IS VENTILATION NECESSARY AND SUFFICIENT FOR ACCEPTABLE INDOOR AIR QUALITY?

Kwok Wai Tham

Department of Building, School of Design and Environment, National University of Singapore
SDE 1, 4 Architecture Drive, Singapore 117566, Singapore
Corresponding author: bdgtkw@nus.edu.sg

ABSTRACT

The role of ventilation in achieving acceptable indoor air quality is examined in the light of emerging challenges, alternative mitigation strategies and performance indices within the spatial and time matrix of the indoor environment. By considering the source of contaminants, their nature, transportation mechanism and participation in source-sink relationships, several studies have shown that it may not be feasible nor adequate to rely on ventilation alone to attain the desired level of exposure, especially with respect to airborne aerosolised droplets with infectious potential. Nonetheless, until a full characterisation of the contaminants and appropriate mitigation strategies are developed and effectively implemented, ventilation provides the generic dilution that is necessary to achieve exposure levels that are within desirable levels.

KEYWORDS

Ventilation, acceptable indoor air quality, exposure, contaminant, air flow patterns, airborne infection

1 INTRODUCTION

Ventilation is the intentional movement of outdoor air into the indoors of a building, and performs the primary function of achieving acceptable indoor air quality (ASHRAE, 2013; CEN, 1998). Outdoor air is subjected to requisite cleaning (including filtration and scrubbing) when it does not meet stipulated standards.

Indoor air quality (IAQ) is influenced by indoor sources (including human bio-effluents), indoor reactions (notably indoor chemistry), source-sink relationships and contaminant removal mechanisms.

The evolution of indoor environments in response to sustainability and economic challenges have accentuated IAQ issues associated with emissions from materials and processes, increased occupant density and the cost of air cleaning and air-conditioning.

Whereas guidance on ventilation has been predicated on macro consideration of uniform (well-mixed) dilution and removal of contaminants, recent findings implicate airflow patterns, source location and even respiratory activity as having strong influence on contaminant (and infection) exposure of the occupant.

The necessity and sufficiency of ventilation for achieving acceptable IAQ is discussed from the perspective of the nature, behaviour and distribution of contaminants, consequential human exposure, and the alternatives for mitigating exposure.

2 METRICS OF INDOOR AIR QUALITY

Conventional metrics of IAQ are health and satisfaction as described by acceptable indoor air quality being “air in which there are no contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction” (ASHRAE 2013). This is evaluated by: (i) measuring exposure, typically through IAQ audits comparing measured selected contaminant values in the occupant zone (or breathing zone) against thresholds, and (ii) ascertaining occupant satisfaction through surveys or analysis of complaints.

Based on population epidemiology and dose-response studies, threshold exposure values (STELs or 8 hour averages) have been specified, and most indoor environmental control strategies are structured on achieving these requirements in the most resource efficient manner. Perception of indoor air quality is dominated by sensory (predominantly olfactory) sense; it is arises from a holistic summation across the entire spectrum of inhaled constituents (chemical, biological and physical) that far exceed the number of targeted contaminants measured in an IAQ audit (Cain, 1979). The *olf* unit of odour perception (Fanger, 1988), and more pragmatically in field studies, the use of acceptability of perceived air quality (PAQ) has gained wide implementation (Zagreus et al, 2004; Wargocki et al, 2002; Tham and Willem, 2010).

Airborne infection has recently emerged as an essential consideration and several performance indices related to exposure have been defined including inhalation fraction (Nazaroff) and Personal Exposure Effectiveness (PEE) (Melikov, Cermak and Majer, 2002; Pantelic, Tham and Licina, 2015).

While IAQ standards and regulations have yet to include infection considerations, the evidence for airborne infection and its occurrence across several indoor environments (offices, airplanes, hospitals, transportation environments), and the upsurge in infectious agents (Li et al 2007, Mangili and Gendreau, 2005) suggests that these metrics are needed to complement the existing ones.

3 NATURE OF CONTAMINANTS

Understanding the nature and behaviour of indoor contaminants would help us evaluate the effectiveness of ventilation in achieving acceptable indoor air quality.

