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Estimation of CO_2 emissions from waste incinerators: Comparison of three methods

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ABSTRACT

Climate-relevant CO_2 emissions from waste incineration were compared using three methods: making use of CO_2 concentration data, converting O_2 concentration and waste characteristic data, and using a mass balance method following Intergovernmental Panel on Climate Change (IPCC) guidelines. For the first two methods, CO_2 and O_2 concentrations were measured continuously from 24 to 86 days. The O_2 conversion method in comparison to the direct CO_2 measurement method had a 4.8% mean difference in daily CO_2 emissions for four incinerators where analyzed waste composition data were available. However, the IPCC method had a higher difference of 13% relative to the direct CO_2 measurement method. For three incinerators using designed values for waste composition, the O_2 conversion and IPCC methods in comparison to the direct CO_2 measurement method had mean differences of 7.5% and 89%, respectively. Therefore, the use of O_2 concentration data measured for monitoring air pollutant emissions is an effective method for estimating CO_2 emissions resulting from waste incineration.

1. Introduction

The United Nations framework convention on climate change (UNFCCC) was adopted in 1992 in Rio de Janeiro Brazil to cope with accelerating climate change. Based on 'The Principle of Common but Differentiated Responsibilities', all countries were motivated to reduce greenhouse gas (GHG) emissions caused by anthropogenic activities (UN, 1992). Parties under UNFCCC are required to report their greenhouse gas emissions and removals by sector as calculated according to the agreed upon methodologies. Based on the 2006 Intergovernmental Panel on Climate Change (IPCC) guidelines (GLs) for national greenhouse gas inventories (IPCC, 2006), targeted GHGs associated with waste incineration are CO_2, CH_4, and N_2O. Carbon dioxide is a major greenhouse gas which accounted for 96.5% of the gases emitted from waste incineration in Annex I countries in 2012 (UNFCCC, 2017).

There are three tier levels used to estimate CO_2 emissions from waste incineration in the 2006 IPCC GLs. The application of the higher tier levels, which use more country-specific (CS) or site specific data, is defined as a good practice (IPCC, 2006). CO_2 emissions using the Tier 1 method can be estimated using waste characteristic parameters such as waste composition, dry matter content (*DM*), carbon content (*CF*), and fossil carbon fraction (*FCF*). Tier 2 uses more CS data than Tier 1, which applies default values given in IPCC GLs. Tier 3 utilizes facility-specific data to estimate CO_2 emissions (IPCC, 2006). In recent years, the application of Tier 3, which reflects site-specific conditions and results in transparency of GHG emissions estimates, are becoming more widespread (Choi et al., 2014).

During the 2010 IPCC Expert Meeting, discussions were held on how facility-level data, including the use of gas concentration information, can be incorporated into national inventories (IPCC, 2011). Some studies suggest that facility-level data might improve national GHG inventories by using them as quality control (QC) tools, for a bottom-up approach, or for CS parameter development (Choi et al., 2017b; Hanle, 2010; IPCC, 2011, 2006; Sturgiss, 2010). Facility-level CO_2 emissions data from incineration facilities can be obtained by direct CO_2 measurements and the mass balance method according to IPCC GLs (IPCC, 2006). Another option may be the utilization of an Environmental Protection Agency (EPA) methods (40 CFR 75.13 and 60.45) that were designed to estimate

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CO_2 emissions from the combustion of fossil fuel such as coal, oil, and natural gas using O_2 concentration and fuel characteristic data.

Previous studies have reported various values for CO_2 emissions and emission factors from waste incinerators. Many of them presented *FCF* values for each composition of waste or fossil origin CO_2 fraction along with emission factors (Astup et al., 2009; Jones et al., 2014; Mohn et al., 2008, 2012; Palstra and Meijer, 2010). A study conducted by Choi et al. (2017a) estimated N_2O and CO_2 emission factors using hourly measured concentration data and compared variabilities in N_2O emission factors with CO_2 emission factors in terms of waste type, incinerator type (i.e., stoker, fluidized bed), and deNOx technology to characterize N_2O emission factors by category. Chen and Lin (2010) compared direct CO_2 measurements in flue gas with the estimated CO_2 emissions using the mass balance method following IPCC GLs and found a significant difference between the two results. However, there has been no study to explore the applicability of O_2 concentration conversion to estimate CO_2 concentration or CO_2 emissions resulting from waste incineration.

A continuous emissions monitoring system (CEMS) has been implemented to determine the compliance of industrial source air pollutant releases within many jurisdictions including in the US, Canada, Germany, UK, China, India, Japan, and South Korea (hereafter, Korea) (Guttikunda and Jawahar 2014; Jahnke, 2010; Nakamura et al., 2010; Zhang and Schreifels, 2011; Appendix A). In order to avoid dilution effects, a measurement of reference quantities of oxygen and moisture in the smokestack gas is essential in the emissions monitoring system. The reference quantities of oxygen are measured simultaneously with the concentration of pollutants in order to correct pollutant data to reference conditions for oxygen. According to '2017 White paper of Environment' published by Ministry of Environment, Korea (Appendix A), continuous air pollutant emissions monitoring has been conducted in Korea since 1998. As of 2016, seven air pollutants including dust, SO_2, NOx, NH_3, HCl, HF, and CO and O_2 at 1568 smokestacks were being measured with real-time monitoring. However, carbon dioxide has not been included in the CEMS.

