Preferred Emission Techniques for Estimating Air Emissions from Industrial Boilers in Nigeria

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Abstract: The purpose of the preferred emission estimation techniques is to assist Nigerian manufacturing, industrial and service facilities to prepare emission inventories and report emissions of listed substances to the Federal Environmental Protection Agency (FEPA). This study describes the procedures and recommended approaches for estimating emissions resulting from combustion in boilers.

Key words: Emissions, boilers, preferred estimation methods, stack sampling, CEMS, fuel analysis

INTRODUCTION

In the past few years, Nigeria has witnessed rapid urban growth, increased economic and technological development and these have brought about increasing industrial development coupled with various forms of environmental pollution (Onipede and Bolaji, 2004). Since the production of wastes is an integral part of industrial activities, it is obvious therefore that industrial growth apparently lead to the increase in production of industrial waste.

Industries emit smokes and various gases of various magnitudes into the atmosphere everyday. In Nigeria, as well as many other developing nations of the world, industries are sited indiscriminately. Therefore, the various gaseous emissions are poured into the atmosphere near and around dwelling places (Ademoroti, 1996).

In this way, most industrial towns and cities in Nigeria are always polluted. Table 1 shows that in many cases, gaseous pollutants (SO_2, NO_2 and suspended particles) exceed the average value acceptable by the Federal Environmental Protection Agency (FEPA). There is a great dearth of data on concentration of air pollutants in the effluent gases emitted by individual process industries in Nigeria. The reason for the dearth is due largely to lack of proper emission estimation technique and proper air quality-monitoring equipment (Bolaji, 2006).

Knowing the quantities of certain substances discharged into the atmosphere is a necessary and

Table 1: Air quality in some selected Nigeria cities and FEPA quality standards

Pollutant	Lagos (mg m^{-3})	Ibadan (mg m^{-3})	Port harcourt (mg m^{-3})	FEPA (mg m^{-3})
Suspended particles	230	310	180	0.35
Sulphur (IV) Oxide, SO_2	60	20	30	26
Nitrogen (IV) Oxide, NO_2	12	10	13	0.075-0.113
Hydrogen Sulphide, H_2S	20	30	5	-

Ademoroti (1996) and FEPA (1991)

fundamental stage in any environmental protection policy to tackle today's problems such as acid rain, the degradation of air quality, global warming and climate change and the depletion of the ozone layer etc. (CITEPA, 2001).

This quantification, usually known as an emission inventory is built on a set of specific rules which may vary from one inventory to another. This state of affairs presents the enormous disadvantage that the data available are not comparable.

At the international level, an attempt at harmonization has been going on for some years between the various international bodies; the European Commission, the United Nations Economic Commission for Europe, the International Panel on Climate Change (IPCC), EUROSTAT and the International Energy Agency etc. This study is being pursued in parallel with the improvement of methodologies to estimate discharges from various types of source.

To take account of changes in specifications and of improvements in understanding of phenomena giving rise

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to atmospheric pollution, the results of inventories of emissions need to be regularly revised even retrospectively to maintain a consistent series.

MATERIALS AND METHODS

The overall objectives of this study are to give a detail description of available boilers that is generally used in various industries and to explain in details the various methods of estimations and then describe the three best methods of estimation and their mathematical analysis. This study is based on theory as the tables used for the analysis were from previously-published emissions data.

Boiler source category: The boiler source category comprises sources that combust fuels to produce hot water and/or steam. Utility boilers utilize steam to generate electricity. Industrial boilers often generate steam for electrical power as well as process steam. Space heaters use the hot water for heating commercial and residential building space (Table 2) fuels typically used in boilers include coal, oil and natural gas. In addition, Liquefied Petroleum Gas (LPG), process and waste gases, tallow and wood waste may be used (USEPA, 1995).

Coal-fired boilers: Coal is broadly classified into one of four types (anthracite, bituminous, sub-bituminous or lignite) based on differences in heating values and amounts of fixed carbon, volatile matter, ash, sulfur and moisture. There are four main types of coal boilers; they are pulverized coal, cyclone, spreader stoker and fluidized bed. Pulverized coal and cyclone boilers employ a technique known as suspension firing: they are sometimes categorized by this technique.

