MASS AND ENERGY AUDIT IN A NIGERIAN IRON AND STEEL SMELTING FACTORY: AN OPERATIONAL AND EFFICIENCY STUDY.

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ABSTRACT

A mass and energy audit study of an iron and steel smelting factory in Nigeria was carried out. Information was obtained on material and energy usage in different sections of the factory with the aid of questionnaires, while suspended particulate concentrations were determined at different sections of production using Negretti 1000 air sampler for collecting total suspended particulate (TSP) samples and a Gent PM_{10} air sampler for particle size fractioned particulates samples. The study was carried out for a period of one year in four major sections of the industry: two electric-arc furnaces (EAF-1 and EAF-2), continuous casting (CC), and rolling mill (RM).

Annual average energy efficiency of 52% was estimated at EAF-1 while that of EAF-2 continuous casting and rolling mill were 59%, 63% and 69% respectively. Also, annual average mass efficiencies of 91% (EAF-1), 89% (EAF-2), 91% (CC) and 97% (RM) were obtained. The annual average of the mass concentration values measured at EAF-1 & 2, CC and RM sampling sites were respectively 2306, 3335, 2534 and 646 g/m^3 for TSP and at EAF-1 & 2, CC and RM sampling sites were respectively 190, 153, 148 and 93 g/m^3 for $PM_{2.5}$ and at EAF-1 & 2, CC and RM sampling sites were respectively 2051, 4570, 3319 and 687 g/m^3 for PM_{10}.

The recorded higher annual average energy efficiency of 63% at continuous casting sections compared with either of the furnaces affirms energy conservation in the tundish (a closed system). High particulate mass loading was recorded at the two electric arc furnaces in comparison with the remaining sections. The high particulate loadings at the said two furnaces corroborate the high emission factors recorded at the furnaces.

Keywords: Steelmaking, Efficiency, Mass Balance, Energy Balance, Emission Factor

INTRODUCTION

There has been a remarkable growth in the establishment of cottage factories in Nigeria in the last two decades and about 70% of these factories are within Lagos state (Adejumo *et al.,* 1994). The state play host to a number of factories, one of these is the secondary iron and steel smelting factory. The high demand for iron rods and the availability of the raw materials (scrap metals) in the country are the main drivers of the growth of this factory. The activity of the smelting factory depends on a lot of scraps and enormous amount of energy. These activities have to be matched with proper planning for the control of environmental pollution problems that are usually associated with the development from such factories. This has been very lacking (Akeredolu, 1989; Ogunsola *et al.,* 1995 & Obiajunwa *et al.*, 2002).

Iron and steel smelting is an oxidation-reduction process in which iron scrap is the major raw materials. The iron scrap, at its varying degree of degradation, is first heated to effect the oxidation of some of its constituent elements such as iron, silicon, sulphides and other impurities. Additives such as the ferro alloys (Fe-Si, Fe-Mn), limestone ($CaCO_3$) and coke (if necessary) are added into the molten steel in the furnace through a charging door by shoveling. Some of the oxides or elements in complex forms, whose reduction is not favoured by the kinetics of the reaction, form complex compounds which go into the slag phase as shown below

$$2FeO_{(L)} + Si_{(S)} \rightleftharpoons 2Fe_{(L)} + SiO_{2\,(S)}$$

$$SiO_{2\,(S)} + CaO_{3\,(S)} \rightleftharpoons \underbrace{CaO.SiO_{2\,(S)}}_{\text{Slag}} + CO_{2\,(g)}$$

$$P_2O_5 + CaCO_{3\,(S)} \rightleftharpoons \underbrace{CaO.\,P_2O_{5\,(L)}}_{\text{Slag}} + CO_{2\,(g)}$$

In an exceptional case when the carbon content of the melt is very low, fine silica sand is usually added coupled with more limestone. This aids the reduction process by separating the slag produced from the molten steel so that the slag and the steel which are both in their molten forms occur in physically two distinct phases (Bradley, 1989). Refining, this often occurs in ladles or sometimes in the furnace is done by removing unwanted impurities, such as sulfur, from the melt (Little, 1992). During these processes, air pollutants are emitted such as FeO, Fe_2O_3, SiO_2, CaO, MgO, volatile organic compounds (VOCs), CO_2 and particulate matter (Swaney and Cignetti, 1990 & Marsosudiro, 1994).

Mass Balance (MB) analysis involves the quantification of material flow going in and out of a process, where the difference between inputs and outputs is assumed to be discharged to the environment as solid, liquid and gaseous wastes. It applies the law of conservation of mass to a facility, process or equipment. Essentially, if there is no accumulation, then all the materials that go into the system must come out. Emissions are determined from the difference in the input and output of a unit operation and it dependent on the source type considered (OECD/IEA/Eurostat, 2004). MB methods may or may not account for emission controls, depending on the system, process or operation to which the mass balance is applied. Anderson *et al.*, 1998 suggested that care should be taken to ensure that the effect of pollution-control equipment is taken into account when performing mass balance calculations.

Energy balance may be relatively simple or complex, it depends on how many kinds of energy sources are used in how many different ways and how much statistical data are available on the various energy transactions (supply, transformation or use of a source), how much is needed in a particular period of time (Thomson *et al.*, 2000). This is used to establish potential losses in the plant. The recorded figures of energy input in different forms provide a convenient information source on the norms of consumption or coefficients for use in material balances. The energy input is used to estimate the required form of energy for each production section, providing detailed insight into the energy.

Scrap iron and steel smelters emit an enormous amount of pollutants consisting of particulate matter and gases into the air. The Suspended Particulate Matters (SPM) generated vary from one production process to another due to difference in inputs and the type of technologies used at each production stage (USEPA, 1995 & Baker Environmental, 1992).

