International Journal of Development and Sustainability
Online ISSN: 2186-8662 – www.isdsnet.com/ijds
Volume 1 Number 3 (2012): Pages: 688-700
ISDS Article ID: IJDS12082305

Special Issue: Development and Sustainability in Africa – Part 1

Assessing the emission factors of low-pour-fuel-oil and diesel in steam boilers

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Abstract

The purpose of this study is to examine the emissions effects resulting from the use of low pour fuel oil (LPFO) and diesel fuels in industrial steam boilers operation. The method of ultimate analysis of the products of combustion and emissions of pollutant analysis were used to estimate the annual rate of emissions of boilers. The results shows that the levels of uncontrolled boiler emissions on the environment can lead to increased greenhouse effects, global warming, and pollution and toxilogical impacts on human health. Only carbon monoxide emission was found to vary with the levels of oxygen generation in the products of combustion, while other substances were generally in relation to constituents and rates of consumption of fuel.

Keywords: Environmental impact, Emissions, Steam boilers, Fuels, Stoichiometric

Cite this paper as: Ohijeagbon, I.O., Jekayinfa, S.O. and Waheed, M.A. (2012), "Assessing the emission factors of low-pour-fuel-oil and diesel in steam boilers", *International Journal of Development and Sustainability,* Vol. 1 No. 3, pp. 688-700.

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1. Introduction

Ecological or environmental indicators are increasingly seen today as necessary tools for sustainable development. By the increasing lack of resources and the destruction of our environment, this is becoming more important year by year. Today, methods like Life Cycle Analysis or Life Cycle Assessment (LCA) has become popular since they indicate the sources of the environmental problems in the production processes. LCA is a framework or methodology for the quantitative environmental assessment of product systems.

The increasing demand of energy and fossil fuels and the considerable environmental impact connected with their exploitation are implications that policy makers cannot disregard would consequently result in energy-related problems to become more pronounced in the future (Tonon et al., 2006). These problems involve major aspects, such as the energetics concern about a more rational use of resources, the environmental impact due to the emission of pollutants, the use of non-renewable resources, etc. (Tonon et al., 2006).

More non-conventional energy sources such as solar energy, biomass and biogas energy, tidal energy, thermo-electric power, thermionic converter, wind energy, geothermal energy, etc., are increasingly being exploited more efficiently in technologically advanced countries (Rajput, 2006). Hence, steam boilers should be developed and operated on a more competitive scale with new technologies. As a matter of fact, most non-conventional energy sources mentioned above possess the advantages of not polluting the atmosphere and availability in large quantities (Rajput, 2006). New technologies effects on energy utilization have significant policy consequences (Popp, 2001). The improvement of more efficient technologies was one of the priorities of the Clinton government in its proposal for the 1997 Kyoto conference on the environment (Popp, 2001).

Jensen (1997) explained that Life cycle assessment (LCA) comprises the assessment of certain ecological factors of a product system throughout its life span. LCA is a fast developing group of tools and methods intended to assist in environmental control and sustainability. Yusoff (2008) and Weeraratne et al. (2008) performed a life cycle assessment (LCA) of crude palm oil production and palm oil mill respectively in Malaysia. Yusoff used both the LCA software SimaPro and the LCA method Eco-Indicator 99 to conduct his study. The assessment was carried out on three stages in the life cycle of crude palm oil. The first stage was the plantation, at which the machinery energy used and the fertilizer production were significant. Secondly the transportation stage that deals with diesel consumption. The third stage was the milling, from where boiler emissions were taken seriously, but where produced electricity can substitute conventional electricity production and function as a positive impact. Among the impact categories, respiratory inorganics and fossil fuel depletion were the most significant with global warming and acidification/eutrophication as outsider impacts.

There is a growing paradigm on a large-scale in several developed countries on the need to consciously ensure that industrial products and social infrastructures and services are developed for efficient energy utilisation and environmental sustainability. On the contrary, little effort is made in many developing countries such as Nigeria to determine the ecological impact and cost of using old conventional technologies such as steam boilers, refrigeration plants, etc. Hence, it is high time to study the implications of the continuous use of steam boilers especially as it relates to the use of different sources of fuel utilisation, economy, and ecological impacts.

The purpose of this study is to conduct the emissions analysis of industrial steam boilers using low pour fuel oil (LPFO) and diesel fuels in order to reveal the ecological impact analysis and to determine sustainable use of industrial steam boilers.

