Journal of Materials and
Environmental Science
ISSN : 2028-2508
CODEN : JMESCN

J. Mater. Environ. Sci., 2021, Volume 12, Issue 02, Page 192-204

http://www.jmaterenvironsci.com

Thermal Analysis of a Conventional Cupola Furnace with Effects of Excess Air on the Flue Gases Specific Heat

Stephen A. Ajah[1,2], Donald Idorenyin [1], Uchenna C. Nwokenkwo[2], Uzoma S. Nwigwe[2], Benjamin O. Ezurike[2]

[1]Applied Renewable & Sustainable Energy Research Group, Department of Mechanical Engineering, University of Nigeria, Nsukka, Nigeria
[2]Department of Mechanical Engineering, Alex Ekwueme Federal University Ndufu-Alike, Ebonyi State, Nigeria
**Corresponding author, Email address: stephen.aroh@funai.edu.ng*
***Corresponding author, Email address: nwigweuzoma@gmail.com*

Received 29 Dec 2020,
Revised 16 Feb 2021,
Accepted 17 Feb 2021

Keywords
- ✓ *Cupola furnace,*
- ✓ Thermal analysis,
- ✓ Combustion,
- ✓ Excess air,
- ✓ Adiabatic temperature.

stephen.aroh@funai.edu.ng
Phone: +2348063194697;

Abstract

A thermal analysis was carried out on a 6.5 m tall and 0.65 m diameter conventional cupola furnace at the Nigeria Railway Corporation, Enugu. This study tries to solve metallurgical problem of the furnace wall due to gases dissociation from unbalance excess air and undefined adiabatic flame temperature used during the operation. A combustion and thermal analysis of the fuel (coke) used for its operation has been carried out and the adiabatic combustion temperature of the fuel has been determined to be 2,175.93K. The stoichiometric and actual air-fuel ratio of the furnace were found to be 10.97 and 12.08 respectively. The percentage of flue gases difference for wet and dry case were also investigated against the percentage excess air. The N_2 and CO_2 curves intercepted at the point of 0.44 (44%). The permissible maximum of 45% (with range of 30% - 45%) excess air is required for the real balanced combustion in the furnace to give the system specified output without the dissociation of the gases and as well as the system's metallurgical consideration.

1. Introduction

Metal production and reproduction is a major aspect of the manufacturing industry as metals are used extensively in manufacturing due to their strength and other properties. Production of these metals or alloys in the specific shapes and sizes require certain processes like casting, machining, welding and other mechanical work, with casting being the primary process. The cupola furnace is mostly used for heating metals with very high melting temperature and for heating for a long period of time due to its design. It is commonly used by metal manufacturing and recycling companies. Cupola furnace is one of the oldest methods of melting ferroalloys, cast iron scrap and steel scrap to produce cast iron [1]. Other melting methods like electric induction melting have led to the decline of the use of the cupola, but the cupola has remained dominant because of its many attractive characteristics [2]. Due to the wide use of cupola furnace, designers and researchers have found it necessary to work towards improving the design of cupola furnace for better production, lower cost, and lower emissions.

The cupola furnace is a type of furnace widely used in foundries for melting of high melting point metals to produce their cast forms. The name cupola furnace was derived from the resemblance of the furnace to the cupola commonly found on top of dwelling houses [3]. It uses fuels with high heating values like coke, charcoal, natural gas for heating. Apparently, the cupola furnace is exposed to temperature in excess of 1300K, and could be labelled a trimmed down version of blast furnace [4]. The cupola furnace is a cylindrical shaped steel furnace lined with refractories or water-cooled surfaces depending on the type of fuel used. Coke is the main source of energy for cupola melting. The name coke cupola resulted from the wide use of coke as the solid fuel in cupolas [5]. Gas cupolas heat faster and more efficiently and are used more in melting of steel, but has great setback in the cost and availability of gas supply, and requires high precaution during operation [6]. The solid fuel cupolas could use fuels like coal, coke or charcoal and different foundries choose either of them for various reasons. The preferential use of the fuels depends on the needed properties like the carbon content (chemical), calorific value (thermal), economic value, etc. Coke widely used as solid fuel in cupolas is a hard carbon material produced by destructive distillation of coal (mostly bituminous coal) in an airless oven at very high temperature (usually 1000 – 1100°C) [7].

1.1 Cupola Furnace Design

The pictorial view of the designed conventional cupola furnace is shown in Figure 1. The design and fuel used for cupola operation is subject to the material to be melted, as they melt different types of metals including steel. Cast iron mostly melted in cupolas due to its wide use in production has a specific heat of 0.42 to 0.73 kJ/kg.K, latent heat of fusion of 96.3 kJ/kg and a melting temperature of 1300K [8,9]. The metal composition needed for particular production/casting makes the selection of charge materials (fuel, metal and flux) very important in the cupola operation. Limestone charged with the metal scrap in cupolas undergoes thermal decomposition to form lime which acts as flux, ridding impurities off the metal to form slag. Limestone has a specific heat of 0.91 kJ/kgK, latent heat of fusion of 57.35 kJ/kg and a melting temperature of 1098K [8, 10]. There are three basic zones in the cupola furnace – the stack zone, the melt zone (combustion zone), and the well zone [11], while other researchers identify zones like the reducing and preheating zone in the stack and combustion zone [12]. The design of cupolas allows the charge materials to start heating up at the stack zone before entering the melt zone using heat from the combustion gases moving up the column, hence the term preheating zone [10].