In this work, airborne particulates are sampled at each production section of an iron and steel smelting factory with the mass and energy budget taken into consideration with a view to estimating the operational efficiency.

In this factory the production processes could be divided into three major sections: the two Electrical arc furnaces (EAFs), continuous casting and the rolling mills. The two EAFs were three-graphite electrode arc furnaces, which had been in operation for 30 and 12 years respectively. The inside of the furnaces were covered with metal clad refractory bricks. Air is introduced into the EAF and electrically heated up to about 1600°C. In the continuous casting section, the molten steel in the ladle was poured into a tundish, from which the moulds for billets were filled, the moulds with the billets inside were cooled with water flowing at the rate of 100 litres per minute. The billets produced were conveyed to the electric oven linked up with rolling machine for producing the finished products of various rod sizes. The finished rolled rods were then cut into specified length as required by customers.

MATERIALS AND METHODS

A reconnaissance survey was carried out under the guidance of operation engineers; and four major production sections were identified in the factory. These are: two electric-arc furnaces (EAF-1 and EAF-2), continuous casting, and rolling mill. Questionnaires were served on the engineers in each of the production section to obtain the following information (resulting in the required data):

Material usage:

(i) for EAFs: tons of scrap (iron, steel and non-ferrous metals), additives (Fe-Mn, Fe-Si, Coke, MgO and limestone), molten steel produced, and slag generated,

(ii) for continuous casting: tons of molten steel input, billets produced, and slag generated,

(iii) for the rolling mill: tons of billets consumption as input, waste rods, milled scale and rolled rod product.

Energy usage:

(i) for EAFs: electricity through the national grid (kWh) and diesel oil (L),

(ii) for continuous casting: low pour fuel oil (LPFO) (L), Gas (kBar),

(iii) for rolling mill: Gas (kBar) and diesel oil (L).

Material balance audit was accomplished using all the total inputs, products, solids and gaseous wastes on monthly and yearly bases. The emission factor (EF) was computed for all the four main production sections using the total tonnage of input charge, molten steel produced and used, total billets produced and used, rolled rod produced, wasted rod, milled scale slag and total waste generated. Estimates of the inputs, the output products and the wastes generated are given as:

$$M_i \quad M_s \quad M_{Fe\ Mn} \quad M_{Fe\ Si} \quad M_{Lime} \quad M_{MgO} \quad M_{Coke} \qquad 1$$

where

M_i is the total weight of inputs, M_S is the total weight of scrap used in EAF 1 & 2, $M_{Fe\ Mn}$ is the total weight of Fe-Mn flux $M_{Fe\ Si}$ is the total weight of Fe-Si flux used, M_{Lime} is the total weight of limestone used, M_{MgO} is the total weight of MgO used as flux and M_{Coke} is the total weight of the coke used, and

$$M_O \quad M_P \quad M_S \quad M_{WR} \quad M_M \quad M_E \qquad 2$$

where

M_O is the total weight of outputs, M_P is the total weight of the products in each section, M_S is the total weight of slag generated in each section, M_{WR} is the total weight of the waste rod (only in the rolling mill), M_M is the total weight of the mill scale (only in the rolling mill) and M_E is the expected total weight of particulate matter both in liquid and gaseous states.

Based on the material balance, the emission factors for emission into the ambient air were estimated from the material deficits in the four production processes using:

$$EF \quad \frac{M_i \quad (\quad M_p \quad M_s)}{M_p} \qquad 3$$

The questionnaire provided detailed information on sources of energy used in each production section such as: average energy used per charging, quantity of fuel used, output energy obtained from the energy consumed per unit product in each production process. The data were analyzed to obtain the energy efficiency using the input and output energies. Using the energy equivalent per litre of diesel oil, the total diesel oil consumed was converted to total energy used through diesel oil. Similar conversion was done to obtain the total energy consumed in preheating ladles where gas was used. The total input energy for EAFs was then obtained using:

$$E_i \quad E_N \quad E_{oil} \quad E_G \qquad 4$$

where,

E_N Is total energy supplied from national grid, E_{oil} is total energy generated through LPFO from generator, and E_G is the energy generated from the liquefied gas.

The total energy consumed at the EAFs was computed using average energy consumed from generating plant per heating and the number of heating carried out for each month. The difference was obtained to estimate the energy efficiency at EAF. Likewise, the energy inputs were computed for the continuous casting and the rolling mill. The main limitation was in the estimation of the energy losses to the environment which were due to conversion losses and standby losses (heat leakage through conduction, convention and radiation).

Also, suspended particulate matter (PM_{10} and $PM_{2.5}$ fraction) were sampled using a Gent PM10 air sampler on the membrane filter in the factory once a month for twelve months starting from April, 2003 to March, 2004, with sampling time varying from 4 to 24 hours depending on the level of activity at each sampling location. The mass concentration ($\mu g/m^3$) of each loaded filter was obtained using:

$$C \quad \frac{W_f \quad W_i}{V} \qquad 5$$

where, W_f is the weight of the filters after sampling, W_i is the weight of the filter before sampling and V is the volume of the air sampled which was obtained using the average flow rate and the sampling time.