Contaminants of outdoor origin, such as particulate matter and environmental bioflora, vehicular and industry related gaseous chemical pollutants opportunistically utilize ventilation to penetrate indoors. When ventilation is not operational, such as after normal operating hours, they infiltrate depending on airtightness and external wind conditions.

Indoor contaminants comprise a multiplicity of sources:

- Building fabric and furniture – gaseous and particulate emissions, thermal and moisture issues; have substantial source-sink capacity
- Ventilation system : coils (especially cooling and dehumidification), filters, ductwork; repositories of particulate and biological contaminants
- Equipment and processes : printers, materials, stationery
- Humans : bio-effluents, infectious particles
- Inter-zonal cross contamination : airborne contamination; pressurization balancing and thermal or mechanically (movement of elevators in lift lobbies) induced

Indoor chemistry, especially associated with highly oxidizing agents such as ozone (introduced via ventilation) may transform primary to secondary contaminants, some of which are more toxic, and often of ultrafine particle size in the form of secondary organic aerosols (Weschler 2000, Fadeyi et al, 2009).

Bacteria and viruses, particularly those that are infectious attach to particulate or moisture nuclei that readily follow micro airflow patterns (Szeto et al., 2009; Pantelic and Tham, 2013).

Source-sink effects are complex. Apart from physical drivers of gravitational settling for larger sized particles and Brownian diffusion for smaller sized ones, chemically gaseous diffusion are motivated by concentration gradients and dispersion by air patterns. Surface and bulk material characteristics, temperature as well as air velocity across surfaces affect the deposition, sorption and subsequent emissions.

4 EXPOSURE

What determines exposure? This relates to spatial and time relationship between contaminants from their release at source and humans, and their transformation during that process. This is contrasted against the more simplistic model of uniform mixing and removal via ventilation alone.

For contaminants that are chemically and biologically inactive, occupant exposure levels are determined by the strength/rate of their emission and their ability to rapidly diffuse across the main airflow streams that transport them within the indoor environment. Gases tend to diffuse well, but the smaller size particulate matter and bacteria and viruses that attach to ultrafine particulate matter tend to follow air streams. Ventilation is effective insofar as their ability to dilute the contaminant concentrations in these two components, and therefore largely depends on how ventilation is being introduced.

Location of sources matter. Melikov (2015) demonstrated that freestream gaseous exposure, using SF6 as a marker, is affected by relative position, whilst Dusan et al (2015a, 2015b) showed the influence of the convective boundary layer in the transport of contaminants from near body sources.

More recent concerns about the movement of aerosolised airborne infectious particles motivated studies which utilized simulated saliva and clearly demonstrated that exposure risk is influenced by both distance and orientation between the infector and susceptible persons. (Pantelic et al., 2015)

The modifying role of air streams in significantly affecting the exposure were established through studies using gaseous surrogates (SF6) as well as particles and simulated saliva. At the zonal level, Pantelic and Tham (2013) showed that downdrafts from air supply diffusers and circulatory vortices generated by the interaction of the airstreams altered the airborne particle movement in the nearfield of an occupant. Dusan et al (2015a) demonstrated the effects of traverse, opposing and assisting flow patterns have varying degrees of influence on particle movement in the breathing zone. At a more individually based scale, Pantelic et al. (2009) demonstrated the advantageous mitigating effect of personalised ventilation against an intruding cough release at various distances and orientations. Personalised ventilation when used alone (Pantelic et al., 2009; Melikov, 2015) or when augmented by personalised exhaust (Yang et al, 2015) have been demonstrated to be effective in reducing personalised exposure in several scenarios.

These series of studies established that a macro evaluation based on ventilation rate for uniform dilution and removal of contaminants is inadequate to ascertain exposure.

5 ACHIEVING ACCEPTABLE IAQ

The efficacy of achieving acceptable IAQ follows a well-established strategy that prioritize source control (elimination, substitution, encapsulation) over air cleaning, and then ventilation (dilution). The cost associated with ventilation is increasing due to the densification and concomitant degradation of ambient air quality of cities, which may necessitate adequate treatment (filtration and contaminant removal) before introduction into the indoors.

