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How incense and joss paper burning during the worship activities influences ambient mercury concentrations in indoor and outdoor environments of an Asian temple?

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HIGHLIGHTS

- A neglected mercury emission source in Asia was revealed in this study, which are the worship activities.
- This study was designated to investigate the speciated atmospheric mercury in the indoor and outdoor environments of a temple during the non-holiday and holiday periods.
- A laboratory-scale combustion chamber was further used to determine the mercury emission factors of TGM and Hg_p from the different incenses and joss papers burning.

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ABSTRACT

This study firstly investigated the species, concentration variation, and emission factors of mercury emitted from the burning of incenses and joss papers in an Asian temple. Both indoor and outdoor speciated mercury (GEM, GOM, and PHg) were sampled by manual samplers, while ambient GEM at an indoor site was in-situ monitored by a continuous GEM monitor. Field measurement results showed that the total atmospheric mercury (TAM) concentrations in indoor and outdoor environments were in the range of 8.03–35.72 and 6.03–31.35 ng/m^3, respectively. The indoor and outdoor ratios (I/O) of TAM in the daytime and at nighttime were in the range of 0.64–0.90 and 1.50–2.04, respectively. The concentrations of GEM, GOM, and PHg during the holiday periods were approximately 1–4 times higher than those during the non-holiday periods. GEM was the dominant mercury species in the indoor and outdoor environments and accounted for 63–81% of TAM, while the oxidized mercury accounted for 19–37% of TAM. Burning incenses and joss papers in a combustion chamber showed that the concentration of GEM from joss paper burning ranged from 4.07 to 11.62 μg/m^3, or about 13.97 times higher than that of incense burning, while the concentration of PHg from incense burning ranged from 95.91 to 135.07 ng/m^3, or about 3.29 times higher than that of joss paper burning. The emission factors of incense burning were 10.39 ng/g of GEM and 1.40 ng/g of PHg, while those of joss paper burning were 12.65 ng/g of GEM and 1.27 ng/g of PHg, respectively. This study revealed that speciated mercury emitted from worship activities had significant influence on the indoor and outdoor mercury concentrations in an Asian temple. Higher intensity of worship activities during holidays resulted in a higher concentration of speciated mercury in indoor and outdoor air, which might cause health threats to worshipers, staffs, and surrounding inhabitants through long-term exposure.

1. Introduction

Mercury (Hg) is a persistent, toxic, and bio-accumulative heavy metal which is currently regulated by the Environmental Protection Agency of the U.S.A. (USEPA) and by the United Nations Environment Programme (UNEP) (Lin and Pehkonen, 1999; Boening, 2000; Clarkson and Magos, 2006; Fu et al., 2010). Atmospheric mercury pollution has been designated by UNEP as the second global environmental issue following global warming induced by greenhouse

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gases (GHGs) (UNEP, 2002). Due to its unique physicochemical properties and potential for long-range transportation via atmospheric dispersion, mercury can be transported and eventually deposited worldwide (Mason and Sheu, 2002; Mason et al., 1994).

Atmospheric mercury comprises three types of mercury species: gaseous elemental mercury (GEM), gaseous oxidized mercury (GOM), and particulate mercury (PHg). Collectively, GEM and GOM are referred as total gaseous mercury (TGM), while together GEM, GOM, and PHg are referred as total atmospheric mercury (TAM) (Lindqvist and Rodhe, 1985; Sheu and Mason, 2001; Feng et al., 2002; Fu et al., 2009; Jen et al., 2013). GEM is easily spread by atmospheric air current, such that it can be transported globally, with its lifecycle in the atmospheric environment being anywhere from six months to two years (Schroeder and Munthe, 1998; Zhang et al., 2013).

As for the atmospheric speciated mercury, GEM is by far the main component, accounting for 98% or higher of TAM in the ambient air, while GOM and PHg combined account for only 2% or less (Feng et al., 2003; Fang et al., 2004; Nguyen et al., 2007). However, in the areas surrounding stationary mercury emission sources, the contribution of oxidized mercury (GOM + PHg) could increase up to 20% of TAM (Sheu and Mason, 2001), while the concentration of GOM and PHg in the flue gas may even reach as much as 60–90% of TAM (Brown et al., 1999; Karatza et al., 1996; Yuan et al., 2004a,b). UNEP Technical Report (2002) reported that mercury could be released into the atmosphere from a variety of natural and anthropogenic sources, and defined lots of Hg emission sources in different sectors. Large amount of speciated mercury were emitted from the burning process for fuel and biomass as the main anthropogenic mercury sources, which contain low concentration of speciated mercury. Accordingly, atmospheric mercury emitted form fuel and biomass burning has been attracted much attention from the scientists and governments which contribute about 36% and 33% of the total amount among the anthropogenic emissions respectively (Friedli et al., 2001, 2009; Pirrone et al., 2010; Lamborg et al., 2002). But up to now, few researches focused on potential mercury sources which emitted fewer amounts of speciated mercury from other burning activities such as worship since the amount of mercury emission is much less during the burning process compared with the fuel or biomass burning. Actually, worship activities, which are common in daily lives all over the world, have been demonstrated to emit large amount of air pollutants such as PAH_s, $PM_{2.5}$, CO, and etc, (Kuo et al., 2016; Dalibalta et al., 2015; Chiang et al., 2009). And the cardiovascular has been conformed to have a close relationship with these air pollutants emitted from incense burning process (Pan et al., 2014). Accordingly, the temples have been labeled as one of the important urban sources and regulated by governments in many countries (Environmental Protection Department of Hong Kong, 2013). However, the potential risk on the health caused by speciated mercury emitted from the worship activities are neglected, what's more, the atmospheric pollution of speciated mercury for the incenses and joss papers are less reported.