RESULTS AND DISCUSSION

The results of mass balance and emission factors analyses in the four major production processes are shown in Figures 1(a) to (d) and Figure 2. For EAF-1 the monthly mass efficiency ranged from 90% to 92% with annual average efficiency of 91% while the average annual mass efficiency for EAF-2 was 89% with a monthly range of 88% to 90%. The average percentage of the gaseous emission per ton-molten steel produced was estimated to be 3.4% for EAF-1 and 3.6% for EAF-2. This is an indication that higher gaseous emission occurred at EAF-2. The mass efficiencies for EAF-1 and EAF-2 compare favourably with typical EAFs in United States and China, which have efficiencies of 94% and 91% respectively (IISI, 1999 and China's Agenda 21, 1994). At the continuous casting process, the

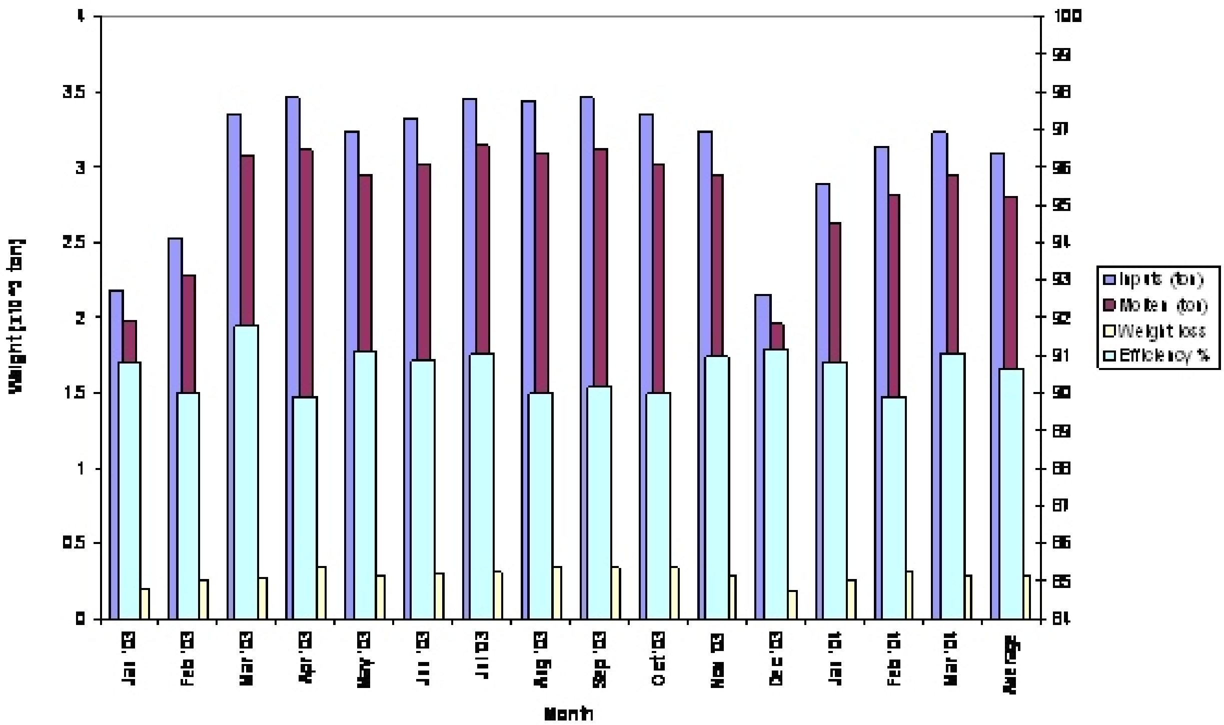

Fig. 1 (a): Monthly Mass Audit with the Mass Efficiency Trends in EAF-1

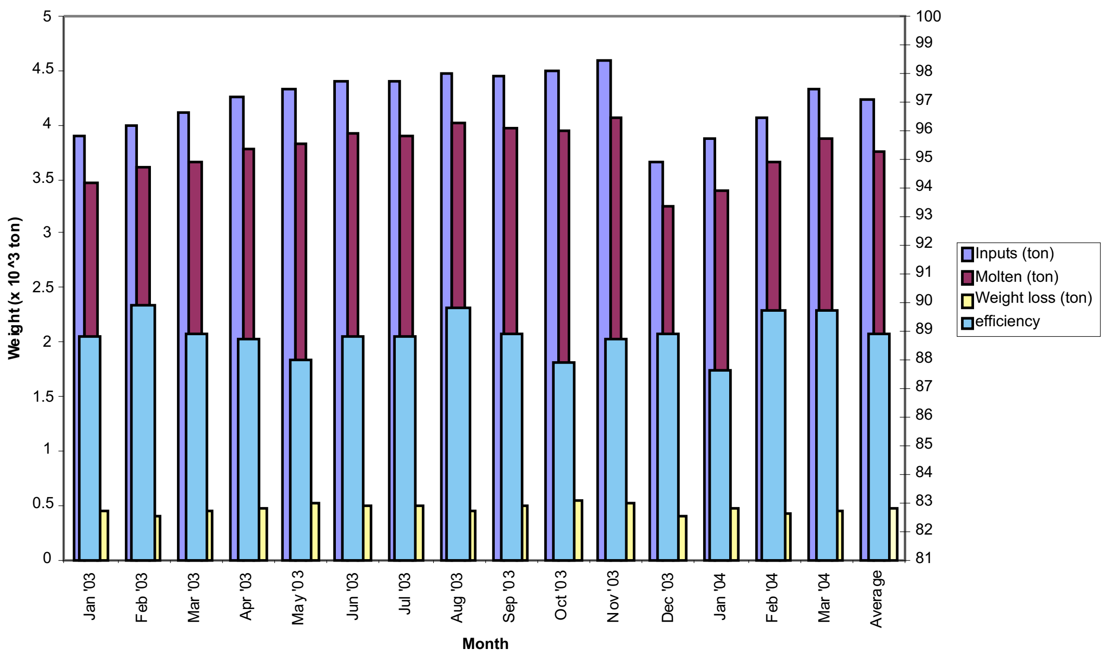

Fig. 1 (b): Monthly Mass Audit with the Mass Efficiency Trends in EAF-2

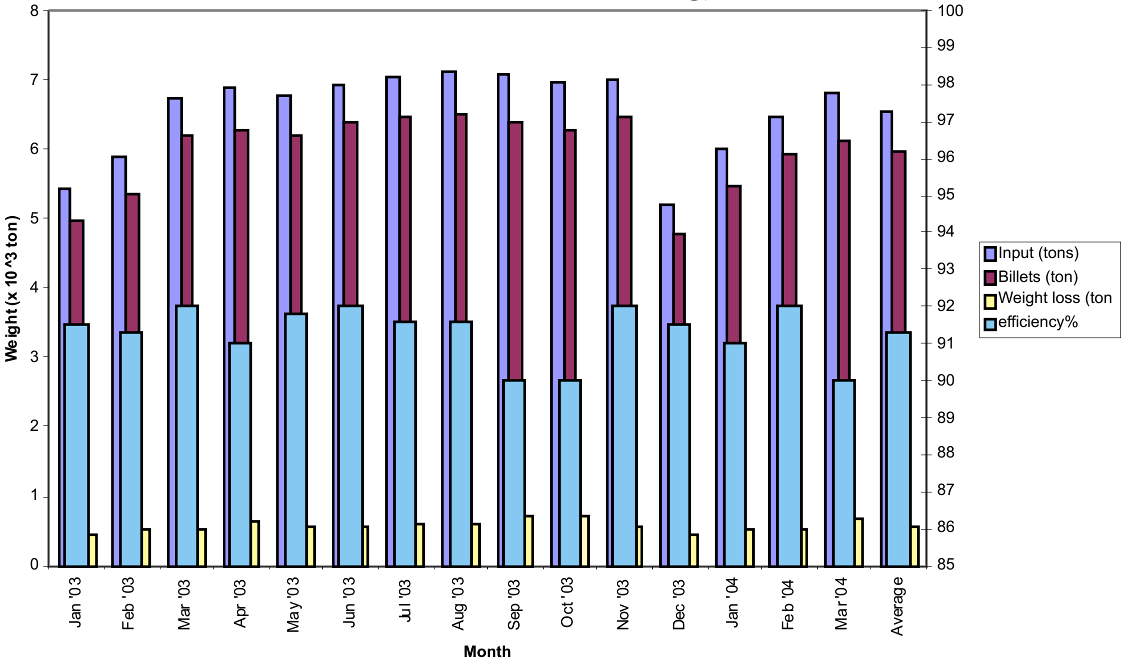

Fig. 1 c: Monthly Mass Audit with the Mass Efficiency Trends in Continuous Casting