Figure 1: Designed pictorial view of a conventional Cupola Furnace

1.2 Divided Blast Cupola

This is simply a design that splits the air supply to the cupola into two levels, one below the coke bed and the other at some distance above the coke level. The divided blast reduces coke consumption by 20 – 32%, increases melting rate of metal by 11 – 23%, increases metal tapping temperature by 40 – 50°C and increases carbon pickup by approximately 0.06% [13]. Air needed for combustion is normally fed through the tuyeres below the coke bed. This air fed speeds up the combustion of coke alone leaving the metal to melt slowly, but when air is divided and supplied at the metal level, it quickens the combustion and melting of metal, thereby reducing the consumption of coke.

1.3 Preheated Blast and Oxygen Enrichment

The preheated blast involves the use of hot air for combustion instead of the conventional cold air blown directly from the blower. This is achieved by attaching either a heater to the air-box which heats the air from the blower before getting into the furnace through the tuyere, or a heat recuperating system (heat exchanger) which collects heat from the cupola emitted gases and sends it back to the cupola with the blown air as hot air [11]. Oxygen enrichment involves the introduction of oxygen from an attached source to the combustion chamber. The efficiency of the cupola in some works has been increased by 2% and above with increased volume of air or oxygen enrichment [14, 15].

1.4 Air Pollution (Emission) Control

Cupolas have been associated with high emission due to the chemical reactions taking place in its combustion chamber. This has raised alarm in many countries and has caused foundries to move to the use of induction furnaces. The control of emissions in cupolas has led to improvements in the cupola design. The emission control devices include bag houses and the high energy wet scrubbers like the venturi scrubber system [16]. These devices trap harmful gases from the cupola and filter them before release to the atmosphere.

The wall of this particular furnace under study had been having metallurgical problem as a result of gases dissociation from unbalance excess air and undefined adiabatic flame temperature used during the operation. In an attempt to solving this problem, mortar/binder, thermal resistance refractory lining and airbox were introduced for better combustion and metallurgical boost of the furnace. Thermal analysis was then carried out for the determination of stoichiometric and actual air-fuel ratio with the effect of excess air on the gases specific heat (Cp) and the adiabatic flame temperature to control the metallurgical problem of the furnace.

2. Methodology

2.1 System Brief Description

A conventional cupola furnace at the Nigeria Railway Corporation was used for this study. A description of this furnace is discussed here as the first step in a thermodynamic analysis which must be the definition of the entity system that is being subjected to analysis. The drawn cupola furnace prototype for the purpose of this study is 6.5 m in height, has an internal diameter of 0.65 m with thickness of 12.5 mm. It consists mainly of the shell casing, the refractory lining, and the blower unit and uses coke as fuel for its operation, melts mostly cast-iron scraps used in the production of grey cast iron train parts like brake pads and other railway accessories. Schematic diagram of the furnace is shown in Figure 2 and dimensions of the furnace's zones are presented in the sectional views in Figure 3.

The cupola operates in batches as the charge materials are introduced and tapped periodically and each batch takes about an hour. The cupola operation uses about 45 kg of coke, 120 kg of limestone and 780 kg of metal per batch. The main body of the furnace was made from rolling a 0.01 m high carbon steel into a cylindrical shape with external diameter of 0.9 m. Joining methods like welding and the use of bolts and nuts were employed to fabricate the cupola shell [14].