In this study, we aimed to identify the applicability of continuously measured O_2 concentration data from incineration facilities of waste which is more heterogeneous than fossil fuel, to determine CO_2 emissions. Therefore, we compared the fossil CO_2 emissions (*FCO_2E*) and fossil CO_2 emission factors (*FCO_2EF*) estimated by three different methods for waste incineration facilities with and without periodic waste composition analysis. The three methods used were: making use of CO_2 concentration data, converting O_2 concentration and waste characteristic data, and using a mass balance method following the 2006 IPCC GLs.

2. Materials and methods

2.1. Waste incineration facilities and data collected

Four municipal waste incinerators (MWIs) and three industrial waste incinerators (IWIs) were selected based on the waste type (i.e., municipal waste (MSW) and industrial waste (IW), incinerator type, operation mode, and the existence of CEMS. As shown in Table 1, all seven facilities were continuously operated with stoker-type incinerators. After CO_2 analyzers were installed on the selected facilities, CO_2 and O_2 concentrations, and the flue gas flow rate were continuously measured and the parameters needed for the estimation of *FCO_2E* and *FCO_2EF* in each facility were collected or calculated (Table 1).

QA/QC (quality assurance/quality control) was conducted with CO_2 instruments (non-dispersive infrared absorption, VA-3001, Horiba; Ultramat 6, Siemens), O_2 instruments, and flue gas flow meters. O_2 instruments and flow meters on site were from various manufacturers however, they were subject to certification, regular accuracy inspection and calibration, and documentation by test standards in line with Appendix A, B, and D of EPA 40 CFR 75 (Appendix A).

Samples were collected at 30 or 60 min intervals for 24–86 days from each facility between July 2008 and September 2011 (Table 1). CO_2 and O_2 concentrations, and operating conditions (flue gas flow rate, daily waste input, furnace temperature) were compared and analyzed to screen for abnormal data. Missing or abnormally measured data were substituted for according to EPA 40 CFR Part 75. In total, a minimum of 576 and a maximum of 3744 samples were used for CO_2 emission estimation.

The daily amount of waste combusted in each facility was also obtained during the CO_2 measurement period (Table 1). Composition data associated with each measurement period for MSW were obtained from 'Annual Statistics on MWIs with energy recovery (Appendix A)' and for IW, obtained from design values (Table 2). Because proximate analysis (i.e., %moisture content, %ash content, %volatile matter content, and %fixed carbon) and elemental fraction results by each waste composition were not always available for each site, dry matter content and the mass fractions of C, H, O, N, and S by waste composition were collected from the latest and most comprehensive nationwide survey (Table 3; Appendix A). Municipal solid waste samples in the survey were stratified for rural/suburban/inner city areas, season, residential structure type (i.e., single family houses/multi-family houses/multi-story building), socio-economic class, source of waste (i.e., household/-commercial). Mass fractions of C, H, O, N, and S from ultimate analysis were based on the American Society for Testing Materials (ASTM) methods using an elemental analyzer. Waste sampling for composition analysis and proximate analysis were performed according to the 'Standard method for waste analysis (Appendix A)' that were associated with ASTM D5231 and ASTM D3173 respectively. Composition data, proximate analysis and elemental fraction results by composition are accepted for facility-level GHG management by the Korean government and also have been used in the national GHG emissions inventories submitted to UNFCCC.

2.2. CO_2 emissions estimate by direct CO_2 measurement

Total CO_2 emissions were calculated using directly measured CO_2 concentrations and associated flow rates. *FCO_2E* in a facility were calculated by multiplying the total emissions in the facility by the *FCF* value as follows:

$$FCO_2E_f(ton\ day^{-1}) = \left\{ \sum_{i=1}^{24} \frac{CO2i(\%)}{100} \times \frac{44(\mathrm{kg})}{22.4(\mathrm{m^3})} \times 10^{-3} \times Q_i(\mathrm{m^3\ h^{-1}}) \right\} \times FCF_f \quad (1)$$

where FCO_2E_f is CO_2 emissions from the fossil carbon combusted in a facility f (ton/day); CO_2 is the hourly average amount of carbon dioxide measured in the flue gas (volume%); Q is the simultaneous flow rate of the flue gas (m^3/h); FCF_f is the average weight fraction of fossil carbon in the total carbon in a facility f; and i is the measurement time.

2.3. CO_2 emissions estimate by O_2 measurement and waste characteristic data

CFR Title 40 appendix F Part 75 and Part 60 of the US *EPA* provide the procedure to determine CO_2 mass emissions from fossil fuel combustion using continuous O_2 concentration monitoring, a flow monitoring system, and fuel characteristic data. Hourly

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