According to Geer's investigation (2012), the cord mercury levels of citizens were relatively higher in the Caribbean community in Brookly, NewYork, and even 16% of the sampled citizens' cord mercury concentration had exceeded 5.8 μg/L of the U.S. Environmental Protection Agency's Reference Dose. Among the pollution sources, the Caribbean unique ritualistic worship materials consisting of elemental mercury are not neglected. Although the worship materials (incenses and joss papers) containing less elemental mercury in Asian countries are distinct from those for the Caribbean religion, the pollutant of mercury emitted from the burning of large amount of incenses and joss papers, which likely expose the prayers to a potential health risk, can also not be neglected. The incenses and joss papers used in the worship activities are classified into four types based on the definition of worship materials by Taiwan Paper Industry Association. These four types of incenses and joss papers covered the most part of the worship materials consumed in Taiwan. In particular, Asian countries have the highest frequencies and intensities of worship activities in the world, during which a huge amount of incenses and joss papers are periodically burned, emitting many hazardous air pollutants (HAPs) including mercury into the atmosphere (Lung and Hu, 2003; Bootdee et al., 2016). The related literature on mercury emissions from worship activities in the temples is rarely reported. Recently, most researches focused on the emission of $PM_{2.5}$ and PAH_s (Chiang et al., 2009; Bootdee et al., 2016). The emission factors of $PM_{2.5}$ and PAH_s ranged from 0.4 to 44.5 mg/g (See and Balasbramanian, 2011) and from 17.1 to 25.2 μg/g (S-PAHs to be exact) (Lung and Hu, 2003), respectively, which are several orders of magnitude higher than those of mercury. However, the potential risk on the health of staffs and prayers caused by speciated mercury in the temples should not be neglected, since the indoor mercury concentrations were commonly much higher than those in the ambient environments. Unfortunately, no related researches have been reported so far. It is estimated that there are more than 12,083 temples in Taiwan with the highest density (0.34 temples/km^2) of temples in the world (Ministry of the Interior Taiwan, 2014). Burning incenses and joss papers emits a large quantity of air pollutants to the ambient air, resulting in high concentrations of mercury in the indoor and outdoor environments, and thus causing severely adverse effects on human health.

This study aims to investigate the concentration and partition of speciated mercury and their variation in indoor and outdoor environments of an Asian temple, and further to estimate the emission factors of speciated mercury from the incense and joss paper burning in a laboratory-scale combustion chamber.

2. Experiments

2.1. Sampling site description

The speciation and concentration of ambient speciated mercury were measured at a selected traditional temple in Taiwan, located in a residential area of Kaohsiung City (22°45′36″ N, 120°16′03″ E). Although the single temple was chosen for field measuring speciated mercury emitted from the burning of the incenses and joss papers, it is a typical Asian temple and all prayers of this temple has the same religious belief. Additionally, the worship activities of this temple are similar to those among the Asian temples, and the incenses and joss papers burned in this temple are the main worship materials in the Asian temples. This study aims to investigate the influence of speciated mercury emissions from worship activities on the air quality of indoor and outdoor environments, thus it is representative for other Asian temples with the same or similar religious belief. The location of the mercury sampling sites in the indoor and outdoor environments of the selected temple is illustrated in Fig. 1. In addition, there were no factories which would cause air pollution as well as particle pollution events around the temple during the sample periods. Active sampling of atmospheric speciated GEM, was conducted at two sites (see Fig. 1) for continuous 12 h (i.e. daytime and nighttime). The daytime sampling interval was from 8:00 to 20:00 and the nighttime sampling interval was from 20:00 to 8:00 next day in the indoor and outdoor environments of the selected temple. The sampling period was divided into two stages according to two different activity intensities of worships. The first stage was in the period of the 11th–14th of December 2012, which was characterized as the non-holiday. The other was set in February 24th–28th of 2013 characterized as the