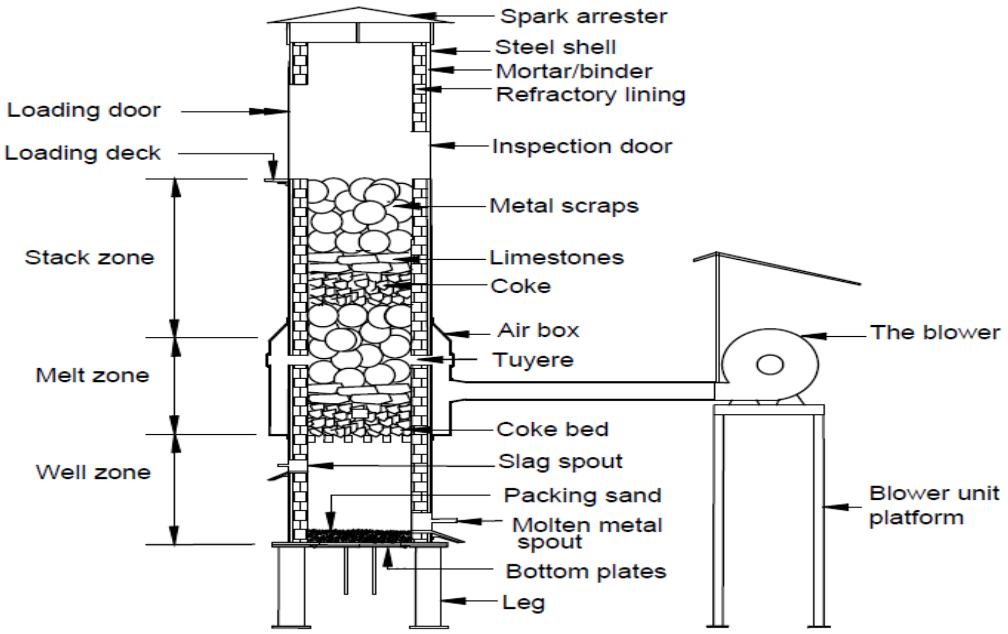

Figure 2: Schematic diagram of a conventional cupola furnace

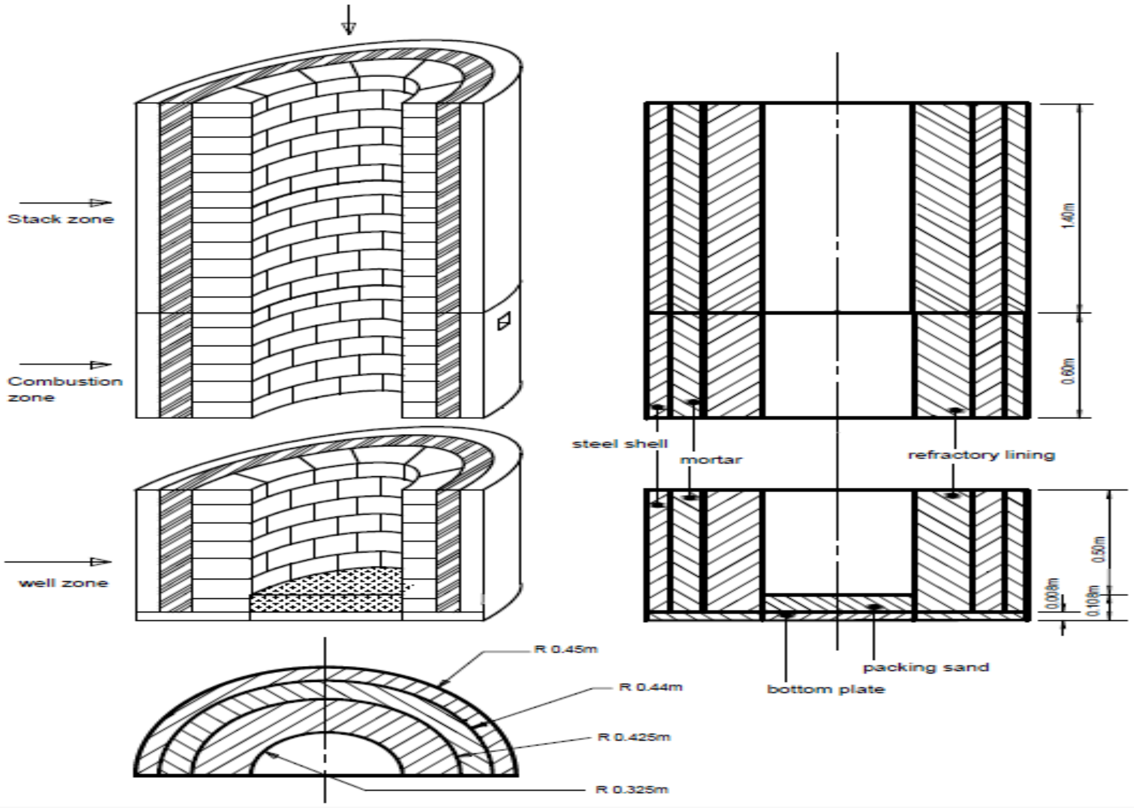

Figure 3: Sectional views of the zones of the furnace

2.2 *Combustion Stoichiometry*

The stoichiometric equation can be written as:

$$\frac{89}{12}C + \frac{3}{1}H + \frac{6}{16}O + \frac{0.7}{14}N + \frac{0.1}{32}S + 1.2Ash + a(0.21O_2 + 0.79N_2)$$
$$\rightarrow bCO_2 + \mathrm{d}H_2O + \mathrm{e}SO_2 + \left(\frac{0.7}{28} + 0.79a\right)N_2 + 1.2Ash \qquad (1)$$

Determining the number of moles, a, b, d, e by material balance;

Carbon balance : $\frac{89}{12} = b; \Rightarrow \ b = 7.42$

Hydrogen balance : $2d = 3; \Rightarrow \ d = 1.5$

Sulphur balance: $\frac{0.1}{32} = e = 0.003125$

Oxygen balance : $\frac{6}{16} + 0.42a = 2b + d + 2e$

$$0.375 + 0.42a = 14.84 + 1.5 + 0.0062$$

$$a = 38.03$$

The amount of air required to burn 1kg of fuel is;

$$a\frac{(0.21 * 32 + 0.79 * 28)}{100} = 0.2884a \qquad (2)$$

Therefore, the stoichiometric air/fuel ratio is;

$$AFR_{stoic} = 0.2884 * 38.03 = 10.97$$

The actual air/fuel ratio, R_{act} is given by:

$$AFR_{act} = \frac{\dot{m}_{air}}{\dot{m}_f} \qquad (3)$$

$\dot{m}_{air} =$ mass flow rate of air

$\dot{m}_f =$ mass flow rate of fuel

The mass flow rate of air is obtained from the volume flow rate of the blower which is rated 0.1275 m^3/s.

