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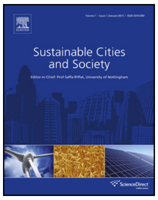

Engineering Advance

Ozone in indoor environments: Research progress in the past 15 years

Moshood Olawale Fadeyi[a,b,*]

[a] Berkeley Education Alliance for Research in Singapore, 1 Create Way, #11-01, Singapore 138602, Singapore
[b] School of Civil and Environmental Engineering, Nanyang Technological University, N1-01a-29, 50 Nanyang Avenue, Singapore 639798, Singapore

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ABSTRACT

Presence of ozone in indoor environment has implications on creation of sustainable indoor environment. A material mass balance model is used to summarize outcome of the review exercise that was conducted to understand what 15 years has taught us, with regards to the chemistry and concentration of ozone in indoor environment, since after a similar review effort by Weschler in the year 2000. Additionally, key knowledge gained on the impact of ozone and its initiated chemistry products on human health and comfort are summarized. This paper is concluded with recommendations for future research directions.

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* Tel.: +65 85753287.
E-mail addresses: mfadeyi@ntu.edu.sg, mofadeyi@gmail.com

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1. Introduction

Ozone exposure is a major public health challenge (The Royal Society, 2008). There is a positive association between increase in ambient ozone concentration and increase in hospital visits, morbidity and mortality rates (Bell and Dominici, 2008; Bell, Dominici, & Samet, 2005; Bell, McDermott, Zeger, Samet, & Dominici, 2004; Ito, De Leon, & Lippmann, 2005; Lee, Cho, & Son, 2010; Levy, Chemerynski, & Sarnat, 2005; Smith, Xu, & Switzer, 2009; Sousa, Alvim-Ferraz, & Martins, 2013; Zhang et al., 2006). Most of the ozone exposures occur in indoor environment (Chen, Zhao, & Weschler, 2012). Evidences have shown positive correlations between increase in outdoor ozone concentration and increase in prevalence of building related symptions among building occupants (Apte, Buchanan, & Mendell, 2008; Buchanan, Mendell, & Mirer, 2008).

Indoor factors affect the concentration of ozone building occupants are exposed to (Weschler, 2000). The factors, as mentioned in Weschler (2000), include: sources of indoor ozone – indoor and outdoor, outdoor air-exchange rate, surface removal by indoor materials, ozone reactions with chemicals in buildings, and indoor air parameters – indoor relative humidity (RH) and temperature. Since after Weschler (2000) was published, research efforts on ozone in indoor environment continued and we have learnt more.

In addition to revisiting issues addressed in Weschler (2000), this paper summarized important knowledge we have gained and update knowledge gained on the chemistry and concentration of ozone in indoor environment since after Weschler (2000) to the present – 2015. I acknowledge that since after Weschler (2000), there have been several review studies on this subject (e.g., Weschler, 2001, 2004, 2006, 2009, 2011, 2015; Weschler, Wells, & Poppendieck, 2006; Rohr, 2013; Salthammer & Bahadir, 2009; Wolkoff, 2013; Wolkoff & Nielsen, 2001; Wolkoff, Wilkins, Clausen, & Nielsen, 2006). However, these studies, albeit detailed, either did not focus specifically on ozone or addressed aspect(s) of ozone studies. This present study, like Weschler (2000), attempts to provide understanding that cut across all aspects of ozone studies on what we have learnt over the past 15 years. This paper is concluded by suggesting future research directions for the next 15 years.

2. Context of the review

A material balance is used to summarize knowledge gained over the past 15 years on the chemistry and concentration of ozone in indoor environment – buildings and aircrafts. Additionally, implications of human exposures to ozone and its initiated chemistry products are also addressed.

Before addressing the above issues, information on typical indoor ozone concentration and materials balance are provided below.

2.1. Typical indoor ozone concentrations

Fig. 1 shows measured ozone concentration range – reported minimum and maximum values – in buildings and aircraft. Indoor ozone concentrations in buildings are usually below recommended exposure limit. However, indoor ozone concentrations in aircraft cabin could be significantly higher than recommended exposure limit.