2. Method

2.1. Air-fuel ratio for complete combustion

During the combustion of fossil fuels, hydrocarbon molecules (C_xH_y) are combined with oxygen to produce carbon dioxide (CO_2) and water (H_2O) in an exothermic reaction (Process Heating, 2010). The stoichiometric quantity of oxidizer is just that amount that is necessary to completely burn a quantity of fuel. The stoichiometric air-fuel ratio is calculated by balancing carbon (C), hydrogen (H), and oxygen (O) atoms in the combustion reaction.

Typical composition of LPFO (No. 6 fuel oil) and diesel (No. 2 fuel oil) given in Table 1, were used to compute the amount of oxygen required, and other products released during the combustion. Hence, the ultimate values of the products of combustion for complete combustion were then determined.

Since air contained 23.3% O_2 by mass,

Table 1. Fuel specifications for LPFO and diesel

Specifications		No. 2 Oil (Diesel)	No. 6 Oil (LPFO)
%Carbon (C)		85.84	87.49
%Hydrogen (H)		12.46	9.92
Gross heating value (HHV)	(Btu/lb)	19,512.00	18,300.00
	(kJ/kg)	45,482.52	42,657.34
Net heating value (LHV)	(Btu/lb)	18,357.00	17,381.00
	(kJ/kg)	42,790.21	40,515.15
CO_2 *max*		15.60	16.50
%Sulfur (S)		1.60	1.40
%Moisture (M)		0	0
%O_2		0.100	1.190

Source: TSI Incorporated (2004)

$$\text{Air required}/kg \text{ of fuel} = \frac{O_2 \text{ required per kg of fuel}}{0.233} \quad (1)$$

Hence, the stoichiometric air-fuel ratio,

$$AFR_{st} = \frac{\text{Air required/kg of fuel}}{1} \text{ by mass (kg of air/kg of fuel)} \quad (2)$$

The actual air-fuel ratio (AAF) was determined by (Process Heating, 2010),

$$AAF = (1 + EA) \times AFR_{st} \quad (3)$$

where, EA = excess air

Recommended excess air of 20% was used (Bureau of Energy Efficiency, 2010a). Since air contained 76.7% of N_2 by mass,

$$\text{Therefore, } N_2 \text{ supplied} = 0.767 \times AAF\ kg/kg \text{ of fuel} \quad (4)$$

Similarly,

$$O_2 \text{ supplied} = 0.233 \times AAF\ kg/kg \text{ of fuel} \quad (5)$$

$$\text{The excess air} = O_2 \text{ supplied} - O_2 \text{ required } kg/kg \text{ of fuel} \quad (6)$$

That is,

$$O_2 \text{ contained in the products of combustion} = \text{The excess air } kg/kg \text{ of fuel} \quad (7)$$

The ultimate analysis values of the products of combustion for complete combustion of LPFO and diesel were determined by Ohijeagbon (2012) and presented in Table 2.

Table 2. Ultimate analysis of the products of combustion for complete combustion of LPFO and diesel

Product	LPFO		Diesel	
	Wet (%)	Dry (%)	Wet (%)	Dry (%)
CO_2	18.740	19.780	17.4764	18.6368
H_2O	5.220	-	6.2265	__
SO_2	0.164	0.173	0.1777	0.1895
O_2	3.660	3.860	3.7152	3.9618
N_2	72.220	76.190	72.404	77.2119
	100.00	100.00	100.00	100.00

Source: Ohijeagbon (2012)

2.2. Carbon monoxide (CO) determination in combustion products

The excess air (*EA*) may be related with the measured or known quantities of oxygen (O_2) and carbon monoxide (*CO*) in the exhaust gas analysis by the following expressions (TSI Incorporated, 2004; Bureau of Energy Efficiency, 2010a; UNEP, 2010; Bureau of Energy Efficiency, 2010b):

$$\%EA = \frac{(\%O_2)_p}{21-(\%O_2)_p} \times 100 \qquad (8)$$

$$\%EA = \frac{(\%O_2)_p - \frac{(\%CO)_p}{2}}{21-\left((\%O_2)_p - \frac{(\%CO)_p}{2}\right)} \times 100 \qquad (9)$$

where,

$\%EA$ = percentage excess air

$(\%O_2)_p$ = percentage oxygen from proximate (volumetric) analysis

$(\%CO)_p$ = percentage carbon monoxide from proximate (volumetric) analysis

Equation (9) can be re-arranged and expressed in terms of percentage carbon monoxide as follows:

$$(\%CO)_p = \frac{2\times(\%O_2)_p(1+EA) - 2\times 21\times EA}{(1+EA)} \qquad (10)$$

