Science of the Total Environment 586 (2017) 696–729

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Indoor air pollutants, ventilation rate determinants and potential control strategies in Chinese dwellings: A literature review

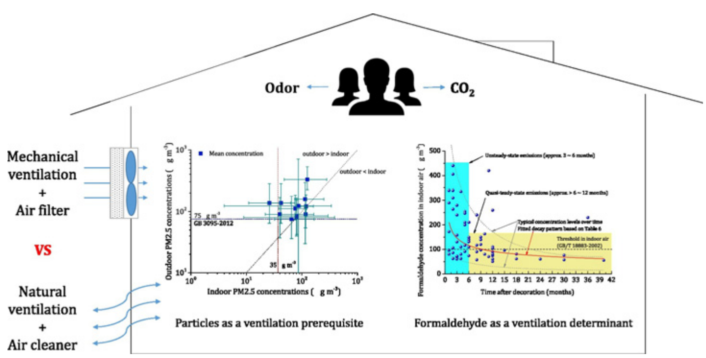
Wei Ye [a,b], Xu Zhang [b,*], Jun Gao [b], Guangyu Cao [c], Xiang Zhou [b], Xing Su [b]

[a] State Key Laboratory of Pollution Control and Resource Reuse, Tongji University, Shanghai, PR China
[b] School of Mechanical Engineering, Tongji University, Shanghai, PR China
[c] Department of Energy and Process Engineering, Norwegian University of Science and Technology, Trondheim, Norway

HIGHLIGHTS

- Indoor air pollution data measured in >7000 residences in China were summarized.
- Particulate matters, VOCs, SVOCs, moisture/mold, inorganic gases and radon were ubiquitous.
- Ventilation prerequisites, determinants and requirements were discussed.
- Natural (window) ventilation + air cleaner and mechanical ventilation + air filtration was compared.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 30 June 2016
Received in revised form 27 January 2017
Accepted 6 February 2017
Available online 20 February 2017

Editor: J. Gan

Keywords:
Bioeffluent
Particular matter
VOC
SVOC
Mold
Radon

ABSTRACT

After nearly twenty years of rapid modernization and urbanization in China, huge achievements have transformed the daily lives of the Chinese people. However, unprecedented environmental consequences in both indoor and outdoor environments have accompanied this progress and have triggered public awareness and demands for improved living standards, especially in residential environments. Indoor pollution data measured for >7000 dwellings (approximately 1/3 were newly decorated and were tested for volatile organic compound (VOC) measurements, while the rest were tested for particles, phthalates and other semi-volatile organic compounds (SVOCs), moisture/mold, inorganic gases and radon) in China within the last ten years were reviewed, summarized and compared with indoor concentration recommendations based on sensory or health end-points. Ubiquitous pollutants that exceed the concentration recommendations, including particulate matter, formaldehyde, benzene and other VOCs, moisture/mold, inorganic gases and radon, were found, indicating a common indoor air quality (IAQ) issue in Chinese dwellings. With very little prevention, oral, inhalation and dermal exposure to those pollutants at unhealthy concentration levels is almost inevitable. CO_2, VOCs, humidity and radon can serve as ventilation determinants, each with different ventilation demands and strategies, at typical occupant densities in China; and particle reduction should be a prerequisite for determining ventilation requirements. Two directional ventilation modes would have profound impacts on improving IAQ for Chinese residences are: 1) natural (or window) ventilation with an air cleaner and 2) mechanical ventilation with an air filtration unit, these two modes were reviewed and compared for their applicability and advantages and disadvantages for reducing human exposure to indoor air pollutants. In general, mode 2 can more reliably ensure good IAQ for occupants; while mode 1 is more applicable due to its low cost and low energy consumption. However,

* Corresponding author.
E-mail address: xuzhang@tongji.edu.cn (X. Zhang).

http://dx.doi.org/10.1016/j.scitotenv.2017.02.047

besides a roadmap, substantial efforts are still needed to develop affordable, applicable and general ventilation solutions to improve the IAQ of residential buildings in China.

1. Introduction

Building envelopes intentionally separate occupants from the outside, making indoor pollutants, such as particulate matter, inorganic gases, volatile organic compounds (VOCs), semi-volatile organic compounds (SVOCs), mold, and radioactive compounds (as summarized in Table 1), more easily to accumulate indoors. Some of the pollutants found indoors can produce odor or cause irritation, while many can pose chronic and/or acute health effects on occupants (Logue et al., 2011; Wouter Borsboom et al., 2016) via inhalation, dermal or other pathways (Gong et al., 2016; Ostro et al., 2015; Tischer and Heinrich, 2013; Tse et al., 2011; Tsushima et al., 2016; Weschler, 2009).

Other than the available technologies for source control and air cleaning, ventilation serves as the basic means to partially dilute indoor pollutants, mostly in the gas phase, and to maintain a habitable space for human beings. Ventilation can be inefficient for reducing human exposure to radon (as the radon entry rates can be the leading factor sometimes) (Andersen et al., 1997), or significantly decrease SVOC concentrations both in the gas phase and on indoor surfaces including human skin (Liu et al., 2015). However, ventilation is still a common method with usually manageable costs.