Mass flow rate, ṁ = volume flow rate ($\dot{\upsilon}$) * density or air (ρ) at 1 atm, $25^{\circ}C$;

$$\dot{m}\left(\frac{kg}{s}\right) = \dot{\upsilon}\left(\frac{m^3}{s}\right) * \rho\left(\frac{kg}{m^3}\right) \qquad (4)$$

$$\dot{m}_{air} = 0.1275 * 1.184 = 0.15096 \text{ kg/s}$$

The mass flow rate of the fuel will amount to 0.0125 kg/s based on 45 kg of coke charged every 1 hour in the cupola furnace. The actual air/fuel ratio becomes;

$$AFR_{act} = \frac{0.15096}{0.0125} = 12.08$$

The excess air (EA) in the combustion is given by :

$$EA = \frac{AFR_{act} - AFR_{stoic}}{AFR_{stoic}} \qquad (5)$$

$$\Rightarrow \frac{12.08-10.97}{10.97} = 0.10 \quad \Rightarrow (10\% \text{ excess air})$$

The combustion equation with excess air is written equation 6. The excess portion of the oxygen was released with other product gases as seen in equation 6.

$$\frac{89}{12}C + \frac{3}{1}H + \frac{6}{16}O + \frac{0.7}{14}N + \frac{0.1}{32}S + 1.2Ash + a(1+x)(0.21O_2 + 0.79N_2) \rightarrow bCO_2 + \text{d}H_2O + \text{e}SO_2 + \left(\frac{0.7}{28} + 0.79a(1+x)\right)N_2 + 0.21axO_2 + 1.2Ash \qquad (6)$$

The composition by weight (mass) and atomic mass of the coke components (reactants) and product gases are shown in Figure 4 and Figure 5 respectively.

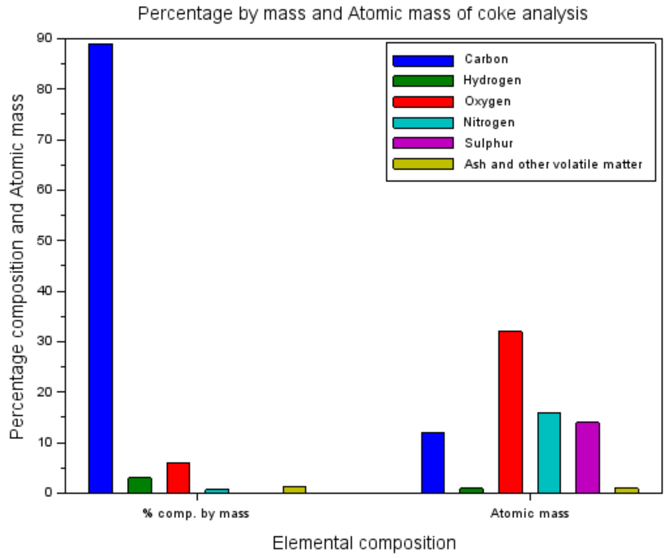

Figure 4: Composition by weight (mass) and atomic mass of the coke components

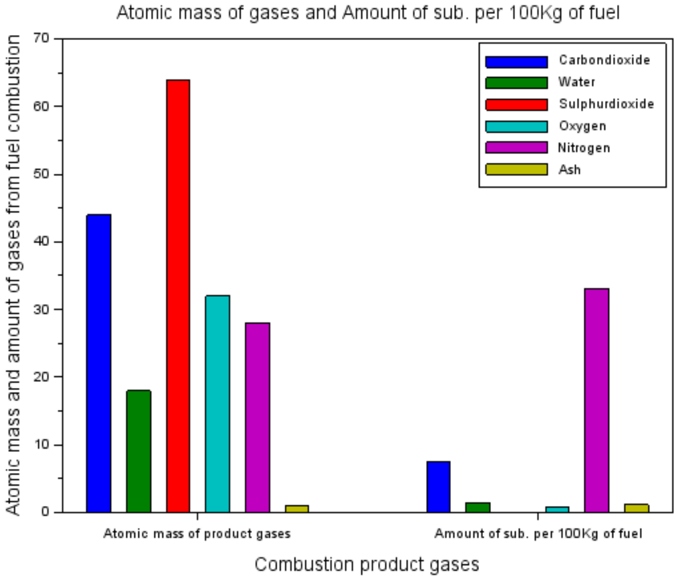

Figure 5: Combustion product gases atomic mass and amount per 100 Kg of coke

The analysis of flue gases of combustion by masses of constituents per unit mass of fuel are carried out on wet and dry bases and recorded in Figure 6.