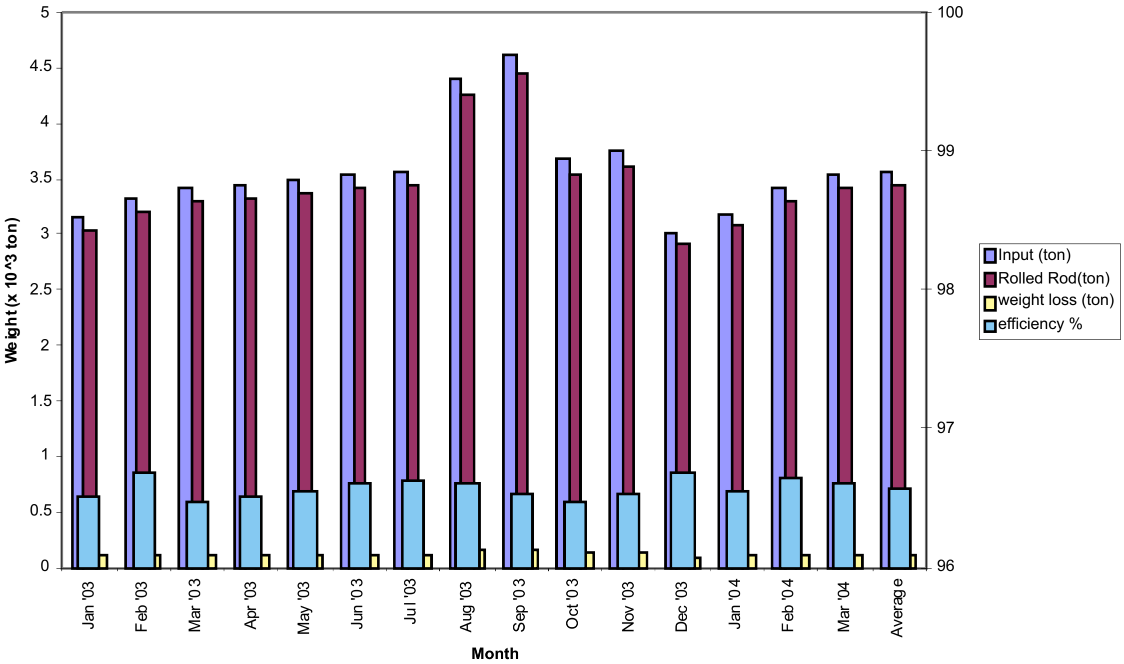

Fig. 1 d: Monthly Mass Audit with the Mass Efficiency Trends in Rolling Mill

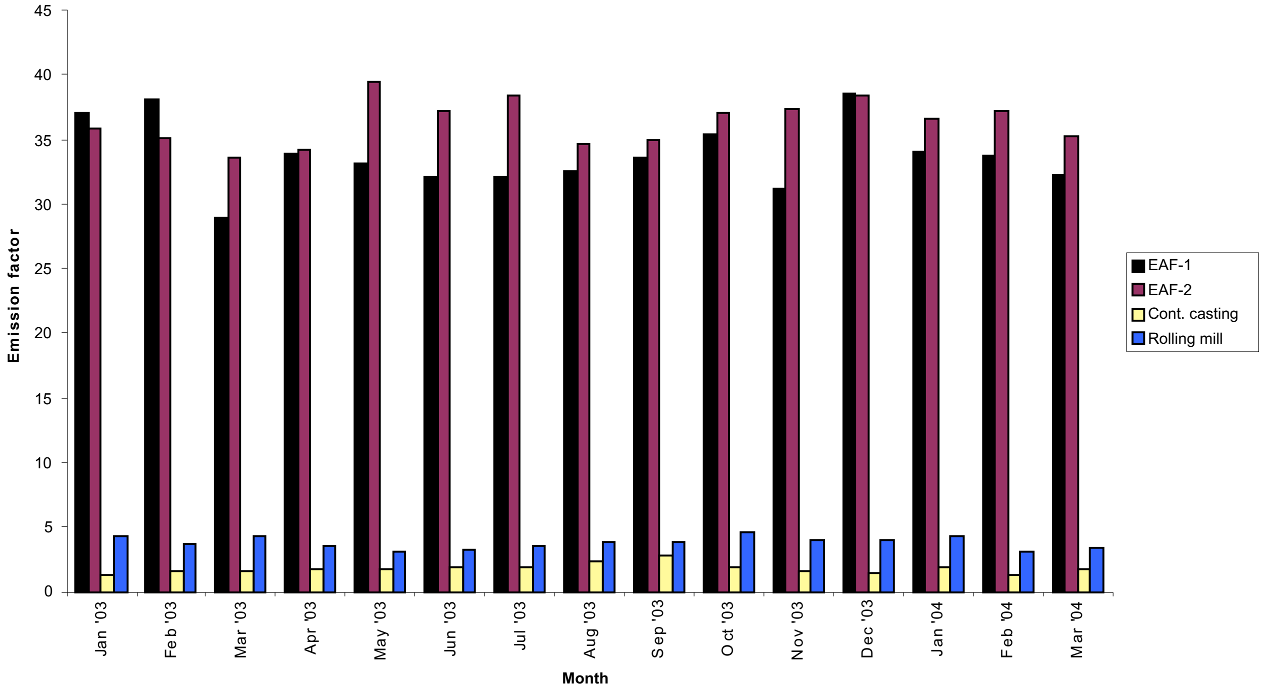

Fig. 2: Average Monthly Emission Factors (kg/ton-product) Trend in the Four Major Production Sections

