilution principle, all long-range airborne transmission probably occurs in poorly ventilated spaces. Therefore, given that more than 6.5 million people have died globally due to SARS-CoV-2 infection (https://covid19.who.int/) and people are continuing to be infected, there is an urgent need to improve ventilation in many buildings worldwide. However, although 2 years have passed since official recognition of airborne transmission of SARS-CoV-2, there have been no significant improvements in the ventilation of the world's buildings, despite some efforts being made. That is, in March 2022, the U.S. Government released its "Clean Air in Buildings Challenge" for improving indoor air quality (www.whitehouse.gov/cleanindoorair/), and in March 2021, the Government of Hong Kong SAR implemented a mandatory policy requiring six air changes per hour in approximately 20,000 dine-in restaurants in the city (Hong Kong 2021).

In the absence of a worldwide effort to improve building ventilation, it is likely that poorly ventilated buildings will remain common, meaning that airborne transmission of SARS-CoV-2 will continue. Moreover, if another novel and highly contagious respiratory virus emerges in future, another pandemic is likely to occur.

There are likely more than a few billion indoor spaces in the world, so it is not feasible to measure the ventilation in every indoor space. Moreover, increasing ventilation increases energy consumption. Thus, ventilation improvement must involve considering the energy efficiency of buildings, which is also crucial for mitigating the effects of climate change (Saunders et al. 2021). Accordingly, reliable techniques for the prediction of ventilation performance must be developed.

History tells us about the future

Prediction is an essential component of human decision-making processes; we use what we already know to predict far into the future or simply our next step. It follows that prediction should also play a role in the development of building ventilation.

Our ancestors learned about the importance of inhaling clean air, which led to their inventing windows and chimneys. However, it was not until 1836 that David Reid (1805–1863) performed perhaps one of the earliest small-scale modeling studies—of the debating chamber of the U.K. Houses of Parliament—followed by field measurements of air temperature and humidity in the 1850s (Schoenefeldt 2014). In the modern era, based on the well-established airflow similarity principle, small-scale modeling has been widely used in designing the ventilation of major buildings, as it allows prediction of ventilation performance at the design stage.

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During Reid's time, knowledge of hydrodynamics and its application in ventilation accumulated. The importance of ventilation-opening area was discovered in the early 19th century, with Tredgold (1824 p 168) suggesting that "the openings for admitting cold air should be about double the area of those at the ceiling. The air should not be taken from very near the ground, nor from a confined place." This recognizes the fact that a strong airflow from a small opening causes discomfort. In addition, the stack (draft) pressure of chimneys was first derived by Jean Eugène Péclet (1793–1857) in 1844, allowing buoyancy-driven ventilation to be predicted at the design stage (Reid 1844). Fire, human, horse, and steam power were used to drive "mechanical ventilation" in mines and buildings (Reid 1844). With the invention of electric fans in the late 19th century, modern mechanical ventilation became available. This was followed by the invention of modern air conditioning in the early 20th century by Willis Carrier (1876–1950).

Knowledge of required ventilation rates also began to accumulate during Reid's time. von Pettenkofer (1858) recognized that CO_2 could be a good indicator of indoor air quality and co-developed the Pettenkofer–Seidel ventilation formula. In 1914, based on the work of Flugge, Billings, and others, the American Society of Heating and Ventilating Engineers (now the American Society of Heating, Refrigerating and Air-Conditioning Engineers) proposed a ventilation standard of 15 L/s per person. Required minimum ventilation rates have been fluctuating since Tredgold (1824), which illustrates the difficulty of establishing the relationship between ventilation and health.

The importance of ventilation in maintaining people's health was recognized scientifically in the early urbanization phase in Europe (Li 2020) by pioneering researchers of hygiene, such as von Pettenkofer (1858), who believed in the traditional filth theory of disease. However, following the 1850 cholera outbreak in London, the old miasma theory of disease (from which the filth theory was derived) was abandoned. Nevertheless, von Pettenkofer did not believe the emerging germ theory of disease that was first proposed by Robert Koch (1843–1910). Following various water-borne disease outbreaks in the 19th century, mandatory regulations were introduced that improved water environments in Europe and the U.S. Consequently, there was a significant reduction in infectious disease caused by water pollution. As a result of these improvements in hygiene and less crowded housing, mortality due to what were probably the greatest killers of the 19th century—tuberculosis, smallpox, and cholera—was dramatically reduced.