2.3. Ecological impact analysis

The presence of certain elements in fuels was employed to estimate their existence in emission streams. One of such elements is sulphur which may be changed into other forms during combustion. The fundamental equation used in fuel analysis emission computations is given as follows (National Pollutant Inventory, 2003);

$$E_{kpy,i} = E_i \times Op_{Hrs} \tag{11}$$

$$E_i = Q_f \times \frac{\text{pollutant concentration in fuel}}{100} \times \frac{MW_p}{EW_f} \tag{12}$$

where:

$E_{kpy,i}$ = annual emissions of pollutant *i, kg/yr*

E_i = Emissions of pollutant *i, kg/hr*

Q_f = fuel use, *kg/hr*

Op_{Hrs} = operating hours, *hr/yr*

MW_p = molecular weight of pollutant emitted, *kg/kg-mole*

EW_f = elemental weight of pollutant in fuel, *kg/kg-mole*

i = concentration of pollutant in fuel expressed as weight percent, %

The impact assessment of the boilers operation was carried out by computing the emissions of pollutants from the exhaust gases. The hourly emissions of pollutant, E_i, weekly and annual emissions of pollutant, $E_{kpy,i}$ were determined by equations (11) and (12) for the LPFO and diesel operated boilers. The fuel use, Q_f in *kg/hr* was easily obtained by multiplying the firing rate of fuel in *litres/hr* by the relative density of the fuels, d_{fuel}.

3. Results and discussion

The fuel use, Q_f were obtained as 759.13, 560.30, 471.26 and 362.55 *kg/hr* (0.7991, 0.5895, 0.5480 and 0.4216 m^3/hr) for Boiler operations 1 to 4 respectively. The molecular weight of pollutant emitted, MW_p (*kg/kg-mole*), elemental weight of pollutant in fuel, EW_f (*kg/kg-mole*) and concentration of pollutant *i* in fuel expressed as weight percent are presented in Table 3.

The standard heating (calorific) values of fuels are given as follows (National Pollutant Inventory, 2003): Fuel oil no's 4, 5 and 6 - 41.8 GJ/m^3; Fuel oil no. 2 and distillate - 39 GJ/m^3; and Fuel gas - 37.2 MJ/m^3. Hence, the operating boiler capacities were determined as 33.40, 24.65, 21.37 and 16.44 *GJ/hr* for Boiler operations 1 to 4 respectively.

Table 3. Emissions of pollutant parameters for complete combustion of LPFO and diesel

Product	MW_p (*kg/kg-mole*)	EW_f (*kg/kg-mole*)	*i* (%)	
			LPFO	Diesel
CO_2	44	12	C = 87.49	C = 85.84
H_2O	18	1	H = 9.92	H = 12.46
SO_2	64	32	S = 1.40	S = 1.60

The maximum theoretical emissions of combustion components per hour were computed using equation (12) as follows;

For boiler operation 1 (LPFO), $E_{CO_2} = 2{,}435.26\,kg/hr$, $E_{H_2O} = 677.75\,kg/hr$, $E_{SO_2} = 21.26\,kg/hr$. From the ultimate analysis of the products in Table 2, it shows that the ratio of N_2: CO_2 = 72.22: 18.74. Hence, $E_{N_2} = 9{,}384.98\,kg/hr$

The *%CO* in the exhaust gases of LPFO and diesel combustion products were determined earlier as 0.336% and 0.486% respectively. Hence, E_{CO} was estimated as follows:

$$E_{CO} = \frac{0.336}{100} \times (E_{CO_2} + E_{H_2O} + E_{SO_2} + E_{N_2}) = 42.06 kg/hr$$

The emissions estimate and factors of boiler operation 1 is presented in Table 4.