Furthermore, one of the key elements of using ventilation to improve indoor air quality (IAQ) is to determine an adequate ventilation rate in a standardized manner at a broader scale. In a sense, the required adequate ventilation can be interpreted as the recommended (minimum) ventilation rate for various buildings as specified in guidelines, standards, building codes or even legislation, and this ventilation rate is usually provided by mechanical ventilation systems (ASHRAE, 2016a; ASHRAE, 2016b; Brelih and Seppänen, 2011; BSI, 2008). However, it should be clarified that the recommended ventilation rate is an engineering approach based on available knowledges and technologies, and can be considered as prescriptions. Sometimes, people use the term of minimum ventilation rate when refereeing to the mandatory ventilation rates in building design codes, such as GB 50736-2012 in China (MOHURD, 2012). And to determine the recommended (or minimum) ventilation rate in practice is a comprehensive task for the following reasons at least: First, it is easy for engineers and building owners to follow this rate during the design phase to reach a target acceptable IAQ. On the other hand, it is also easy to be overlooked and poorly accomplished during both the design and service phases, compromising occupants' living and working environments. Second, the recommended (or minimum) ventilation rate must balance improving IAQ, which usually requires more ventilation, with the energy consumption, which needs less ventilation (Sundell, 2004). Third, more diversified indoor air pollutant sources require flexible methods for determining the ventilation rate, while the regulations of the minimum ventilation rate in a standardized manner need to avoid complexity.

Table 1
Typical indoor air pollutants and their corresponding sources and causes.

Pollutant category	Examples of substance	Typical sources/causes
Inorganic gases	SO_2, NO_x, CO, CO_2, NH_3, O_3	Metabolism, combustion processes; traffic emissions; reaction with organic compounds, etc.
Organic gases/compounds	Volatile organic compounds; semi-volatile organic compounds; (formaldehyde is considered as a VOC in this review)	Building materials and consumer products; solvents; cosmetics, etc.
Non-biological particles	Smoke and dust; $PM_{2.5}$; PM_{10}	Combustion; road pollution; industrial sources; air-borne soil and sand, etc.
Biological particles	Dust mites; mold; pollen; bacteria and organisms	Usually naturally occurring

The scientific minimum ventilation rate, on the other hand, is another topic of debates. In modern society, exposure to indoor compounds is almost inevitable regardless of where people live (Weschler, 2009). The ultimate question on indoor pollutants should be whether people are exposed to pollutant levels that are above health-based criteria. And the corresponding minimum ventilation rate should be adequate enough to minimize the health effects that indoor air pollutants can pose on occupants. In general, as summarized by (Carrer et al., 2015), available epidemiological data show that higher ventilation rates will reduce health outcomes and that there are minimum rates of ventilation above which some acute health outcomes can be avoided (the data on chronic health effects are still rare). But, no clear causality has been established and no universally applicable ventilation-health relationship can be established. The primary reason is that ventilation is indirectly related to health because it only modifies exposures to indoor and outdoor sources that affect health (Carrer et al., 2015).

Therefore, ventilation rate should be strongly based on the strength of the pollutant sources that are present indoors. And therefore, indoor air pollutants that have unhealthy concentrations can be considered as ventilation determinants. In a broader sense, ventilation determinants include temperature, humidity, emissions from occupants (bioeffluents), and emissions from indoor materials, furniture and work processes (Persily et al., 2005; Zuraimi and Tham, 2008). This paper only considers the indoor pollutants that can be used to determine the ventilation rates to be ventilation determinants.

Throughout the approximately 200-year history of the minimum ventilation rate, many indoor air pollutants, e.g., formaldehyde, VOCs, total volatile organic compounds (TVOC), SVOCs, and particles, have been discussed and proposed as potential determinants for the ventilation rate (Jokl, 2000; Liu et al., 2015; Noh and Hwang, 2010; Sherman and Hodgson, 2004; Ye et al., 2014c). At present, the regulated ventilation rate is primarily based on IAQ surrogates that represent the bioeffluent mostly emitted from humans, such as CO_2 and odor. Due to the groundwork laid by Pettenkofer (1858) and Yaglou et al. (1936), the link between the minimum ventilation rate and CO_2 (or odor) has been extensively studied. The idea of determining the minimum ventilation rate based on sensory end-point (odor and irritation) has been further developed in the concept of perceived IAQ (Fanger, 1988). Ultimately, the ventilation rate should be more dependent on the health end-point of indoor pollutant exposure, such as short- and long-term health consequences, instead of on occupants' perception of IAQ alone (Sundell et al., 2011). It was not until recently that moderate concentrations of bioeffluents with CO_2, not pure CO_2, were proven to be a causative agent and to have deleterious effects on acute health symptoms and cognitive performance of occupants during typical indoor exposures (Zhang et al., 2016a). This result suggests that to dilute the concentrations of indoor bioeffluents is not only an effort for sensory-related purposes, but also a measure to avoid potential health effects. This is an epitome to the limited but growing scientific bases to determine ventilation rate. As (Persily, 2015) summarized, there are many challenges and efforts in developing ventilation rate standards, and to date, the purpose of recommending adequate ventilation rate shifts