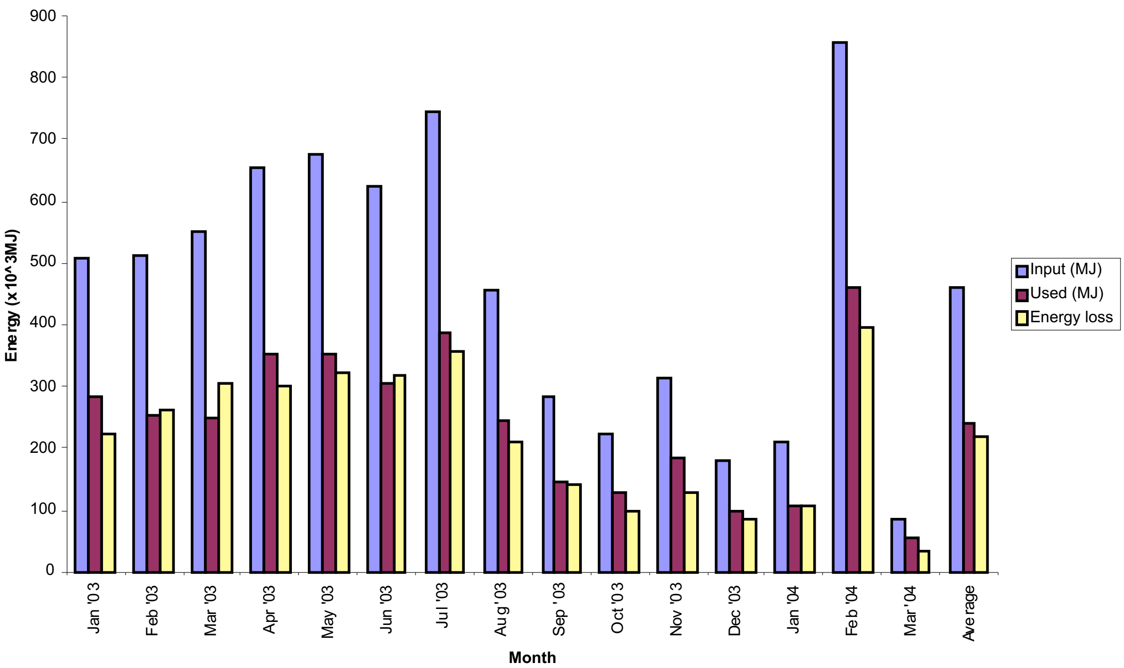

Fig. 3 (a): Monthly Average Energy Trend in EAF-1 Section

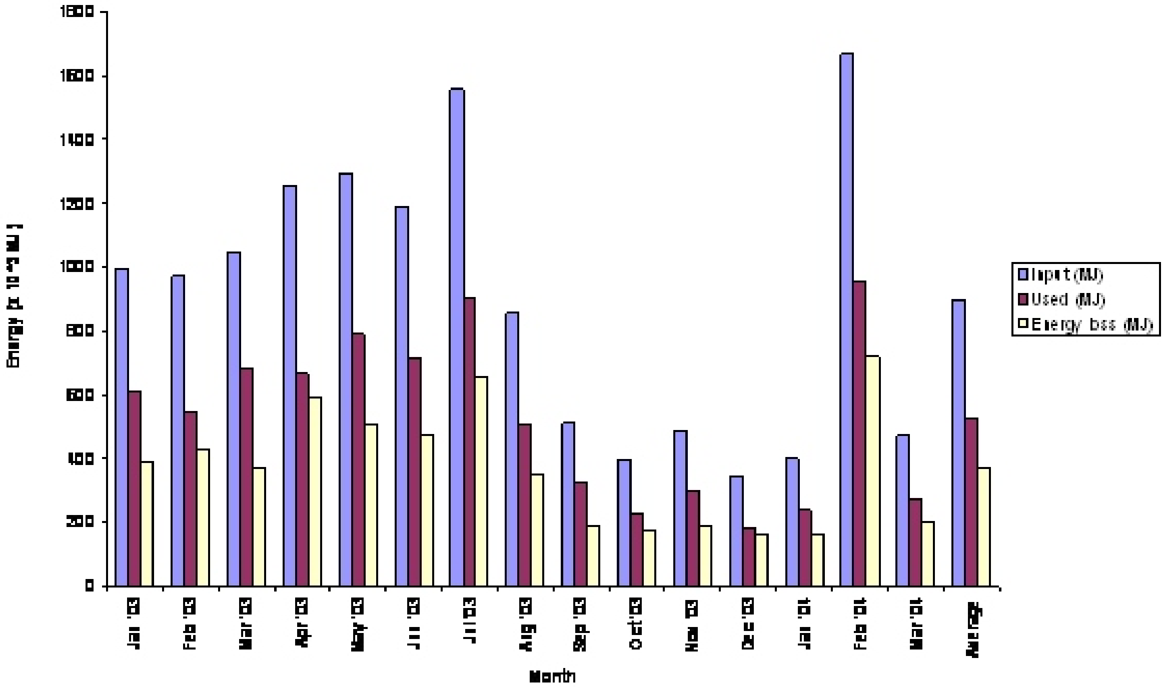

Fig 3 (b): Monthly Average Energy Trend in EAF-2 Section

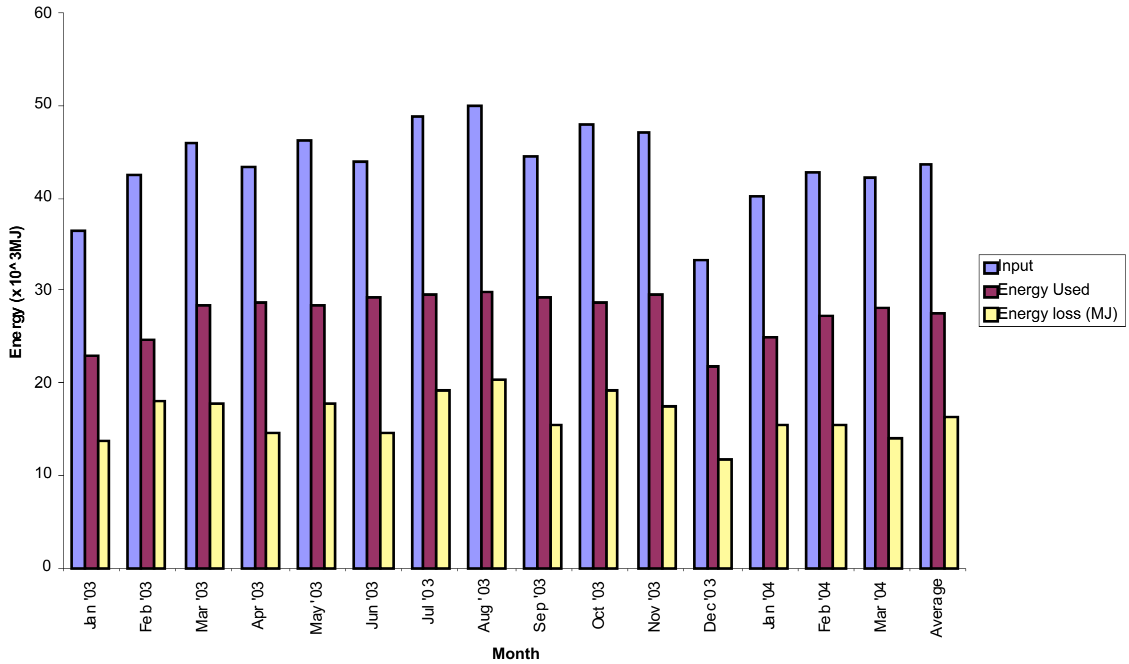

Fig.3 (c): Monthly Average Energy Trends in Continuous Casting Section

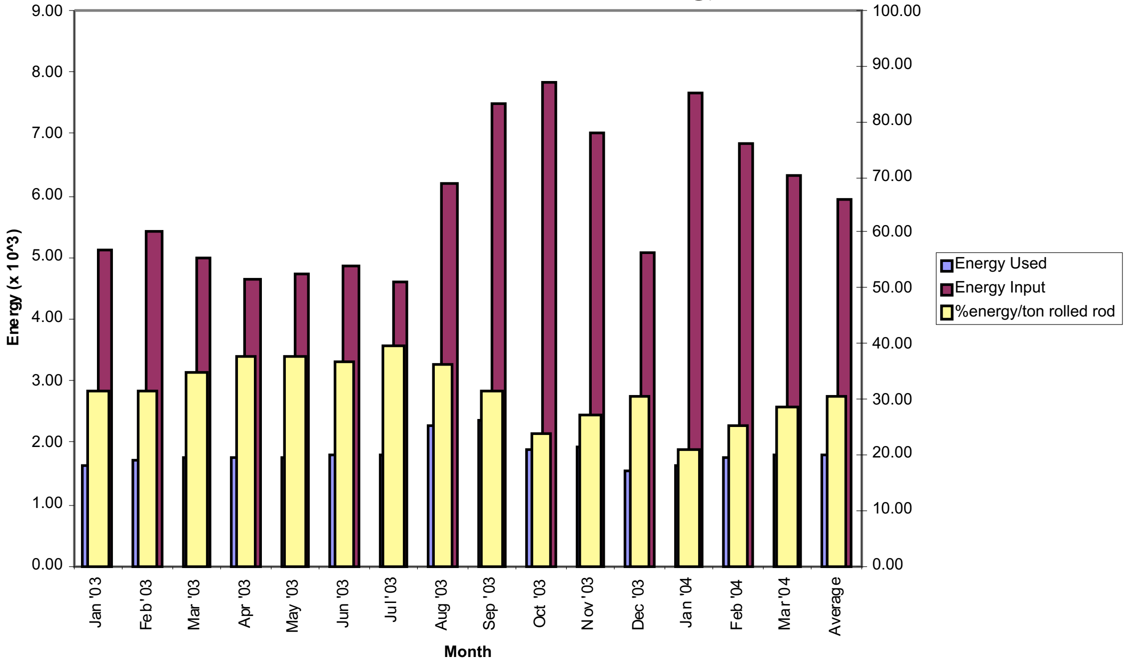

Fig. 3 d: Monthly Average Energy (MJ) Trends in Rolling Mill Section

annual average mass efficiency is 91% with monthly range of 90% to 92%. The average percentage of the gaseous emission per ton-billet is 0.18% which is relatively small when compared with emission from either furnace, which might be due to the tundish used in the continuous casting process being a closed system. At the rolling mill section, the annual average mass efficiency was 97%, ranging from 96% to 97%. This high efficiency is expected because of the recycling of the waste rod back into the system.

The monthly emission factor for EAF-1 ranges from 29 to 38 kg/ton-molten steel produced with a monthly average of 34 kg/ton, while that of EAF-2 ranges from 34 -39 kg/ton-molten steel produced with monthly average of 36.4 kg /ton. These values at EAFs were higher than the 25 kg/ton-molten steel of recycling iron and steel industries for an EAF in USA (US EPA, 1995a). The high values might be an indication of the emissions of gaseous pollutants into the air at EAF-1 and EAF-2 due to partial closure of the furnaces during charging of the scrap and opening of the furnace during pouring of the molten steel. At the continuous casting, the monthly emission factor ranges from 1.24 to 2.82 kg/ton-billet produced with an average of 1.8 kg/ton-billet. Also, at the rolling mill the monthly emission factor ranges from 3.15 to 4.51 kg/ton-rolled rod with average value of 3.8 kg/ton-rolled rod.