In the 19th century, air-leaky buildings were likely the norm and heating systems were also widely used in Europe. However, these systems were different from the thousand-year-old *kang* system used in northern residences in China (Li et al. 2009), which provides better ventilation due to its cleverly combining cooking, heating, and ventilation functions. Commercial insulation for buildings was invented much more recently, in the early 20th century (Close 1946), and it was not until the late 1970s that the blower-door system was invented for measuring building air leakage (Sherman and Dickerhoff 1998), following the 1970s energy crisis. Axley (2007) notes that various multi-zone airflow models have been developed from the single-zone model (Dick 1949). Moreover, computational fluid dynamics (CFD) approaches have been applied for airflow-pattern prediction since Nielsen (1973). Advances in fluid mechanics and computers mean that is now possible to model airflows in and around complex buildings. However, such modeling cannot predict air leakage or the optimal operation of a ventilation system.

The widespread and growing adoption of air conditioning and heating in the 20th century led to improvements in the air tightness and insulation of buildings, which reduced energy usage. Today, debate continues on the relative merits of natural ventilation and mechanical ventilation.

Differences between thermal performance and ventilation performance

Thermal performance and ventilation performance are two key components of building energy performance. Humans can detect thermal conditions, and almost anyone can use a low-cost thermometer to perform a simple measurement of the degree of coldness or warmness, i.e., temperature. We also receive daily weather reports that help us to decide what to wear, and our electricity bills tell us how many kilowatt-hours we use in our homes. Unfortunately, however, although we can detect odors, we cannot sense or predict the ventilation performance in buildings, so we cannot detect most air pollutants, such as infectious aerosols. This contributes to the indoor air crisis.

Crisis leads to revolution. Like the environmental crisis in the 19th century, which led to government-mandated improvements in water quality and hygiene in most countries, ongoing energy-security concerns and the climate crisis have led to the worldwide mandatory effort to improve the energy performance of buildings. Mandatory guidelines have been implemented, such as the European Union's (2010) *Energy Performance of Buildings Directive*. This requires energy performance certificates, which include practical advice on improving such performance, to be posted on all buildings, refrigerators, and air conditioners. Certificates were originally required to indicate "the energy performance of a building or building unit, calculated according to a methodology" (European Union 2010), but this requirement was subsequently changed to "the energy performance of a building shall be determined on the basis of *calculated* or actual energy use" (Directive (EU) 2018/844).

However, owners may not wish to monitor their buildings' ventilation performance, especially if poor ventilation performance or a reported fault would decrease buildings' market values. This is where governments must play a role, as without mandatory requirements, there will be no improvement in buildings' ventilation performance.

Nevertheless, there have been very few measurements of ventilation rates of buildings. Persily (2016) identified approximately 3,500 individual ventilation rate measurements that have been made in some U.S. offices, with slightly fewer than half being less than 10 L/s per person. Nazaroff (2021) identified only approximately 40 studies that have measured air-change rates in approximately 10,000 homes, which is a tiny fraction of the estimated more than one billion homes in the world, given the current world population of approximately seven billion. In addition, despite the World Health Organization having recognized the airborne transmission of SARS-CoV-2, there have been very few measurements of ventilation rates in venues, even after SARS-CoV-2 infections have occurred in such venues.

A phenomenon must be measured to be scientifically investigated. In addition, human-focused measures are required. For example, we measure length, area, and volume to determine the size of our land size or home. We measure air temperature, humidity, wind speed, and direction to determine how we may be affected by weather. Utility companies measure our use of electricity, water, and gas, so they can determine how much to charge us. Analogously, we need to measure building ventilation as poor air quality adversely affects our health.