Table 4. Estimated emissions from products of combustion for boiler operation 1

Product	Maximum Hourly Emissions E_i (*kg/hr*)	Ultimate Analysis (%)	Hourly Emissions (*kg/hr*) E_i x (Ultimate Analysis)	Emission Factor (*kg/ton* of fuel consumed)
CO_2	2,435.26	18.740	456.368	0.456
H_2O	677.75	5.220	35.379	0.035
SO_2	21.26	0.164	0.035	3.5E-5
N_2	9,384.98	72.220	6,777.833	6.778
CO	42.06	0.336	0.141	1.41E-4

For boiler operation 2 (LPFO); $E_{CO_2} = 1{,}797.42\,kg/hr$, $E_{H_2O} = 500.23\,kg/hr$, $E_{SO_2} = 15.69\,kg/hr$. From the ultimate analysis of the products in Table 2, it shows that the ratio of N_2: CO_2 = 72.22: 18.74. Hence,

$E_{N_2} = 6{,}926.88\, kg/hr$, $E_{CO} = 31.05 kg/hr$. The emissions estimate and factors of boiler operation 2 is presented in Table 5.

Table 5. Estimated emissions from products of combustion for boiler operation 2

Product	Maximum Hourly Emissions E_i (*kg/hr*)	Ultimate Analysis (%)	Hourly Emissions (*kg/hr*) E_i x (Ultimate Analysis)	Emission Factor (*kg/ton* of fuel consumed)
CO_2	1,797.42	18.740	336.837	0.337
H_2O	500.23	5.220	26.112	0.026
SO_2	15.69	0.164	0.026	2.6E-5
N_2	6,926.88	72.220	5,002.593	5.003
CO	31.05	0.336	0.104	1.0E-4

For boiler operation 3 (diesel); $E_{CO_2} = 1{,}483.28\, kg/hr$, $E_{H_2O} = 528.47\, kg/hr$, $E_{SO_2} = 15.09\, kg/hr$. From the ultimate analysis of the products in Table 2, it shows that the ratio of N_2: CO_2 = 72.40: 17.48. Hence, $E_{N_2} = 6{,}143.56\, kg/hr$, $E_{CO} = 39.71 kg/hr$. The emissions estimate and factors of boiler operation 3 is presented in Table 6.

Table 6. Estimated emissions from products of combustion for boiler operation 3

Product	Maximum Hourly Emissions E_i (*kg/hr*)	Ultimate Analysis (%)	Hourly Emissions (*kg/hr*) E_i x (Ultimate Analysis)	Emission Factor (*kg/ton* of fuel consumed)
CO_2	1,483.28	17.4764	259.224	0.259
H_2O	528.47	6.2265	32.905	0.033
SO_2	15.09	0.1777	0.027	2.7E-5
N_2	6,143.56	72.404	4,448.183	4.448
CO	39.71	0.486	0.193	1.9E-4

For boiler operation 4 (diesel); $E_{CO_2} = 1{,}141.17\, kg/hr$, $E_{H_2O} = 406.56\, kg/hr$, $E_{SO_2} = 11.61\, kg/hr$. From the ultimate analysis of the products in Table 2, it shows that the ratio of N_2: CO_2 = 72.40: 17.48. Hence, $E_{N_2} = 4{,}726.59\, kg/hr$, $E_{CO} = 30.55 kg/hr$. The emissions estimate and factors of boiler operation 4 are presented in Table 7.

Table 7. Estimated emissions from products of combustion for boiler operation 4

Product	Maximum Hourly Emissions E_i (*kg/hr*)	Ultimate Analysis (%)	Hourly Emissions (*kg/hr*) E_i x (Ultimate Analysis)	Emission Factor (*kg/ton* of fuel consumed)
CO_2	1,141.17	17.4764	199.435	0.199
H_2O	406.56	6.2265	25.314	0.025
SO_2	11.61	0.1777	0.021	2.1E-5
N_2	4,726.59	72.404	3,422.240	3.422
CO	30.55	0.486	0.148	1.5E-4

Figures 1 to 5 show the emission factors (*kg/ton* of fuel consumed) of boiler capacities of 33.40, 24.65, 21.37 and 16.44 *GJ/hr* which used LPFO and diesel for combustion. The Figures 1 to 4 shows that the emission factors for carbon dioxide and nitrogen were directly proportional to the amount of fuel consumption as a result of the stoichiometric air requirement for combustion of fuel. Boiler operation 1 operating on LPFO at a capacity of 33.40 *GJ/hr* had the highest emission factor of 0.456 and 6.778 for carbon dioxide and nitrogen respectively, while boiler operation 4 operating on diesel at a capacity of 16.44 *GJ/hr* had the lowest emission factor of 0.199 and 3.422 for carbon dioxide and nitrogen respectively.