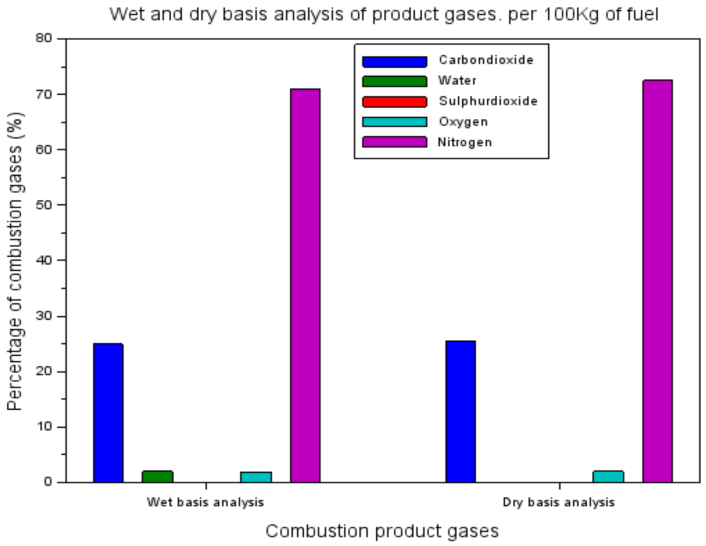

Figure 6: Wet and dry basis combustion gas analysis

2.3 *Determination of Adiabatic Flame Temperature*

The temperature that would be achieved by the products in the limit of adiabatic operation of a reactor or combustion system is called the adiabatic flame temperature or adiabatic combustion temperature. The adiabatic flame temperature, T_{ad} of the fuel in the combustion zone of the furnace is determined by employing the steady state flow energy equation in the combustion chamber while neglecting potential and kinetic energy changes. The energy equation is given by:

$$\sum_{in} \mathrm{MH} - \sum_{out} \mathrm{MH} = 0 \qquad 7$$

M and H are the mass and enthalpy of fuel which is represented as heat released, given by [10] as:

$$Q = H_{P2} - H_{R1} = 0 \qquad 8$$

where Q is the heat energy, H_{P2} represents the total enthalpy of the products of combustion, and H_{R1} represents the total enthalpy of reactants.

Expanding equation (8), we have

$$H_{P2} - H_{R1} = (H_{P2} - H_{P0}) + (H_{P0} - H_{R0}) + (H_{R0} - H_{R1}) = 0 \qquad 9$$

H_{R0} and H_{P0} are enthalpies of reactants and products at reference temperature, T_0

This is rewritten as;

$$(H_{P2} - H_{P0}) + \Delta H_0 + (H_{R0} - H_{R1}) = 0 \qquad 10$$

Where $\Delta H_0 = (H_{P0} - H_{R0})$ is the enthalpy of combustion at reference temperature, T_0

The enthalpy changes may be written for an ideal gas approximately as;

$$(H_{P2} - H_{P0}) = \sum_{P} M_i Cp_i (T_2 - T_0) \qquad 11$$

$$and \qquad (H_{R0} - H_{R1}) = \sum_{R} M_i Cp_i (T_0 - T_1) \qquad 12$$

Where M_i and Cp_i are masses and specific heat capacities of reactants and products. T_0, T_1, T_2 are reference, initial and final temperatures respectively.

Substituting these in equation (3.10) follows that

$$\sum_{P} m_i Cp_i (T_2 - T_0) + \Delta H_0 + \sum_{R} m_i Cp_i (T_0 - T_1) = 0 \qquad 13$$

Hence, the final temperature, T_2 which is the adiabatic flame temperature, T_{ad} is calculated thus

$$T_2 = T_0 - \frac{\Delta H_0 - (T_0 - T_1) \sum_R M_i Cp_i}{\sum_P M_i Cp_i} \qquad 14$$

The absolute value of the enthalpy of combustion, $|\Delta H_0|$ for the fuel is the heating value (calorific value) of the fuel [7, 10]. Coke has a calorific value ranging from $28{,}000\ \mathrm{kJ/kg}$ to $31{,}500\ \mathrm{kJ/kg}$, therefore choosing a value of $30{,}500\ \mathrm{kJ/kg}$ which is given as lower heating value (LHV) of coke [15] gives an enthalpy of combustion equal to $30{,}500\ \mathrm{kJ/kg}$.

3. Results and Discussion

3.1 Evaluation of the Adiabatic Flame Temperature

The calculations in this work which include the determination of adiabatic flame temperature, solution to the energy balance equations and the parametric study were carried out with the high performance matrix-based software, SCILAB (version 6.0.0). SCILAB is a programming language associated with a rich collection of numerical algorithms covering many aspects of scientific computing problems. From the plotted bar chart in Figure 4, the percentage composition by mass of the coke constituent elements were shown. It can be observed that carbon has the highest percentage composition by mass when compared to other elements in the coke. This is followed by oxygen, nitrogen and ash while sulphur has the least composition by mass. In Figure 5, the amount of substance released after the combustion of 100 Kg of coke were plotted in a bar chart also. nitrogen gas (N_2) is the highest among the released substance. This is followed by carbon dioxide (CO_2), water vapour (H_2O), ash and excess oxygen (O_2) while sulphur was found to be infinitesimally small and hence was not seen on the plot as captured in the legend. In Figure 6, the product wet and dry basis analysis result of were plotted to show the percentage of each substance found in the combustion products. It can be observed that nitrogen has the highest percentage content among the gases in both dry and wet basis analysis, followed by CO_2, H_2O and O_2 with sulphur been infinitesimally small. In the wet basis analysis, H_2O is slightly higher than O_2 even though it was not used for dry basis analysis. The flow chart for the SCILAB computation are presented in Figure 7. On the flow chart, the input parameters were supplied and initialized in the SCILAB program after which the initial guess value of the adiabatic flame temperature was initialized. Different subcomponent functions of specific heat (Cp), average temperature computation and gas temperature data to compute the Cp at different flame temperature. The newly computed adiabatic flame temperature is substituted into the function for evaluation of the new sets of the Cp for different gases. The iteration continues until the adiabatic flame temperature as well as the gases Cp converged. The computed results were stored in comma separating values (csv) and open when needed.