Figures 3(a) - (d) show the average monthly trend of total energy inputs, energy used to produce products and energy loss in the four production processes. When fully loaded with scraps, the average input energy was very high in the EAF-2 due to the higher capacity of the furnace (6.84 tons) when compared with EAF-1 (4.88 tons). But the annual average energy consumption per ton (23.6kWh/ton) of molten steel for EAF-2 was lower when compared with average energy consumption per ton molten steel (29.4kWh/ton) for EAF-1. This reflected in the energy efficiencies of the two furnaces in which the annual average energy efficiency for EAF-1 was 52% while that of EAF-2 was 59%. The reason might be as result of EAF-2 being a newer furnace and of improved technology, since both furnaces are of the same brand, though of different capacities. The efficiencies can be compared with a typical EAF in steel-making process in USA which has energy efficiency of 67% (Costa et al., 2001). IISI (1998) had studied the efficiency of a Basic Oxygen furnace (BOF) and found it to be about 72%. This is significantly higher than the EAFs considered here. The reason for this might be due to the energy lost as a result of high conventional loss in the EAF. The annual average energy consumption per ton of billet produced at continuous casting was 1.27kWh/ton billet with the annual average energy efficiency of 63% which is higher compared with either of the furnaces. The monthly energy efficiency of the continuous casting ranged from 58% to 67% from January, 2003 to March, 2004. The reason for higher energy efficiency when compared with EAFs might be due to energy conservation in the tundish (a closed system). From figure 3d for rolling mill, the monthly energy used ranged from

Table 1 (a): Range and Annual Average Concentration (μg/m³) for TSP in each Production Process of a Scrap Iron and Steel Smelter in Lagos, Nigeria.

Section	Range	Annual average
EAF-1	1150-4125	2306
EAF-2	1632-5432	3335
Continuous casting	250-4140	2534
Rolling mill	96-1261	646

Table 1(b): Range and Annual Average Mass Concentration (μg/m³) for $PM_{2.5}$ in each Production Process of a Scrap Iron and Steel Smelter in Lagos, Nigeria.

Section	Range	Annual average
EAF-1	36-475	190
EAF-2	49-462	153
Continuous casting	9-311	148
Rolling mill	34-316	93

Table 1(c): Range and Annual Average Mass Concentration (μg/m³) for PM_{10} in each Production Process of a Scrap Iron and Steel Smelter in Lagos, Nigeria.

Section	Range	Annual average
EAF-1	461-6098	2051
EAF-2	311-8844	4570
Continuous casting	312-7388	3319
Rolling mill	183-1110	687

21% to 39% when compared with the total energy input and with an annual average energy consumption of 505kWh/ton-rolled rod amounting to 31% of the total input energy. About 69% of the annual average energy used in different components of the rolling mill (preheating the oven, roller, etc) was not included in this efficiency estimated.