The emission factor for water vapour was found to be higher in boiler operation 3 operating on diesel at a capacity of 21.37 *GJ/hr* compared with that of boiler operation 2 operating on LPFO at a capacity of 24.65 *GJ/hr* (Figure 2), despite the fact that boiler operation 2 was operating at a higher capacity compared with boiler operation 3. The higher emission factor for water vapour experienced in the diesel operated boiler operation 3 was attributed to higher water vapour content of diesel obtained in the ultimate analysis, given as 6,2265% while that of LPFO was determined as 5.220% as indicated in Tables 4 to 7 respectively. The sulphur content in LPFO and diesel and rate of fuel consumption were responsible for the level of emission factor of sulphur dioxide in the boilers (Table 1 and Figure 3).

Hourly emissions of Carbon monoxide, *CO* (Tables 4 to 7) would be higher than the present values of 0.141, 0.104, 0.193 and 0.148 *kg* in the products for boiler operations 1 to 4, if the air-fuel mixture departs from stoichiometric. The emission factor for carbon monoxide in the boilers as indicated in Figure 5 reveals that higher emission levels were obtained in the diesel operated boilers compared with those operated with

LPFO. Carbon monoxide emission was proportional to the levels of oxygen generation in the products of combustion.

This study further elucidates the fact that burning of fossil fuels in industrial facilities as steam boilers continues to increase environmental pollution. It is obvious that increased density of emissions from boiler operations would impact on the environment by increasing greenhouse effects and global warming through the release of such greenhouse gases as carbon dioxide, nitrous oxide, and water vapour. Carbon monoxide emissions would result in air pollution and toxilogical impacts on human health.

4. Conclusion

The annual emissions from the boilers were generally in direct proportion of the rate of fuel consumption in the boilers and the fuel constituents. Only carbon monoxide emissions were proportional to the levels of oxygen generation in the products of combustion. Hourly emissions of Carbon monoxide, *CO* would be higher than the present values of 0.141, 0.104, 0.193 and 0.148 *kg* in the products for boiler operations 1 to 4, if the air-fuel mixture departs from stoichiometric. Increased density of emissions from boiler operations would increase greenhouse effects and global warming. Carbon monoxide emissions would result in air pollution and toxilogical impacts on human health.