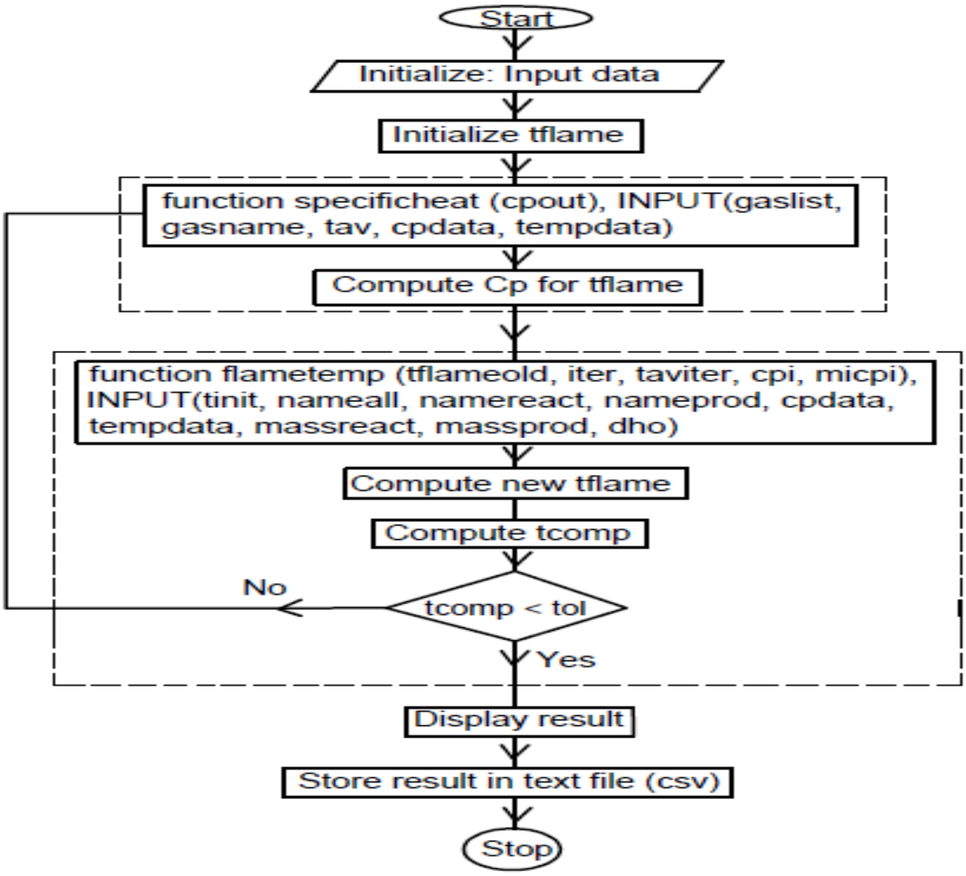

Figure 7: Flow chart for SCILAB computation of adiabatic flame temperature

The adiabatic flame temperature of the fuel (coke) used in the furnace was determined by an iterative procedure with an initial value of 1000K assumed, and the intermediate values of the specific heat of various gases were calculated by interpolation using equation 14. The procedure converged at the 8th iteration, and a constant value of T_2 was obtained, giving an adiabatic combustion temperature (T_2) of 2175.93K as shown in Figure 8 which is the plot of the C_p of CO_2 against the iterative adiabatic temperature.

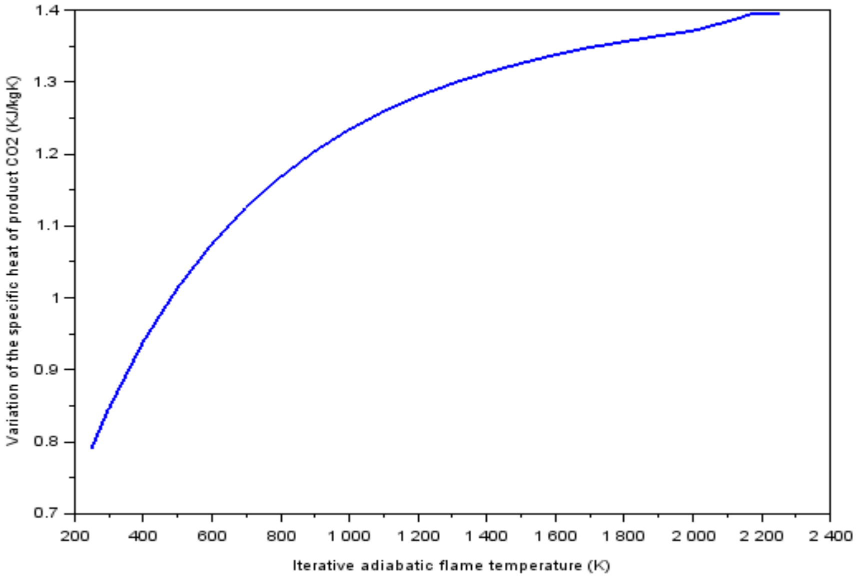

Figure 8: Effect of adiabatic flame temperature on CO_2 specific heat

The C_p of CO_2 was first plotted against the adiabatic flame temperature before plotting the C_{ps} of other product gases as shown in Figure 9. The C_p of the products keep increasing with increasing temperature from the initial guess value until the value of 2175.93K. After the adiabatic temperature, there was no appreciable change in the C_{ps} of CO_2 and the other products. The ash has no contribution in the combustion process and so was not necessarily captured in this analysis.