Like energy use, ventilation rates exhibit spatiotemporal variation within an indoor space. Wind and temperature differences drive natural ventilation, and supplies of outdoor air change due to the use of free cooling in the air-conditioning systems. Therefore, rather than monthly or annual data (akin to energy-use data), real-time hourly ventilation rates are needed to determine the ventilation performance of buildings.

As mentioned, given the current world population of seven billion, and assuming there is an average of five people per home, there are likely more than one billion homes globally. There are also hundreds of millions of other indoor spaces, such as offices and movie theatres. To identify the poorly ventilated spaces among this enormous number of spaces, the ventilation performance of each indoor space must be subjected to real-time hourly monitoring, which is an unrealistic goal at present.

Furthermore, it is difficult to measure effective ventilation directly as outdoor air can enter via leakages in addition via air ducts; instead, a surrogate measurement is often made, such as the indoor concentration of CO_2. There is thus a need to develop simple methods for the continuous measurement of ventilation. It is encouraging that Belgium (2022) will probably become the first country to mandate the continuous monitoring of indoor CO_2 concentrations in public buildings.

Why prediction?

Measuring the ventilation in billions of buildings is not a realistic goal, but nor is it sufficient to know that there are many poorly ventilated spaces. That is, spaces with poor ventilation need to be identified to allow their ventilation to be improved or to enable them to be avoided.

For example, consider the European Union's (2010) *Energy Performance of Buildings Directive*. Initially, as noted, its energy performance certificates were issued based on calculations rather than on actual energy performance. The calculated energy performance of a building is an inherent property of the building, whereas its actual performance also depends on its occupancy and usage. The same should be true for building ventilation performance, as it is likely to be affected by similarly complicated factors as is building energy performance.

The COVID-19 pandemic clearly illustrated that there are enough poorly ventilated spaces in almost all countries and cities to sustain chains of infection. Given this reality, it was asked why such spaces' ventilation was not improved immediately (Dancer et al. 2021). The answer is that achieving such improvements is highly challenging. First, there is a lack of ventilation performance data. Second, ventilation performance is not constant. Third, it is not the overall ventilation performance that matters, but ventilation rate per person at any time, and occupancy varies significantly, in both space and time. Therefore, a building must provide sufficient ventilation at its maximum occupancy. That is, its ventilation ability dictates its maximum occupancy; a higher number of occupants than the maximum should be avoided.

The power of prediction for determining the ventilation performance of buildings lies in the fact that a validated predictive tool can be applied at low cost to many buildings, provided adequate input data are available. Prediction is therefore an economic approach for assessing ventilation performance at a city or global scale, as it is cheaper to use a reliable predictive tool based on building, system, and climatic factors than to perform field measurements. Such a tool can be physics-based or driven by building ventilation system, envelope leakage, and weather data, supplemented by other monitored data, such as CO_2 concentrations.

Integrating prediction with big data and the Internet of things

In general, the simulation capabilities of a predictive tool are limited by knowledge, experience, and input (i.e., monitoring) data. Consequently, the space accessible by computer simulation is a minute subspace of the actual space of a product, building, or larger system. The number of subspaces that can be accessed by a predictive tool increase over time, as knowledge, experience, and input data improve. A major improvement in input data for buildings is the inclusion of occupancy profiles of buildings (e.g., Menezes et al. 2012).

One of us (Yuguo Li) recalls meeting with Professor Peter Nielsen—who pioneered the application of CFD for modeling buildings—in his office at Aalborg University in 2003. Peter showed a photograph of his office when it was empty after a recent renovation. He talked about how airflows and ventilation in such an empty space (generally predictable by CFD) would differ from those in the occupied space. This underlies the so-called performance gap, which is understood in building energy performance certification to mean that "buildings are not performing as well as expected" (Menezes et al. 2012). This performance gap was found to be likely to occur if building performance is estimated or predicted based on ideal settings. Thus, this gap is closed if building performance is estimated or predicted based on post-occupancy data. The same performance gap is expected for building ventilation performance.

Internet of things (IoT) technologies enable the collection of good-quality real-time data inside buildings. Thus, the integration of predictive tools with IoT, big data, and machine learning approaches, i.e., digital twin technologies, appear to herald a bright future for assessing the ventilation performance of buildings, although more development is required.