Oil-fired boilers: There is little variation between the design of oil-fired units and the design of coal-fired units: almost all are either tangential fired or wall fired. Fuel oils are broadly classified into two major types: distillate and residual. Distillate oils (fuel oil grade No. 1 and 2) are used mainly in domestic and small commercial applications in which easy fuel burning is required. Distillates are more volatile and less viscous than residual oils. Being more refined, they have negligible ash content and usually contain <0.3% weight sulfur. Residual oils (grade No. 4-6) are used mainly in utility, industrial and large commercial applications with sophisticated equipment. Residual No. 4 oil is sometimes classified as a distillate and No.6 is sometimes referred to as Bunker C. the heavier residual oils (grade No. 5 and 6) are more viscous and less volatile than distillate oils and therefore must be heated to facilitate handling and proper atomization.

Table. 2: Boiler type and size

Types of boilers	Size (MM Btu h^{-1})
Utility	>100
Industrial	10-250
Commercial	<10
Residential	<10

Because residual oils are produced from the crude oil residue after lighter fractions (gasoline, kerosene and distillate oils) have been removed, these oils contain significant quantities of ash, nitrogen and sulfur (USEPA, 1995). However, low sulfur residual oil is becoming more common place.

Natural gas-fired boilers: Natural gas is used for power generation, industrial process steam and production activities and domestic and commercial space heating. The primary component of natural gas is methane, although, small amounts of ethane, nitrogen, helium and carbon dioxide (CO_2) can also be present (USEPA, 1995).

Natural gas boilers are considered clean relative to coal or oil-fired boilers but improper operating conditions (such as poor air-fuel mixing) may still result in smoke (unburned carbon) in the exhaust, as well as Carbon monoxide (CO) and perhaps small amounts of unburned hydrocarbons. NO_x emissions are usually the major pollutants of concern in a well-operated natural gas boiler. NO_x emissions are primarily a function of the combustion chamber temperature. Several modifications can be made to natural gas boilers to reduce NO_x emissions. Staged combustion can reduce NO_x emissions by 5-20% (USEPA, 1995) low excess air levels and flue gas recirculation also often lower NO_x emissions.

Emission sources: Air pollutant emissions associated with boilers can occur at the following points/processes. However, it is important to note that emissions from combustion in boilers will generally be directed through an air stack unless there is a spill.

Material handling (Fugitive emissions): These are emissions that are not release through a vent or stack. It involves material handling which includes the receipt, movement and processing of fuel and materials to be used at the boiler facility. Coal, limestone, wood, bark and solid waste may all be included and their handling may result in particulate emissions. Organic compound emissions can also result from the transfer of liquid and gaseous fuels. This source category includes open vessels, volatilization of vapour from vats, storage bins and open stockpiles, as well as the processes used to transfer these materials, e.g., unloading, loading and conveying (NPI, 1999).

Process emissions: For boilers, emissions resulting from the process (combustion of fuel to generate hot water and steam) are typically vented to the atmosphere via a stack or vent. The major pollutants of concern from boilers stacks are Particulate Matter (PM), Sulfur oxides (SO_2 and Sulfur trioxide (SO_3)), Volatile Organic Compound (VOC) and Nitrogen oxides (NO_x). Carbon Monoxide (CO) and unburned combustibles, including numerous organic compounds (e.g., benzene) can also be emitted under certain boiler operating conditions. Most of the carbon in fossil fuels is emitted as CO_2 during combustion and may be inventoried due to its role as a greenhouse gas. Trace metals, such as arsenic and cadmium may also be emitted as a result of combustion of coal and oil. Additionally, organic pollutants such as formaldehyde and Polycyclic Organic Matter (POM) may be formed during combustion and emitted (USEPA, 1989).

Storage tanks: Storage tanks are used to store fuel oils at boiler facilities and should be inventoried as a source of organic compound emissions. Storage tanks at boilers facilities are usually one of two types: fixed roof or floating roof. Emissions at fixed-roof tanks are typically divided into two categories: working losses and breathing losses. Working losses refer to the combined loss from filling and emptying the tank. Filling losses occur when the organic compounds and VOCs contained in the saturated air are displaced from a fixed-roof vessel during loading. Emptying losses occur when air drawn into the tank becomes saturated and expands, exceeding the capacity of the vapor space. Breathing losses are the expulsion of vapor from a tank through vapor expansion caused by changes in temperature and pressure (USEPA, 2001).

