Sustainable Cities and Society 28 (2017) 466–472

Contents lists available at ScienceDirect

Sustainable Cities and Society

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

Indoor ozone and climate change

L. Zhong*, C.-S. Lee, F. Haghighat

Concordia University, Quebec, Canada

ARTICLE INFO

Article history:
Received 24 April 2015
Received in revised form 20 August 2016
Accepted 22 August 2016
Available online 23 August 2016

Keywords:
Ozone
Climate change
Buildings
Ozonation
Photocatalytic oxidation

ABSTRACT

It has been anticipated that climate change impacts ambient air pollution and thereby affects indoor air quality through ventilation. Yet, it is not clear how a changing climate, along with new developed interior building materials, products, and air cleaners, affects indoor air quality, and how to minimize negative effects. In this paper, ozone, as one of the greenhouse gases, has been selected to examine the photochemical mechanism for the explanation of ground level changes in the outdoors. The effects of temperature and precursors on ground level ozone formation have been discussed. Ozone concentration changes for different regions within Canada in recent 20 years are examples to demonstrate the trend of ozone levels in the future. In addition, the indoor sources contributing to the ozone levels are characterized. Moreover, this paper explores the feasibility of photocatalytic oxidation (PCO) technology based air cleaners for indoor ozone removal with the objectives of providing reliable technology and updating the literature.

1. Introduction

Climate change has been increasingly drawing people's attention in past decades due to its close relationship to the people's daily life and the ecosystem development. Research relevant to this topic is blooming, which covers areas of environment, agriculture, health, meteorology, sociology, and so on (Confalonieri, Lima, Brito, & Quintao, 2014; Jaroszweski, Hooper, & Chapman, 2014; Johnson & Hutton, 2014; Kulmala et al., 2014; Matyssek, Kozovits, & Wieser, 2015; Yuan, Mu, Zuo, & Wang, 2015). Much evidence over the past 20 years indicates that climate change can be associated with adverse health outcomes, including heat-related disorders, respiratory disorders, infectious diseases, food insecurity, and mental health disorders (Patz, Frumkin, Holloway, Vimont, & Haines, 2014). For example, Fukuda et al. (2014) found that climate change leads to increased male fetal deaths in Japan through the interaction relationships between temperature differences and sex ratios of newborn infants from 1968 to 2012. In addition, negative impacts of climatic factors and air pollution on the tourism industry through deforestation and natural resource depletion were observed in Asia, Africa, and the Pacific regions over a period of 1975–2012 (Sajjad, Noreen, & Zaman, 2014).

Although research on climate change normally focuses on outdoor air quality, the majority of people spending most of their time inside buildings have caused researchers to enhance interest in examining impacts of climate change on indoor environments. Climate change evolves the composition and level variations of outdoor air pollutants, which may impact upon the indoor air quality in a variety of ways. Nazaroff (2013) proposed that there are three ways by which indoor air quality gets affected: (1) outdoor air quality change, (2) building operations in a different manner, and (3) humans' new activities adapted to the climate change. Due to the limited available publications in this field, our objectives are to study fundamental physical and chemical factors contributing to indoor air quality and to explore the feasibility of photocatalytic oxidation technology on elimination of indoor pollutants.

Considering that hundreds of indoor air pollutants have been identified in the literature (Gallego, Roca, Perales, & Guardino, 2009), it is too complicated to clearly determine their fates in indoor environments in the context of climate change. This project selected ozone to carry out outdoor and indoor emission sources analysis, examine photochemical reaction, as well as the investigation of potential ozone removal technology. Ozone naturally exists in the atmosphere; however, ozone concentration has been varied due to the humans' activity. It is known that ozone has adverse effects on human health, ecosystems and reduction in agricultural yields (Confalonieri et al., 2014; Eiswerth, Shaw, & Yen, 2005; Kulmala et al., 2014; Lee, Lee, & Bae, 2014; Yuan et al., 2015), including irritation of the respiratory system, damage of lung function, and interference with photosynthesis for some plants, it is

* Corresponding author at: Department of Building, Civil and Environmental Engineering, Concordia University, Montreal, Quebec, Canada.
E-mail addresses: lexuan.zhong@yahoo.com, lexuanz@umich.edu (L. Zhong).

http://dx.doi.org/10.1016/j.scs.2016.08.020
2210-6707/

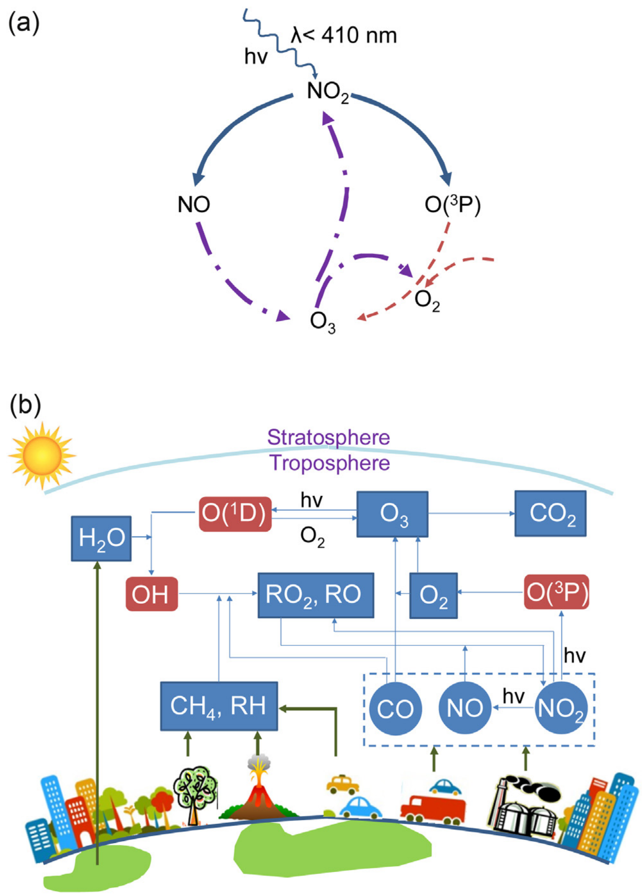

Fig. 1. A diagram of ozone formation: (a) ozone equilibrium without the presence of VOCs; (b) ozone generation in the troposphere.

necessary to fully study the trends of ozone concentration outdoors and indoors in order to propose reliable technologies or strategies for ozone control.