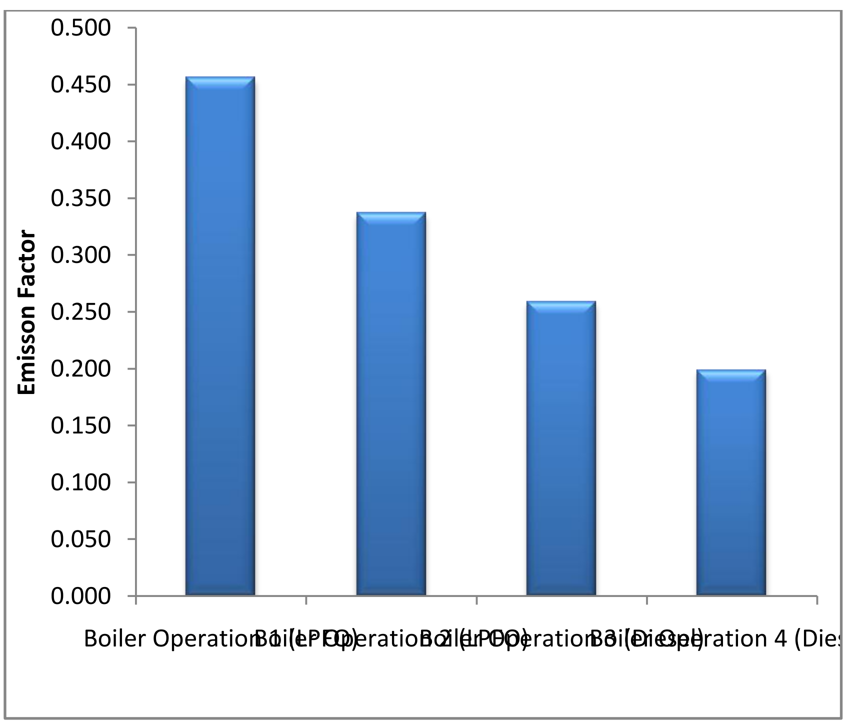

Figure 1. Emission factor of carbon dioxide in the boilers

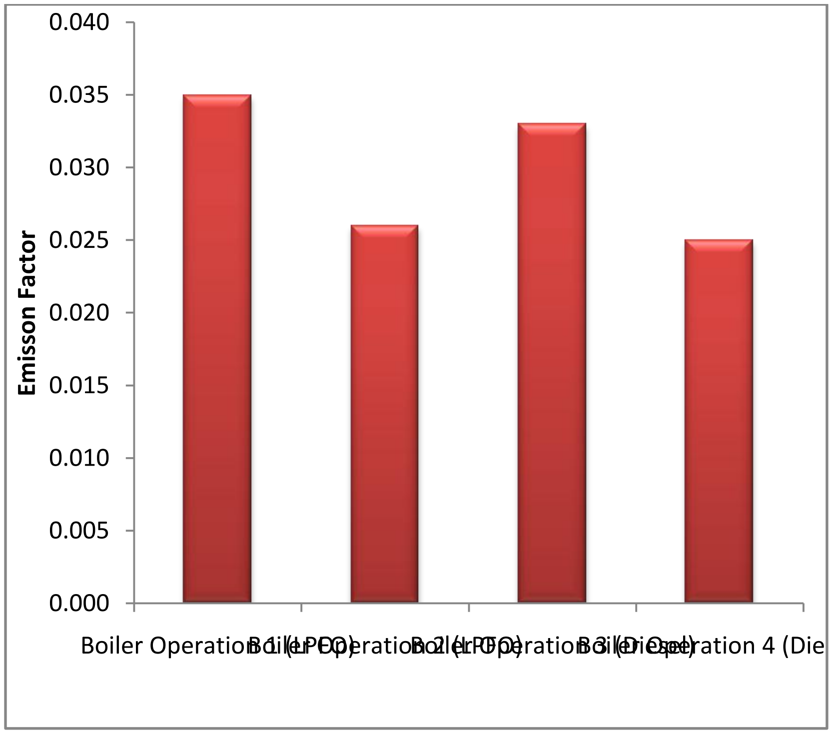

Figure 2. Emission factor of water vapour in the boilers

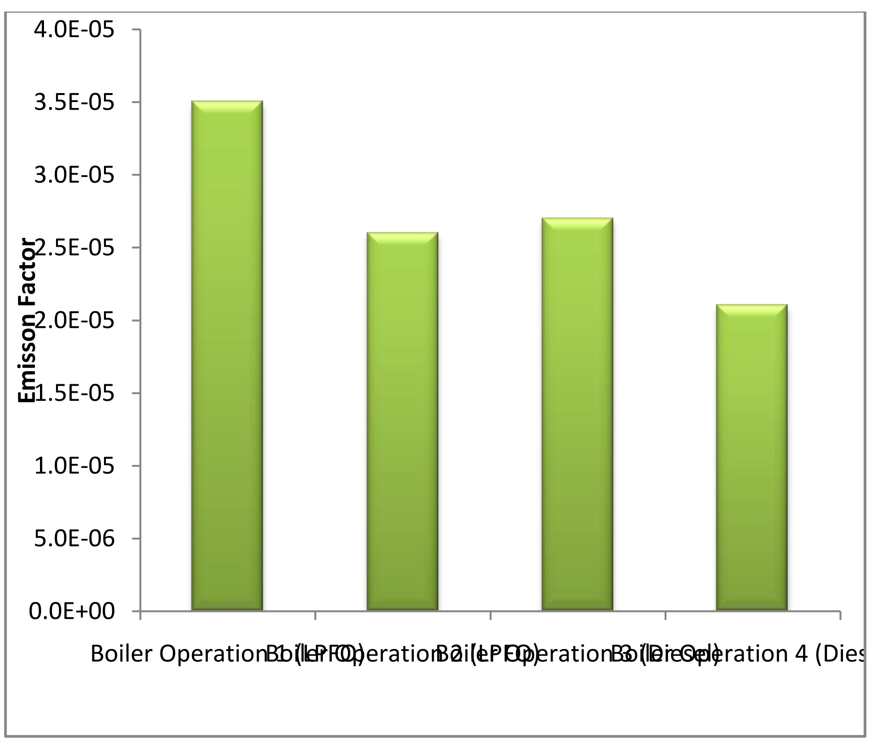

Figure 3. Emission factor of Sulphur dioxide in the boilers