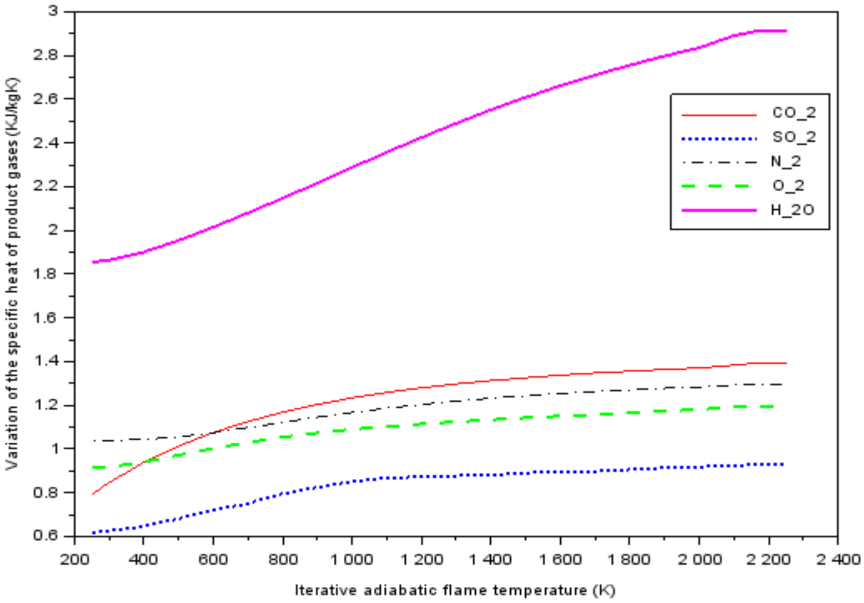

Figure 9: Effect of adiabatic flame temperature on gas specific heat

This temperature is in range with adiabatic flame temperatures recorded for coke at initial temperature of 293K to be 2142K [16].

3.2 Parametric Analysis

The operating temperature was assumed to be constant in other to test the effect of the different excess air on the flue gases both on wet and dry analysis basis from the already generated models as shown in Figure 10 and Figure 11 respectively. The percentage excess air was varied from 5% to 120% for the determination of their effects on the C_p of the gases in both wet and dry basis analysis cases. It was observed that the C_p of water remain almost constant at all level of percentage excess air with just differential change. That of CO_2 and N_2 shown decreasing and increasing trend respectively as the percentage excess air increase. Both gases intercepted at 43% excess air indicating a balanced excess air for either gas. The behavior of oxygen and water vapour from the combustion also shows the same trend but had their intercept at 39% excess air which as well indicates a balanced excess air for both gases. The percentage composition of SO_2 in the combustion is infinitesimally small when compared other product gases as it is within 0.05% to 0.1%. It can be observed that in both wet and dry basis analysis, percentage composition of SO_2 is unchanged and that of water in the wet basis remain nearly constant even on excess air increment. The percentage composition of CO_2 and N_2 demonstrated slight increasing and decreasing curves respectively on increase in excess air in the combustion as shown in Figure 10 and Figure 11. From the dry basis analysis of the flue gases percentage shown in Figure 11, it can be seen that similar behavior occurred for their interception at exactly 45% whereas O_2 had same behavior with little increase compared to the wet analysis case. The combine effects on both wet and dry analysis case can be shown in Figure 12.