Emissions at floating roof tanks are shown in two categories: standing losses and withdrawal losses. Withdrawal loss is the vaporization of liquid that clings to the tank wall and that is exposed to the atmosphere when a floating roof is lowered by withdrawing of liquid. Standing losses result from wind-induced mechanisms and occur at rims seals, deck fittings and deck seams.

Overview of available techniques for estimating emissions: Several techniques are available for calculating emissions from boilers. The method used is dependent upon available data, available resources and the degree of accuracy required in the estimate.

Continuous Emission Monitoring System (CEMS): A CEMS provide a continuous record of emissions over an extended and uninterrupted period of time, usually reporting pollutant concentration. Once a pollutant concentration is known, emission rates are obtained by multiplying the pollutant concentration by the volumetric gas or liquid flow rate of that pollutant. The accuracy of this method may be problematic at low pollutant concentrations (NPI, 2008).

Predictive Emission Monitoring (PEM): PEM is based on developing a correlation between pollutant emission rates and process parameters and could be considered a hybrid of continuous monitoring, emission factors and stack tests. A correlation test must first be performed to develop this relationship. Emissions at a later time can be estimated or predicted using process parameters to predict emissions rates based on the results of the initial source test. For example, emission from a boiler controlled by an SO_2 scrubber could be predicted based on the correlation of the scrubbing solution to the pH and flow rate.

Stack sampling: Stack sampling provides a snapshot of emissions during the period of the test. Samples are collected using probes inserted into the stack and pollutants are collected in or on various media and sent to a laboratory for analysis. Some stack test methods provide real time data where the gas sample is analyzed on-site by continuous analysis. Pollutant concentrations are obtained by dividing the amount of pollutant collected during the test by the volume of the sample. Emissions rates are then determined by multiplying the pollutants concentration by the volumetric stack flow rate.

Fuel analysis: Fuel analysis data can be used to predict emissions by applying mass conservation laws. For example, if the concentration of a pollutant or pollutant precursor in a fuel is known, emissions of that pollutant can be calculated by assuming that all of the pollutant is emitted. This approach is appropriate for Pollutants such as metals, SO_2 and CO_2. It should be noted, however that some of the pollutant may end up in physical or chemical (ash, unburned hydrocarbons, etc.) not emitted to the atmosphere.

Emission factors: An emission factor is a tool that is commonly used to estimate emissions to the environment. It relates the quantity of substances emitted from a source to some common activity associated with those emissions. Emission factors are usually expressed as the weight of a substance emitted divided by the unit weight, volume, distance or duration of the activity emitting the substance (NPI, 2003).

Mass balance: A mass balance identifies the quantity of substance going in and out of an entire facility, process

or piece of equipment. Emissions can be calculated as the difference between input and output of each listed substance. Accumulation or depletion of the substance within the equipment should be accounted for during calculation.

RESULTS AND DISCUSSION

Mathematical analysis of the preferred methods: The preferred method for estimating boiler emissions is to use some form of direct measurement which include stack sampling and CEMS and indirect measurement which include fuel analysis. The preferred method is determine by the time specificity of the emission estimate (i.e., an average acceptable or is the value on a given day needed) and the data quality; the quality of data will depend on a variety of factors including the numbers of data points generated, the representativeness of those data points and the proper operation and maintenance of the equipment being used to record the measurements.

Stack sampling: Stack sampling is the preferred emission estimation methodology for PM, PM_{10}, speciated organics and sulfuric acid mist. It is worthy to note that when using stack sampling, test should be conducted under normal operating conditions as these will reflect emissions accurately. Stack sampling test reports often provide emissions data in terms of kg h^{-1} or g m^{-3} (dry). Annual emissions for FEPA reporting can be calculated from this data.

The study shows how to calculate emissions in kg h^{-1} based on stack sampling data and how to convert this to an annual emissions figure. Calculations involved in determining particulate (PM) emissions are used as an example. Concentration of PM_{10} in g m^{-3} can be calculated using Eq. 1 while the hourly emission of PM_{10} in kg h^{-1} can be calculated using Eq. 2:

$$C_{PM} = \frac{C_f}{V_{m,STP}} \quad (1)$$

Where:
C_{PM} = Concentration of PM or gram loading (g m^{-3})
C_f = Filter catch (g)
V_{mSTP} = Metered volume of sample at STP (m^3)