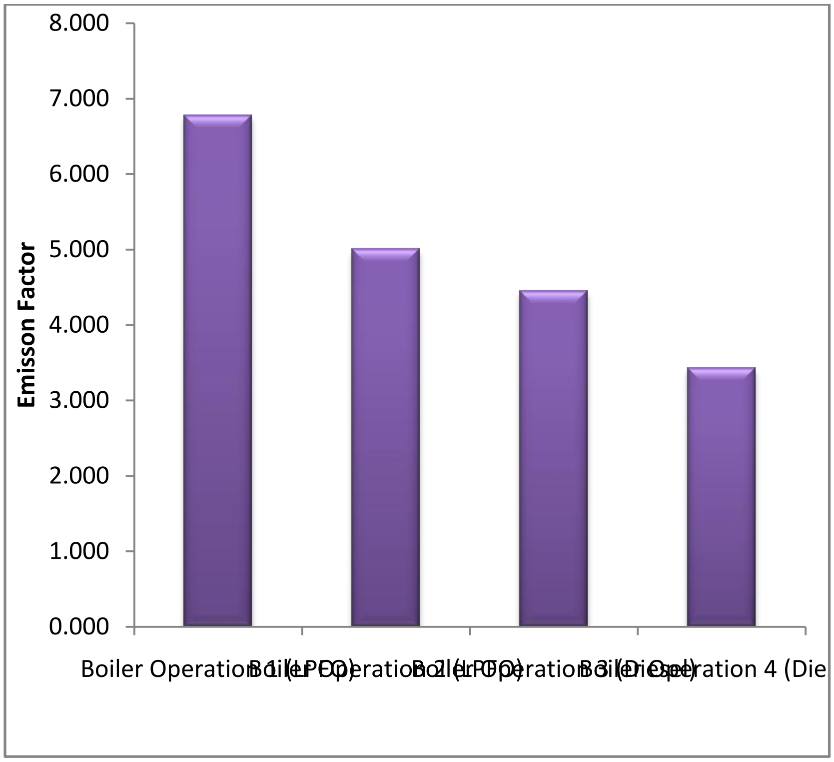

Figure 4. Emission factor of nitrogen in the boilers

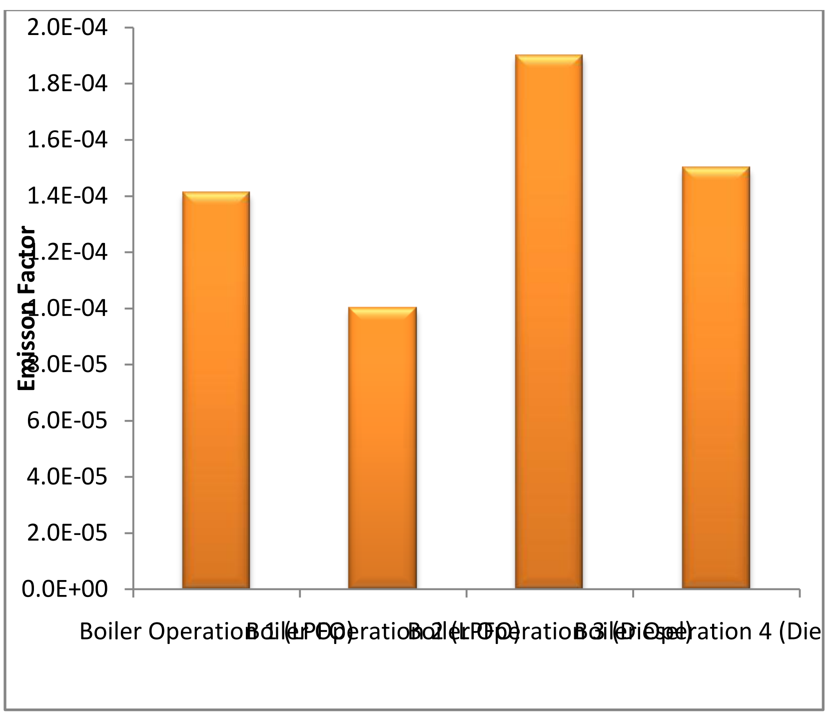

Figure 5. Emission factor of Carbon monoxide in the boilers

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