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Review

A review on black carbon emissions, worldwide and in China

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HIGHLIGHTS

- BC formation from open burning and controlled combustion are summarized.
- Different sampling and measuring processes for open burning and controlled combustion are compared.
- BC inventory prediction methods and results are reviewed.
- Results of BC inventory estimation in China showed lower values than other researches.

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ABSTRACT

Black carbon (BC) produced from open burning (OB) and controlled combustion (CC) is a range of carbonaceous products of incomplete combustion of biomass and fossil fuel, and is deemed as one of the major contributors to impact global environment and human health. BC has a strong relationship with POPs, in waste combustion, BC promotes the formation of POPs, and then the transport of POPs in the environment is highly influenced by BC. However less is known about BC formation, measurement and emissions estimation especially in developing countries such as China. Different forms of BC are produced both in CC and OB. BC emission characteristics and combustion parameters which determine BC emissions from CC and OB are discussed. Recent studies showed a lack of common methodology and the resulting data for describing the mechanisms related to BC formation during combustion processes. Because BC is a continuum carbonaceous combustion product, different sampling and measuring methods are used for measuring their emissions with great quantitative uncertainty. We discuss the commonly used BC sampling and measuring methods along with the causes for uncertainty and measures to minimizing the uncertainty. Then, we discuss the estimations of BC emission factors and emission inventory for CC and OB sources. The total emissions of BC from CC and OB in China are also estimated and compared with previous BC emission inventories in this review and we find the inventories tend to be overestimated. As China becomes the largest contributor to global BC emissions, studies for characterizing BC emissions from OB and CC sources are absent in China. Finally, we comment on the current state of BC emission research and identify major deficiencies that need to overcome. Moreover, the advancement in research tools, measuring technique in particular, as discussed in this review is critical for researchers in developing countries to improve their capability to study BC emissions for addressing the growing climate change and public health concerns.

Contents

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1. Introduction

BC is an important composition of incomplete combustion byproducts commonly referred to as soot (Andreae and Crutzen, 1997). It is mainly produced from CC and OB. As is known, BC causes major environmental problems. It contributes to global warming, induces effects such as glacier retreat and sea ice melting (Ramanathan and Carmichael, 2008), and causes serious health problems (Koelmans et al., 2006) by carrying carcinogenic compounds. It contributes the second strongest global warming effect only after CO_2 (Ramanathan et al., 2001; Chung et al., 2005; Ramanathan and Carmichael, 2008; Shrestha et al., 2010).

BC has a strong influence on human health (Bice et al., 2009; Kandlikar et al., 2009; Shrestha et al., 2010). The particle size and substances absorbed on the surface are the main factors influencing the health effect. Smaller BC particles, size ranging from ultra-fine (less than 0.1 μm) to fine (less than 2.5 μm), can do more harm to health than particles of larger size. Ultra-fine particulate air pollutants can migrate deep into the alveolar region (Shrestha et al., 2010) and usually carry very toxic, even carcinogenic substances for example polycyclic aromatic hydrocarbons (Koelmans et al., 2006). Particles whose size is larger than 4 μm or smaller than 0.002 μm have less harm to human health, because after inhalation, most of them are intercepted in the mouth and throat region (Hinds, 1999).

BC is formed in nearly all traditional combustion processes. In different combustion conditions such as OB and CC, the incomplete combustion byproducts are different. Particles from CC contain a higher fraction of BC, while OB produces more particles than CC. During the formation of BC particles, large amounts of PAH and small hydrocarbon molecules are produced. When chlorine presents in the combustion, BC particles along with PAHs in the stack will react with chlorine to form PCDD/Fs, PCBz, PCBs, etc. These compounds are toxic and permanent in the environment.

Much research attentions were paid to the measurement, emission inventory estimation, and global warming effects of BC recently. The shortcomings of current standard measuring methods lead to the estimation of BC emission inventory with high uncertainty. Moreover, the lack of characterization studies on BC emission sources makes it even difficult to get accurate estimation of BC emissions in developing countries. Computer simulation is a widely used approach in previous studies, and the accuracy of the simulation results depends on the model, BC emission inventory and emission source characterization, etc. More detailed BC emission inventory and well characterization of emission sources are even more important in the BC emission evaluation and estimation. This paper aims to provide a current understanding of BC emissions from two major source categories, CC and OB, the sampling and quantitative measuring methods, and an estimation of BC emissions in China. We also identify major breakthroughs that are necessary for the advancement of BC emission research especially for researchers from developing countries to improve their capability to study BC emissions as a growing climate change and public health concern.

2. BC and POPs

2.1. BC and PCDD/Fs formation

BC (or called soot) is formed in nearly all combustion process. In the formation process of BC, large amount of aromatic molecules are formed. With the presence of metal ion catalysts such as Cu, Fe, reactions take place and aromatics and chlorine (HCl, Cl_2) forms PCDD/Fs. In most flue stack, a lot of BC particles are present and precipitate in the stack. For *de novo* synthesis of PCDD/Fs, presence of carbon particles is a crucial factor. The degenerated graphitic structure of soot particles, O_2 in the flue gas, trace amount of chlorine, and catalysts absorbed on the particles provides sufficient conditions for the *de novo* synthesis of PCDD/Fs. In the *de novo* reaction process, a variety of organic byproducts are produced including PCDD/Fs, PCBz, PCPh, PCNP and PCB (Stieglitz et al., 1989).

Researchers found that the PCDD/Fs emissions of a newly built waste incinerator increase dramatically after a short phase of disturbed combustion conditions e.g. transient disturbance or malfunctions and the increase can last for a fairly long time (1–2 years) (Zimmermann et al., 2001). This phenomenon is called memory effect. During the disturbed combustion condition process, the combustion is incomplete and large amount of carbonaceous particles (BC, soot or fly ash) deposit on the wall of the stack. Large amount of PAH species and metallic compounds (Cu, Fe) are absorbed on the surface of BC particles due to their large specific surface area. It is proved that elemental carbon has high catalytic activities in a wide temperature range and metal ions are the most effective catalysts for PCDD/Fs formation. The PAHs absorbed on the surface of particles play the role of precursors. As said in the literature, PAH emission in the waste incinerator also showed similar memory effects to PCDD/Fs (Zimmermann et al., 2001).

BC particles in the incinerator provide precursors, catalysts for PCDD/Fs formation in an appropriate temperature range, promotes the emissions of PCDD/Fs and some other persistent organic pollutants dramatically.

2.2. POPs transportations by BC

BC particles emitting into the air absorbed a variety of incomplete combustion products such as PCDD/Fs, PAHs, PCBz, PCBs, and PCPh, most of which are carcinogenic. The particles will stay in the air for a long time.

BC aerosols influence human health via respiratory system (Kandlikar et al., 2009). Fine particles have strong absorption