In summary, we call for national governments to consider mandating real-time indoor air quality monitoring in at least all public buildings, as people have a right to healthy air in the buildings they must use (Mølhave and Krzyzanowski 2000). We remain optimistic that future innovation will result in advances in economic monitoring and predictive tools for determining ventilation performance in the billions of indoor spaces worldwide. One can also a glimpse of our joint effort by reading other papers in this *Building Simulation* topical issue on *COVID-19 Prevention and Control in the Built Environment with Low Resource Consumption* co-edited by Nan Zhang of Beijing University of Technology and Zhengtao Ai of Hunan University. There is a hope that we will be better prepared in future than we are now for the next airborne microbial pandemic.

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References

Axley J (2007). Multizone airflow modeling in buildings: History and theory. *HVAC&R Research*, 13: 907–928.

Belgium (2022). Draft law on the improvement of indoor air quality in enclosed places accessible to the public (Wetsontwerp betreffende de verbetering van de binnenluchtkwaliteit in gesloten plaatsen die publiek toegankelijk zijn), DOC 55 2820/001, July 12, 2022.

Close PD (1946). Building Insulation: A Treatise on the Principles and Application of Heat and Sound Insulation for Buildings. Chicago: American Technical Society.

Dancer SJ, Bluyssen PM, Li Y, et al. (2021). Why don't we just open the windows? *BMJ* (*Clinical Research Ed*), 375: n2895.

Dick JB (1949). Experimental studies in natural ventilation of houses. *Journal of the Institution of Heating and Ventilating Engineers*, 17(173): 420–466.

European Union (2010). Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast).

Hong Kong (2021). A guide on compliance with requirement on air change/air purifiers in seating areas of dine-in catering premises (fehd.gov.hk). March 2021. Available at https://www.fehd.gov.hk/english/licensing/guide_general_reference/A_Guide_for_Registration_on_Air_Change_Installation_of_Air_Purifier_in_Catering_Premises.pdf

Li Y, Zhuang Z, Liu J (2009). Chinese kangs and building energy consumption. *Chinese Science Bulletin*, 54: 992–1002.

Li Y (2020). Indoor air: A short history of holistic and reductionistic approaches. *Indoor Air*, 30: 3–6.

Li Y, Nazaroff WW, Bahnfleth W, et al. (2021). The COVID-19 pandemic is a global indoor air crisis that should lead to change: A message commemorating 30 years of Indoor Air. *Indoor Air*, 31: 1683–1686.

Menezes AC, Cripps A, Bouchlaghem D, et al. (2012). Predicted *vs.* actual energy performance of non-domestic buildings: using post-occupancy evaluation data to reduce the performance gap. *Applied Energy*, 97: 355–364.

Mølhave L, Krzyzanowski M (2000). The right to healthy indoor air. *Indoor Air*, 10(4): 211.

Nazaroff WW (2021). Residential air-change rates: A critical review. *Indoor Air*, 31: 282–313.

Nielsen PV (1973). Berechnung der luft-bewegung in einem zwangsbelüfteten raum (calculation of air movement in a forced ventilation room), gesundheits-ingenieur (Sanitary Engineer), H10: 299–302.

Persily AK (2016). Field measurement of ventilation rates. *Indoor Air*, 26: 97–111.

Reid DB (1844). Illustrations of the Theory and Practice of Ventilation. London: Longman, Brown, Green, & Longmans.

Saunders HD, Roy J, Azevedo IML, et al. (2021). Energy efficiency: what has research delivered in the last 40 years? *Annual Review of Environment and Resources*, 46: 135–165.

Schoenefeldt H (2014). The temporary houses of parliament and David Boswell Reid's architecture of experimentation. *Architectural History*, 57: 175–215.

Sherman MH, Dickerhoff DJ (1998). Airtightness of U.S. dwellings. *ASHRAE Transactions*, 104(2): 1359–1367.

Tredgold T (1824). Principles of Warming and Ventilating. London: Josiah Taylor.

von Pettenkofer M (1858). Über den luftwechsel in wohngebäuden (About the air exchange in residential buildings), Cotta, München.