It is important to note that if there is considerable amount of ozone in buildings, but at concentrations below exposure limit provided by health authorities, it does not necessary mean everything is alright. This is because exposures to oxidation products derived from indoor air chemistry initiated by ozone may be more harmful than being exposed to ozone alone (Wolkoff, 2013; Wolkoff et al., 2006). There are numerous sources that emit ozone reactive organic compounds – unsaturated hydrocarbon – into indoor environment (Nazaroff & Weschler, 2004; Weschler, 2006). Needless to say that efforts should be made to reduce indoor ozone concentration as much as possible even if its concentration is below exposure limit.

2.2. Material balance

Eqs. (1) and (2) show parameters that would determine concentrations of indoor ozone and its initiated chemistry product, respectively when human are not physically present in indoor environment. "$[C_{O3}]_{ss}$" is the concentration of indoor ozone at steady state. "$(\eta_v\lambda_v)\ C_{out}$" is the contribution of outdoor environment to ozone in indoor environment through fraction (η_v) of outdoor ozone (C_{out}) that enters indoor environment through dedicated outdoor inlet meant for outdoor–indoor air exchange (ventilation rate – λ_v). "$(\rho\lambda_L)\ C_{out}$" is the contribution of outdoor environment to ozone in indoor environment through fraction (ρ) of outdoor ozone (C_{out}) that enters indoor environment through leakages (λ_L) in buildings. "(E_{O3})" is the rate at which ozone is emitted by indoor source of ozone into indoor environment; "V" is the volume of indoor environment. "$k_{sr,O3}$" is the rate at which ozone is removed by indoor materials. "$k_{O3,chem}[chem.]_{ss}$" is the rate at which ozone is removed from indoor environment by reactive organic compounds through chemical reactions – "$k_{O3,chem}$" is the second rate constant for the reactions between ozone and reactive organic compound, and "$[chem.]_{ss}$" is the concentrations of reactive organic compound at steady state.

"$[C_{prod}]_{ss}$" is the concentration of ozone initiated chemistry product in indoor environment at steady state. "$\{(y'_{prod}\%\ k_{O3,chem}[chem.]_{ss}\ [C_{O3}]_{ss})$" is the rate at which ozone initiated chemistry product is generated indoors, while y'_{prod} is the yield of formation of chemistry product. "f" is the filtration efficiency. "λ_{recirc}" is the rate at which the chemistry product formed is recirculated – assuming the building is air-conditioned and it is operating under recirculation mode. "$k_{sr,prod}$" is the rate at which the chemistry product is removed by indoor surface.

Eqs. (3) and (4) show parameters that would determine concentrations of indoor ozone and its initiated chemistry product, respectively when human are physically present in indoor environment. "$k_{sr,O3\_human}$" is the rate at which ozone is removed by human surfaces. "$k_{O3\text{-}inhal}$" is the rate at which ozone is removed by human through inhalation. "$k_{sr,prod\ human}$" is the rate at which ozone initiated chemistry product is removed by human surface. "$k_{prod\text{-}inhal}$" is the rate at which the product is removed by human through inhalation. Other parameters have been defined earlier.

$$[C_{O3}]_{ss} = \frac{(\eta_v\lambda_v + \rho\lambda_L)C_{out} + (E_{O3}/\mathrm{V})}{(\lambda_v + \lambda_L + \mathrm{k}_{sr,O3} + \mathrm{k}_{sr,O3,chem}[\mathrm{chem.}]_{ss})} \tag{1}$$

$$[C_{prod}]_{ss} = \frac{\left\{(y'_{prod}\%\, k_{O3,chem}[\mathrm{chem.}]_{ss}[C_{O3}]_{ss})/V\right\}}{(\lambda_v + \lambda_L + f(\lambda_v + \lambda_{recirc}) + k_{sr,prod})} \tag{2}$$

$$[C_{O3}]_{ss} = \frac{(\eta_v\lambda_v + \rho\lambda_L)C_{out} + (E_{O3}/V)}{(\lambda_v + \lambda_L + K_{sr,O3\_human} + K_{inhal} + k_{O3,chem}[chem.]_{ss})} \tag{3}$$

$$[C_{prod}]_{ss} = \frac{\left\{(y'_{prod}\%\, k_{O3,chem}[\mathrm{chem.}]_{ss}\right\}}{(\lambda_v + \lambda_L + f(\lambda_v + \lambda_{recirc}) + k_{sr,prod} + k_{sr,prod\_human} + k_{prpd\_inhal})} \tag{4}$$

The numerator and denominator parameters in the equations represent sources and sinks, respectively. Key knowledge gained sequel to the impact of these parameters on ozone and initiated