Equation 2 can be used to convert the concentration of a substance calculated in Eq. 1 to an hourly emission of the substance:

$$E_{PM} = C_{PM} \times Qd \times 3.6 \times \left[\frac{273}{273+T}\right] \quad (2)$$

Where:
E_{PM} = Hourly emissions of PM or gram loading (g m^{-3})

C_{PM} = Concentration of PM or gram loading (g m^{-3})
Q_d = Stack gas volumetric flow rate (m^3 sec^{-1}) dry
3.6 = 3600 sec h^{-1} multiplied by 0.001 kg g^{-1}
T = Temperature of the gas sample (°C)

The information from some stack test may be shown in kilograms of particulate matter per cubic meter of exhaust gas (wet). Equation 3 is used to calculate the dry particulate emissions in kg h^{-1}:

$$E_{PM} = Q_w \times C_{PM} \times 3.6 \times \left(1 - \frac{moist_R}{100}\right) \times \left(\frac{273}{273+T}\right) \quad (3)$$

Where:
E_{PM} = Hourly emissions of PM in kg h^{-1}
Q_w = Wet cubic metres of exhaust gas sec^{-1} m^3 sec^{-1}
C_{PM} = Concentration of PM or gram loading (g m^{-3})
3.6 = 3600 sec h^{-1} multiplied by 0.001 kg g^{-1}
$Moist_R$ = Moisture content (%)
273 = 273 K (0°C)
T = Stack gas temperature (°C)

Total Suspended Particulates (TSP) are also referred to as total particulate matter (total PM). To determine PM_{10} from total PM emissions, a size analysis may need to be undertaken. The weight PM_{10} fraction can be multiplied by the total PM emission rate to produce PM_{10} emissions. Alternatively, assume that 100% of PM emissions are PM_{10}; i.e., assume that all particulate matter emitted to air has an equivalent aerodynamic diameter of 10 micrometres or less i.e., ≤10 µm. To calculate moisture content use Eq. 4:

$$moist_R = 100\% \times \frac{\dfrac{g_{moist}}{1000 \times V_{m,STP}}}{\dfrac{g_{moist}}{(1000 \times V_{m,STP})} + \rho_{STP}} \quad (4)$$

Where:
$Moist_R$ = Moisture content (%)
g_{moist} = Moisture collected (g)
$V_{m,STP}$ = Metered volume of sample at STP (m^3)
ρ_{STP} = Dry density of stack gas sample, kg m^{-3} at STP (if the density is not known a default value of 1.62 kg m^{-3} may be used. This assumes a dry gas composition of 50% air, 50% CO_2)

An example of test results is shown in Table 3. The Table 3 shows the results of three different sampling runs conducted during one test event.

The source parameters measured as part of the test run include gas velocity and moisture content which are used to determine exhaust gas flow rates in m^3 sec^{-1}. The

filter weight gain is determined gravimetrically and divided by the volume of gas sampled, as shown in Eq. 1 to determine the PM concentration in g m^{-3}.

CEMS: The use of site-specific CEMS data is the preferred method for estimating NO_x, CO, CO_2, SO_2 and Total Hydrocarbons (THC) emissions because it provides a detailed record of emissions over time. For annual (long term) emissions inventories, CEMS data should always be used. To monitor CO_2, SO_2, NO_x, CO and THC emissions using a CEMS, a facility uses a pollutant concentration monitor which measures concentration in parts per million by volume air (ppmvd). Flow rates are measured using a volumetric flow rate monitor. This method shows how to estimate emissions using CEMS data. Table 4 shows a CEMS output average for a boiler firing waste fuel oil.

Hourly emissions can be used based on concentration measurements as shown in Eq. 5:

$$E_I = \frac{(C \times MW \times Q \times 3600)}{\left[22.4 \times \left\{\frac{T+273}{273}\right\} \times 10^6\right]} \quad (5)$$

Where:
E_I = Emissions of pollutant i (kg h^{-1})
C = Pollutant concentration (ppm$_{v,d}$)
MW = Molecular weight of the pollutant (kg kg^{-1}-mole)
Q = Stack gas volumetric flow rate (m^3 sec^{-1})
3600 = Conversion factor (sec h^{-1})
22.4 = Volume occupied by one mole of gas at standard temperature and pressure (0°C and 101.3 kPa, m^3 kg^{-1}-mole)
T = Temperature of gas sample (°C)