A responsible design and procurement that addresses contaminant sources would alleviate the burden of achieving acceptable IAQ both in terms of capital investment and operational costs for air treatment. Facilities management with a clear commitment to sustaining acceptable IAQ is essential; however these are usually non-tenant related responsibilities involving air intake, treatment and air distribution such that at least the ventilation portion is of acceptable quality.

Indoors, the contamination is determined by tenants – choice of materials, equipment and processes and occupant related issues. These translate to source location and concentration characteristics, with air distribution patterns conspiring to mix and transport contaminants resulting in exposure characteristics in a space-time matrix.

Achieving acceptable IAQ is therefore necessitate an understanding of these complex interactions and to address them through a combination of strategies that should include:

- Source treatment of airborne contaminants(both ventilation and recirculated air);
- Source removal or reduction through responsible use of materials and processes, or even provision of isolation and dedicated exhaust as justifiable;
- Supplementary air cleaning where pragmatic constraints and economic considerations favour these over ventilation
- Localised technologies of air cleaning or ventilation judiciously deployed in relation to disrupt or mitigate contaminant pathways towards occupants (here personalized ventilation has been actively developed for targeted environments particularly those associated with healthcare environments).

Given the advancements in these areas, coupled with sensor and control technologies which could embrace occupant feedback in a more engaged manner, the indoor environment is likely set to be transformed to one whereby acceptable IAQ need not be a macro indicator, but one which is much more individual-oriented. Societal evolution towards dynamic workforce and variation in office occupancy, and the diversity of occupant preference of micro-environmental conditions provide impetus in this direction.

6 NECESSITY FOR VENTILATION

Ventilation nonetheless retains a primary role in achieving acceptable IAQ. Its necessity is argued from the following considerations.

Firstly, the indoor environment is an extremely complex mix of chemical and biological contaminants. These may act alone or may react / interact to produce adverse consequences. Recent understanding of ozone-initiate chemistry is a case in point. Ventilation provides the generic dilution, and if judiciously distributed, would significantly enhance IAQ by reducing exposure: generically in the overall room concentration, or at the individual level through personalised ventilation.

Secondly, there are constraints in the efficacy and upper limits of economically feasible air cleaning. Air cleaning works well if the targeted volume of air is effectively channelled through the air cleaning device – this may not be easily achieved. The combination of air cleaning and ventilation may be a considered strategy.

An important consideration is that of exposure being experienced at different locations. A matrix for characterizing exposure would include the following considerations:

- Spatial granularity (floor, zonal, individual)
- Sources and nature (passive sources, active source, human related eg respiratory, speaking, coughing etc …)
- measures of performance against such exposure (eg ACH, PEE, Exposure index, etc…)

Spatial granularity is determined by the envisaged occupancy, usage and contaminant characteristics and the desired response achieved by ventilation and air distribution. It is tightly coupled with the thermal loads and requires suitable sensing and control, ventilation and air distribution design. Sources, processes, activities and nature of contaminants affect the suitability and effectiveness of single, or combination of strategies to achieve a dynamic response commensurate with the desired exposure level. These are defined by the measures that reflect the specificity of performance ranging from comfort through satisfaction to exposure indices.

7 CONCLUSION

Ventilation has a definite role in the overall strategy to achieve acceptable indoor air quality. The multiplicity of contaminant sources, transportation and sinks, further compounded by their interactions bestow upon ventilation a general dilution capability that complements targeted mitigation air cleaning technologies and air distribution strategies. Whilst necessary, it may not be sufficient, nor economically feasible, to be relied upon solely for achieving the desired indoor air quality and exposure levels. Its sufficiency needs to be considered in a matrix dimensioned along spatial granularity, sources and nature of contaminants, and the performance measures. At this present knowledge and technology, it is necessary but its sufficiency depends on the location in the matrix.

8 REFERENCES

ASHRAE. (2013). ANSI/ASHRAE Standard 62.1-2013. Ventilation for Acceptable Indoor Air Quality. ASHRAE, Atlanta, USA.