2. Ozone reaction mechanisms

The understanding of ozone formation/decomposition and the knowledge of the complex mechanisms by which man-made/natural emissions influence ambient ozone concentrations are essential to examine the trends and variations of the future ozone concentration. In this section, the photochemical reactions contributing to ozone formation/decomposition are discussed.

2.1. Ozone formation

Ozone is regarded as one of the photochemical reaction products when nitrogen oxides (NOx), volatile organic compounds (VOCs) and carbon monoxide (CO) are presented as precursors under the exposure of sunlight. NOx and CO are the major emissions from fossil fuel combustion and motorized vehicles. VOCs come from transportation, organic solvent evaporation, and natural emissions from vegetation and volcanos. In the presence of only NO_2 and sunlight, Fig. 1(a) shows ozone can be the product of O_2 in combination with $O(^3P)$ (atomic oxygen) generated by photolysis of NO_2. Moreover, formed ozone further oxidizes NO to NO_2. Hence, a dynamic equilibrium is established so that ozone concentration keeps a constant level in this scenario.

When VOCs participate in the photochemical reactions, the oxidation chains are becoming complicated due to the involvement of more radicals. Here, the three governing equations are listed to demonstrate ozone production from VOCs, methane, and CO. Methane is the major biogenic gas from vegetation. In all cases, OH radicals play an important role to initiate photochemical reactions and then the resulting intermediates continue to be oxidized in a manner of propagation reactions. Photolysis of NOx plays a significant role in the generation of single oxygen atoms which are quickly trapped by O_2 to create ozone. Fig. 1(b) presents the atmospheric chemistry process pertinent to the ozone generation and decomposition occurring in the troposphere. Interactions of anthropogenic and natural emissions of selected primary pollutants with second pollutants are illustrated under the exposure of sunlight. Different VOCs react at different rates to form ozone, which leads to ozone generation rates associated with the availability of VOCs in the atmosphere. In atmospheric chemistry, alkenes behave more reactive than the other VOCs in ozone formation, the process of which may take several days to complete. Fanizza, Incoronato, Baiguera, Schiro, and Brocco (2014) found that propene, ethene and toluene are the primary VOCs to form ozone in Rome.

$$CO \xrightarrow{NO_x} CO_2 + O_3 \tag{1}$$

$$CH_4 \xrightarrow{NO_x} CO_2 + O_3 + OH^{\bullet} \tag{2}$$

$$RH \xrightarrow{NO_x} R'CHO + O_3 \tag{3}$$

Eqs. (1)–(3) show that the ozone concentration is a function of precursors' concentrations. RH in Eq. (3) denotes a generic VOC. Sportisse (2010) found that emission reduction strategies for ozone precursors are associated with the ratio of VOCs to NOx. To be specific, in the high-NOx regime, a decrease in NOx or an increase in VOCs concentration contributes to higher ozone generation; in the low-NOx regime, a decrease in NOx helps to reduce ozone concentration, while changes in VOCs emissions make little contributions. Therefore, ozone concentrations are strongly influenced by changes in NOx emissions (Escudero, Lozano, Hierro, del Valle, & Mantilla, 2014; Lacressonniere et al., 2014). Controlling strategies may be determined after composition analysis of outdoor air at various elevations is completed, which demonstrate territorial characteristics. It is noted that the VOC/NOx ratio measured near the ground might not represent the ratio in the troposphere. It is necessary to take enough samples at different heights to get the accurate ratio so as to apply correct regulations for ozone control.

2.2. Ozone-initiated products

Ozone is one of the greenhouse gases (GHG). GHG, especially CO_2 and water, absorb a band of infrared radiation emitted by the earth, promoting an increase of temperature. As a major component of urban smog, ozone is able to oxidize NOx and SO_2 to acids with the presence of water vapor, which can corrode building surfaces, such as metals, stones, and polymers. Ozone is also a reagent for the ultrafine particles (UFPs) formation under reaction with VOCs. For example, average 7.7×10^{10} particles with a size of 40 nm were observed when one lemon-scented marker was put inside the chamber with 150 ppb ozone for 1 min (Fung, Shu, & Zhu, 2014).

Another serious concern on health effects of ozone is the number of oxygenated and poly-oxygenated reaction products from reactions with ozone-initiated VOCs. Thousands of organic airborne pollutants, directly or indirectly emitted from human and nature activities, undergo physical, chemical, photochemical, and catalysis processes in the atmosphere. Scientists have proved that ozone reacts with organic compounds with double bonds (Gary & van Loon, 2011). The phenomenon of ozonation with aromatics, alkanes, and alcohols have been observed in a dynamic flow system, although they are less reactive as compared with alkenes (Zhong & Haghighat, 2014). Therefore, ozone along with its photolysis product, $^{\bullet}OH$ radicals, plays a role to oxidize hydrocarbons to oxygenated species, some of which are known to be carcinogens