The airborne particulate load (g/m³) is presented in terms of the range and the mean of the mass concentration for SPM, $PM_{2.5}$ and PM_{10} particulate fraction in all the selected sites. The results presented in Tables 1(a) to (c) show high particulate mass loading at the two electric arc furnaces in comparison with the remaining sections. The high particulate loadings at the said two furnaces corroborate the high emission factors recorded at the furnaces.

CONCLUSIONS

The activity of the iron and steel smelting factory was monitored for a period of one year in relation to the mass and energy usage as well as airborne particulate emissions. The study identified four major production sections. Annual average energy efficiency of 59% was estimated for EAF-2 while 52% was estimated for EAF-1. The efficiencies were compared with a typical EAF in steelmaking process in USA which had energy efficiency of 67%. On energy efficiency, the conclusion is that, it is lower for both furnaces, when compared to what is obtainable in Untied State. In case of mass efficiency, the efficiencies at all the production processes were between 89% and 97%. The highest average gaseous emission/ton-molten steel produced at EAF-2 was 3.6% when compared with total molten steel produced, indicating that more particulate was emitted at the furnaces. High particulate mass loading has been recorded at the two electric arc furnaces in comparison with the remaining sections. The high particulate loadings at the said two furnaces corroborate the high emission factors recorded at the furnaces.

For energy and material efficiencies, it is recommended that proper documentation of total input in terms of sources of energy used, capacity of the machine used, material input like scrap used, fluxes at each stage of production must be carried out from time to time. Also, documents on problem day when machine have fault, nature of the fault, should be properly maintained and this assessment should be encouraged every five years. There is the need to improve on dust control strategy and devices in this industry and regular monitoring should be encouraged so as to have proper documentation of air quality in each production process.

REFERENCES

(1) Adejumo, J.A., Obioh, I.O, Ogunsola, O.J., Akeredolu, F.A, Olaniyi, H.B., Oluwole, A.F., Asubiojo, O.I., Akanle, O.A. and N.M. Spyrou, 1994. The Atmospheric Deposition of Major, Minor and Trace Elements within and Around Three Cement Factories, *J. Radioanal. and Nucl. Chem. Articles*, 179 (2): 195-204.

(2) Akeredolu F. 1989. Atmospheric Environment problems in Nigeria. An overview; *Atmospheric Environment*, 23 (4): 783-792.

(3) Anderson, S. H., Goodfellow, H. D, and E. J. Evenson, 1998. 'EAF optimization increases productivity while reducing pollution and production costs. In *Environmental Innovations in the Metals Industry for the 21st Century': Proceedings of a Specialty Conference Cosponsored by the Air & Waste Management Association*.

(4) Baker Environmental Inc. 1992. *Report on Steel Industry Waste Generation Disposal*.

(5) Bradley, E. 1989. High-Performance Castings. A Technical Guide. ASM International.

(6) China's Agenda-White Paper on China's Population, Environment, and Development in the 21st Century, 1994. China Environmental Science Press, Bejing.

(7) Costa, M. M., Schaeffer, R, and E. Worrell, 2001. Exergy accounting of energy and materials flows in steel production systems. *Energy*, 26: 363-384.

(8) International Iron and Steel Institute 1998. Energy use in steel industry. Brussels: Committee on Technology.

(9) Little, A. D. 1992. Alternative Melting Technologies in Scrap-Based Steelmaking. EPRI Center for Material Production.

(10) Marsosudiro, P.J. 1994. *Pollution Prevention in the Integrated Iron and Steel Industry and Its Potential Role in MACT Standards Development*.'94-TA28.02. U.S. Environmental Protection Agency.

(11) Obiajunwa, E. I., Johnson-Fatokun, F.O., Olaniyi, H.B., A.F. Oluwole, 2002. Determination of the elemental composition of aerosol samples in the working environment of a secondary lead smelting company in Nigeria using EDXRF technique. *Nuclear Instruments and Methods in Physics Research* B, 194: 65-68.

(12) OECD/IEA/Eurostat 2004. Energy Statistics Manual. Available at website: http://www.iea.org/dbtwwpd /textbase/nppdf/free/2004/statistics_manual.pdf.

(13) Ogunsola, O.J., Obioh, I. O, Akeredolu, F. A, Olaniyi, H. B, Asubiojo, O. I, Oluwole, A. F, and G. Baumbach, 1995. Continuous Monitoring of Air Quality in Large Tropical Metropolis- Lagos City. *Proc. of the 10th World Clean Air Congress.* Volume 2: Air Pollution, (P. Antilla, J. Kamari and M. Tolvanien (eds.), 28 May to 2 Jun. 1995), Espoo, Finland, The Finish Air Pollution Society Helsinki, ISBN 952-6473-X, Paper.

(14) Thomson, M. J., Evenson, E. J., Kempe, M. J., And H. D. Goodfellow, 2000. Control of Greenhouse Gas Emissions from Electri Arc Furnace *Steelmaking' Ironmaking and Steelmaking*, 27(4): 273-279.

(15) U.S. Environmental Protection Agency 1995a. *Profile of the Iron and Steel Industry*. EPA 310-R-95-005.

(16) U.S. Environmental Protection Agency 1995b. '*Draft Iron and Steel Regulatory Review, 40 CFR Part 420.' Effluent Limitations Guidelines and Standards for the Iron and Steel Manufacturing Point Source Category*.

(17) U.S EPA (1999). *Air Quality Criteria for Particulate Matter II*. United States Environmental Protection Agency, Research Triangle Park. NC., Report No. EPA 600/P-99/002b.

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