Cain, WS. (1979). To know with the nose: keys to odour identification. Science 203 (4379), 467-470.

CEN (1998). CR 1752: Ventilation for Buildings: Design Criteria for the Indoor Environment.

Licina D, Melikov A, Sekhar C and Tham KW. (2015a). Human convection flow in spaces with and without ventilation: personal exposure to floor-released particles and cough-released droplets, Indoor Air, DOI: 10.1111/ina.12177.

Licina D, Melikov A, Sekhar C and Tham KW. (2015b). Transport of Gaseous Pollutants by Convective Boundary Layer around a Human Body, Science and Technology for the Built Environment, DOI:10.1080/23744731.2015.1060111.

Fadeyi MO, Weschler CJ and Tham KW. (2009). The impact of recirculation, ventilation and filters on secondary organic aerosols generated by indoor chemistry, Atmospheric Environment 43(22):3538-3547.

Fanger, PO. (1988). Introduction of the olf and the decipol units to quantify air pollution perceived by humans indoors and outdoors, Energy and Buildings, Volume 12, Issue 1, 24 April 1988, Pages 1–6.

Li Y, Leung GM, Tang JW, Yang X, Chao CYH, Lin LZ, Lu JW, Nielsen PV, Niu J, Qian H, Sleigh AC, Su H-JJ, Sundell J, Wong TW and Yuen PL. (2007). Role of ventilation in airborne transmission of infectious agents in the built environment – a multidisciplinary systematic review, Indoor Air 17(1):2-18.

Mangili A and Gendreau MA. (2005). Transmission of infectious diseases during commercial air travel, Lancet 365 (9463):12-18.

Melikov A. (2015). Advanced air distribution: improving health and comfort while reducing energy use, Indoor Air, doi:10.1111/ina.12206.

Melikov AK, Cermak R, Majer M. (2002). Personalized ventilation: evaluation of different air terminal devices, Energy and buildings, Volume 34(8): 829–836.

Nazaroff WW. (2006). Inhalation intake fraction of pollutants from episodic indoor emissions, Building and Environment, 43(3): 269–277.

Pantelic J, Sze-To GN, Tham KW, Chao CYC and Khoo YCM. (2009). Personalized ventilation as a control measure for airborne transmissible disease spread, Journal of Royal Society Interface : S715 – S726.

Pantelic J and Tham KW. (2013). Adequacy of air change rate as the sole indicator of an air distribution system's effectiveness to mitigate airborne infectious disease transmission caused by a cough release in the room with overhead mixing ventilation: A case study. HVAC&R Research 19(8):947-961.

Pantelic J, Tham KW and Licina D. (2015). Effectiveness of a personalized ventilation system in reducing personal exposure against directly released simulated cough droplets, Indoor Air, DOI: 10.1111/ina.12187.

Sze-To, G.N.,M.P.Wan, C.Y.H.Chao, L.Fang, and A. Melikov. 2009. Experimental study of dispersion and deposition of expiratory aerosols in aircraft cabins and impact on infectious disease transmission. Aerosol Science and Technology 43:466–85.

Tham KW and Willem HC. (2010). Room air temperature affects occupants' physiology, perceptions and mental alertness, Building and Environment 45 (1):40-44.

Wargocki P, Lagercrantz L, Witterseh T, Sundell J, Wyon DP and Fanger PO. (2002). Subjective perceptions, symptom intensity and performance: a comparison of two independent studies, both changing similarly the pollution load in an office, Indoor Air, 12 (2): 74–80.

Weschler CJ. (2000). Ozone in indoor environments:concentration and chemistry, Indoor Air 10(4):269-288.

Yang J, Sekhar SC, Cheong KWD and Raphael B. (2015). Performance evaluation of a novel personalized ventilation–personalized exhaust system for airborne infection control, Indoor Air 25(2):176-187.

Zagreus L, Huizenga, Arens E and Lehrer D. (2004).Listening to the occupants: a Web-based indoor environmental quality survey, Indoor Air 14 (s8): 65–74.