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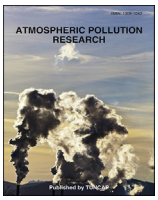

Original article

Substance flow analysis of mercury in Malaysia

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ABSTRACT

For the appropriate management of mercury, sources of emissions and release, as well as the amounts released, need to be clarified. We developed a mercury emissions inventory for Malaysia by measuring the actual emissions levels in two solid waste incineration facilities (SWIF-a and SWIF-b) and a coal-fired power station, as well as the mercury concentrations in the combustion residues and feedstock. The mercury concentration in the emissions from SWIF-a ranged from 1.1 to 27.6 μg/Nm^3, while that from SWIF-b averaged 35.1 μg/Nm^3. The estimated mercury concentration in emissions from the coal-fired power station ranged from 5.2 to 39.5 μg/Nm^3. We estimated the emissions and release of mercury into various media, and applied a substance flow analysis to link the flows and stocks. The total potential emissions in Malaysia in 2012 were an estimated 7.60–59.09 Mg (7.60–38.09 Mg excluding artisanal and small-scale gold mining [ASGM]). The measurements for the SWIFs and the coal-fired power station were used to refine the emissions inventory for Malaysia. In the future, it will be necessary to create reliable inventories for both atmospheric emissions and release into other media in Malaysia by collecting more reliable measurement data.

1. Introduction

Mercury is a heavy metal of special concern because it has many serious impacts on human health and the environment (Danish EPA, 2004). It can be found in many minerals, although cinnabar is the only ore being extracted for the principal product (Danish EPA, 2004). However, mercury is often extracted as a by-product together with other metals such as gold, zinc, and copper (Danish EPA, 2004; UNEP, 2010). This element has many uses, and is a component of various products such as dental fillings, batteries, light sources, and thermometers (Danish EPA, 2004; UNEP, 2010; IMERC, 2008; L. Peralta and Pausing, 2008; SR, 2011; Chang et al., 2007). In addition, the combustion of natural resources such as coal, oil, and gas as well as solid wastes, including municipal solid waste (MSW) and medical waste, can result in significant mercury emissions into air if it is processed without adequate controls.

As a consequence of rapid industrialization, Asia has become the main source region of mercury emissions into air, with east and southeast Asia accounting for about 40% of the global total (UNEP, 2013). Malaysia, as a developing country in Asia, has experienced problems with regard to mercury pollution. High concentrations of mercury have been reported in the areas of West Port, Malacca Straits, Prai, and Johor due to industrial activities, i.e., the total mercury concentration in sediments from West Port and Sungai Pulau, Johor ranges from 0.11 to 0.41 mg/kg, and high mercury concentrations (0.03–0.08 mg/L) have been detected in the rivers of Sungai Pok Kecil, Sungai Pok Besar, and Teluk Buih in Johor, as well as in seawater around Merambong Island (Praveena et al., 2013). High concentrations of mercury in food have been found on the west coast of the peninsula and are related to seafood intake from specific geographical locations, i.e., mercury levels in food samples from the Straits of Malacca have been reported as 1.1–3.2 μg/g (the permitted level in Malaysia is 0.5 μg/g) (Praveena et al., 2013). Mercury is also present in tropical fruits due to agro-chemical and fertilizer usage in Malaysia (Praveena et al., 2013; Hajeb et al., 2012). Because of its impacts on human health, the identification and reduction of mercury in the environment and its

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bioaccumulation has become an urgent issue. To protect human health and the environment from the adverse effects of mercury, the Minamata Convention on Mercury (MCM) was agreed upon in January 2013 and adopted by the Conference of Plenipotentiaries on 10 October 2013 in Minamata. The main outcomes of the MCM included a ban on the opening of new mercury mines (mining is allowed for a further 15 years in currently active mines), a phase-in of mercury control measures to tackle atmospheric emissions, and international regulation of the informal sector of artisanal and small-scale gold mining (ASGM) (WMCM, 2015). Malaysia signed the MCM agreement on September 24, 2014.

For the appropriate management of mercury, it is necessary to clarify the emissions and release sources, as well as the amount released. The United Nations Environment Programme (UNEP) has conducted an inventory of mercury emissions from 15 individual countries, including 5 in Asia (Cambodia, Pakistan, Philippines, Syria, and Yemen) using the UNEP Toolkit Inventory (UNEP, 2015). In addition, the Danish Environmental Protection Agency has conducted an emissions inventory for northern Europe, America, Canada, and Russia using inventory data collected by questionnaire surveys (Danish EPA, 2005). Many studies have subsequently applied inventory data either from the UNEP Toolkit Inventory or other sources, including published literature, internet resources, personal communications, and assumptions to assess the emissions and release of mercury in areas such as Turkey (Civancik and Yetis, 2015), the European Union (EU) (Sundseth et al., 2011), the United States (US) (Cain et al., 2007; MPCA, 2001), Australia (Reisinger et al., 2009), Japan (MOE, 2010), and Malaysia (MNRE and DOE, 2006). However, the published results described above contain many uncertainties due to inaccurate mercury emission inventory data. Therefore, it is important to clarify the actual mercury emissions to support policy decisions.