Table. 3: Stack sample test results

Parameter	Symbol	Test 1	Test 2	Test 3
Total sampling time (sec)		7200.00	7200.00	7200.00
Moisture collected (g)	gmoist	395.600	372.6.00	341.100
Filter catch (g)	C_f	0.08510	0.0449.0	0.06250
Average sampling rate (m^3 sec^{-1})		1.67×10^{-4}	1.67×10^{-4}	1.67×10^{-4}
Standard metered volume (m^3)	$V_{m,STP}$	1.185.0	1.160.0	1.163.0
Volumetric flow rate (m^3 sec^{-1}) dry	Q_d	8.48.00	8.43.00	8.45.00
Concentration of particulate (g m^{-3})	C_{PM}	0.0718	0.0387	0.0537

Queensland Department of Environment and Heritage, 1998

Table 4: Example CEM output averaged for a boiler firing waste fuel oil

Time	O$_2$ (percentage by volume)	Concentration (C) ppm$_{vd}$				Gas flow rate (Q)	Combustion rate (A) (tons h^{-1})
		SO$_2$	NO$_x$	CO	VOC		
1	10.3	150.9	142.9	42.9	554.2	8.52	290
2	10.1	144.0	145.7	41.8	582.9	8.48	293
3	11.8	123.0	112.7	128.4	515.1	8.85	270

Queensland Department of Environment and Heritage, 1998, *ppmvd = parts per million volume dry

Actual annual emissions can be calculated by multiplying the emission rate in kg h^{-1} by the number of actual operating hours per year (OpHrs) as shown in Eq. 6 for each typical time period and summing the results:

$$E_{kpy,i} = \sum (Ei \times OpHrs) \quad (6)$$

Where:
$E_{kpy,i}$ = Annual emissions of pollutant i (kg year^{-1})
E_i = Emissions of pollutant i (kg h^{-1}) (Eq. 5)
OpHrs = Operating hours (h year^{-1})

Fuel analysis: Site-specific fuel analysis is the preferred emission estimation methodology for metals when air pollution control equipment (e.g., scrubber, ESP) are not installed. In cases where control equipment is installed, fuel analysis may still be preferred if accurate data are available on pollutant specific collection efficiencies and the amount of pollutant present in bottom ash and fly ash are known. Fuel analysis is also useful in determining SO_2 and CO_2 emissions. The presence of certain elements in fuels may be used to predict their presence in emission streams. This includes elements such as sulfur which may be converted into other compounds during the combustion process.

The basic equation used in fuel analysis emission calculations is the following:

$$E_{kpy,i} = Q_f \times \text{Pollutant concentration in}$$
$$\text{fuel} \times \left(\frac{MW_p}{EW_f}\right) \times OpHrs \quad (7)$$

Where:
$E_{kpy,i}$ = Emissions of pollutant i (kg year^{-1})
Q_f = Fuel use (kg h^{-1})
Mw_p = Molecular weight of pollutant emitte (kg kg^{-1}-mole)
Ew_f = Elemental weight of pollutant in fuel (kg kg^{-1}-mole)
OpHrs = Operating hours (h year^{-1})

For instance, SO_2 emissions from oil combustion can be calculated based on the concentration of sulfur in the oil. This approach assumes complete conversion of sulfur to SO_2. Therefore, for every kg of sulfur (EW = 32) burned, 2 kg of SO_2 (MW = 64) are emitted.

CONCLUSION

The use of emission factor as an emission estimation tool is not preferred in this study because the emission estimation obtained from using emission factors is based upon emission testing performed at similar facilities and may not accurately reflect emissions at a single source. Thus in most cases, emissions factors are averages of

available industry-wide data with varying degrees of quality and may not be representative for an individual facility within that industry. Although, PEM also provides an accurate estimate of emissions but since emissions are not directly measured on a continual basis, PEM should not be used if CEMS data is available.

Finally, mass balance is not considered a preferred estimation technique in this study, the reason is that inaccuracies associated with individual material tracking or other activities inherent in each material handling stage can result in large deviation of total facility emissions and because emissions from specific materials are typically below 2% of gross consumption, an error of only 5% in any one step of the operation can significantly skew emission estimation. Therefore, the use of stack sampling, CEMS and fuel analysis in this study is preferred over others because they can give the highest quality (most accurate) data for any giving point in time. They are easier to use than others. While, flow rate can be measured using short-term stack sampling measurements, CEMS provides accurate long-term data.

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