Thus, in this study, we provide reliable quantitative information regarding mercury emissions as a basis for implementing strategic mercury management policies in Malaysia. We initially developed a mercury emissions inventory using: (1) measurements of actual mercury emissions from two solid waste incineration facilities (SWIF-a and SWIF-b) and a coal-fired power station, as well as the mercury concentrations in combustion residues and feedstock in Malaysia; and (2) interviews with the Department of Environment (DOE), Malaysia. Then we estimated the emissions and release of mercury into various media at the substance level, and applied substance flow analysis (SFA) to link the flows and stocks in Malaysia.

2. Materials and methods

2.1. Identification of uses and sources in Malaysia

By considering studies conducted for the UNEP and in Malaysia (UNEP Chemicals, 2011; Hajeb et al., 2012; MNRE and DOE, 2006), mercury uses and source categories were identified. For the purposes of this study, they were divided into four categories of combustion, manufacture, intentional use, and others. Combustion emissions are mainly derived from six sources: coal, oil (petroleum), natural gas, oil refineries, solid waste, and medical waste. Manufacturing emissions are mainly derived from eight sources: non-ferrous metals, cement, gold mining (no amalgamation), ASGM, ferrous metals, pulp and paper, limestone, and biomass power stations. Emissions from intentional uses of mercury are mainly derived from eight sources: thermometers, dental filings, batteries, electric switches and relays, light sources, manometers, gauges, and miscellaneous uses. Other emissions include the landfilling of MSW and crematoria.

2.2. Developing a mercury emissions inventory in Malaysia

To develop the mercury emissions inventory, we measured the actual emissions levels from two private-sector SWIFs and a coal-fired power station in Malaysia, as well as the mercury concentrations in combustion residues and feedstock during 2012. The MCM requires participating nations to control mercury air emissions from coal-fired power plants, coal-fired industrial boilers, the production of certain non-ferrous metals, waste incineration, and cement production. In this study, as a result of negotiations with the DOE and business entities, a limited number of measurements were permitted from the three facilities referred to above. In addition, we also conducted interviews with the DOE.

2.2.1. Target facilities

In an onsite survey in Malaysia, we measured the mercury concentration in emissions from three facilities. Measurements were made from SWIF-a (20 Mg per day) and SWIF-b (150 Mg per day) and a coal-fired power station (700 MW per unit). These were operational values at the time of the study. The number of SWIFs and coal-fired power stations in Malaysia is less than 10 each (Asean Centre for Energy, 2014 and Abd Kadir et al., 2013).

2.2.2. Experimental methods

(1) Analysis of mercury in flue gas

To sample mercury from flue, we used a portable continuous emissions monitor (CEM: model EMP-2/WLE-8, Nippon Instruments, Co., Ltd, Osaka, Japan). The analyzer consisted of two units, a preprocessor (WLE-8) and detector (EMP-2). It measured the total gaseous mercury in the sample gas. The CEM used in this study was operated in accordance with the JIS K0222 standard, and the results obtained correlated well with the mercury concentration measured from a sewage sludge incinerator (Tanida et al., 2013) and a small-scale gold mining site (Kono and Tomiyasu, 2013). In the preprocessor, the sample gas is absorbed with 10% (w/v) stannous chloride ($SnCl_2$) reducing solution (5% sulfuric acid), and Hg^{2+} is reduced to the gaseous elemental mercury (Hg^0). After the acid gas is absorbed in a gas cleaning tube containing 1 mol/L KOH solution and is dehumidified, it enters the detector and the amount of mercury is measured. The principle of measurement is cold atomic absorption spectrometry and the measuring range is 0.1–1000 μg/Nm^3. The measured value was recorded continuously every second. The detection limit of this device is 0.1 μg/Nm^3. A polytetrafluoroethylene (PTFE) tube with an inner diameter of 6 mm was used as a sampling tube, with glass wool inserted in the end to prevent contamination by dust, in accordance with the JIS K 0095: 1999 standard. The sampling tube was inserted into the sampling hole in the side of the duct and was fixed in place using a piece of rag wadding. The sample gas was collected at a flow rate of 1 L/min. The sampling time was 50 min for SWIF-a, 120 min for SWIF-b, and 65 min for the coal-fired power station. The temperature of the sample gas at the collection point was measured using a thermocouple thermometer, and was 82 °C at SWIF-a, 232 °C at SWIF-b, and 146 °C at the coal-fired power station. The sensitivity of the CEM was confirmed manually before and after the sampling campaign by measuring a 50 μg/Nm^3 Hg vapor.

(2) Analysis of mercury in solid samples

Six solid samples were collected: fly ash and bottom ash from SWIF-a and bottom ash and three types of coal (Coal-a, Coal-b, Coal-c) from the coal-fired power station. The sampling location is shown in Fig. 1. The fly ash from the coal-fired power station was

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