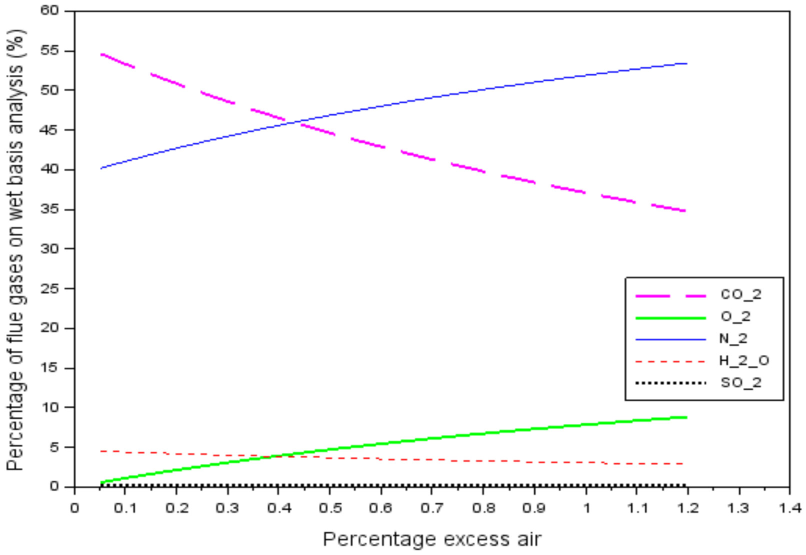

Figure 10: Effect of percentage excess air flue gases on wet basis analysis

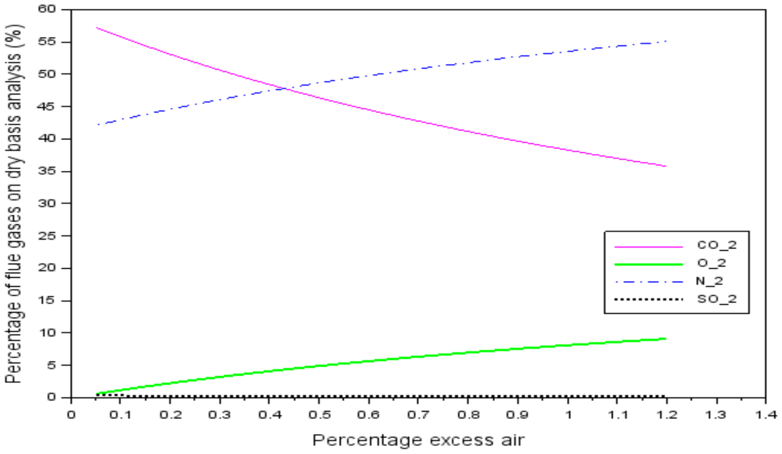

Figure. 11: Effect of percentage excess air flue gases on dry basis analysis

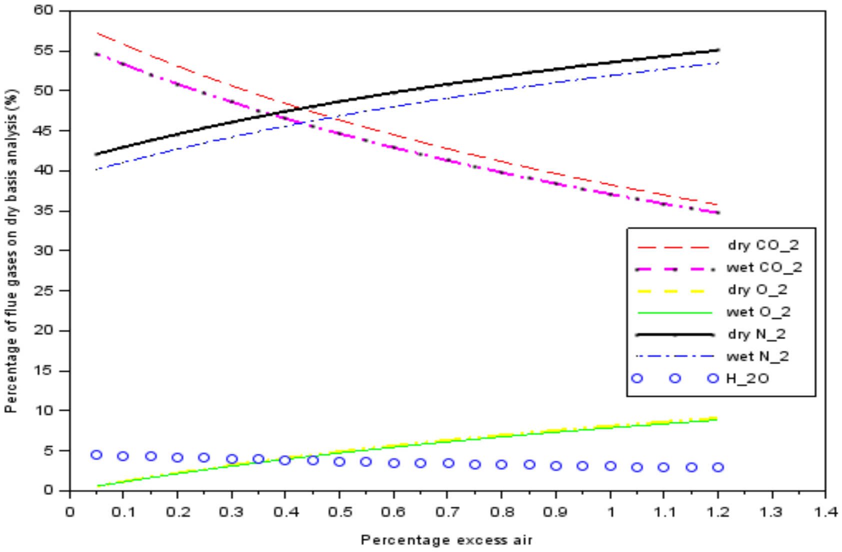

Figure 12: Effect of percentage excess air flue gases on both dry and wet basis analysis

The percentage of flue gases difference for wet and dry case was plotted against the percentage excess air as shown in Figure 13. From Figure 13, the difference in percentage excess air has effects on N_2 and CO_2 formed as product but with virtually no effect on the O_2. The N_2 and CO_2 curves intercepted at the point of 44% on the graph. This implies that the maximum of 45% (between 30% - 45%) excess air is required for the real balanced combustion in the furnace to give the system specified output without much energy loses from too much air combustion and as well as the system's metallurgical consideration. Excess air above this can result to drop of the system's recommended output and possibly leads to dissociation of the products.

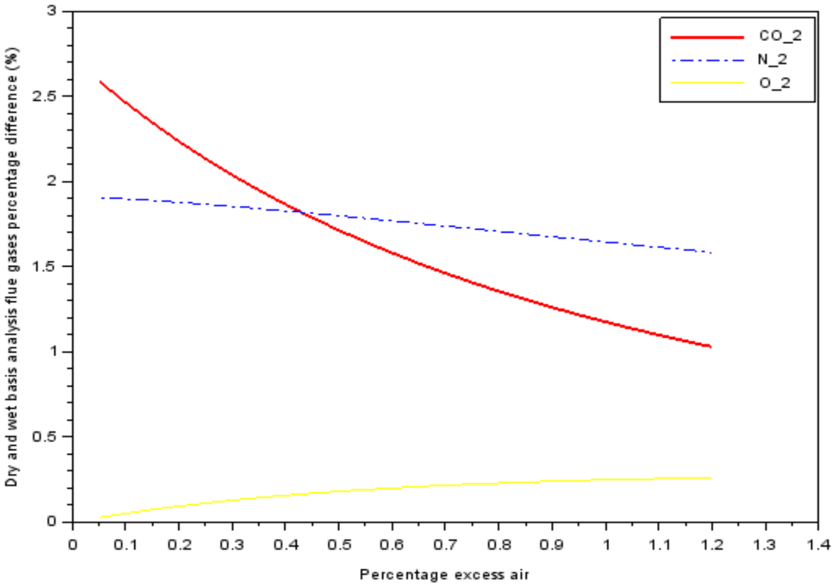

Figure 13: Dry and wet basis analysis flue gases percentage difference on different percentage excess air.

Conclusion

In this study, the thermal analysis of a conventional cupola furnace at the Nigeria Railway Corporation, Enugu District was carried out. The efficiency of the furnace was calculated and a parametric study was carried out to simulate possible design and operating variations for improvement of the furnace efficiency. The adiabatic flame temperature of the fuel (coke) used for operation was calculated to be 2175.93K, a high temperature value that cannot be easily controlled. Performance variations of the system was evaluated with variation of design and operating parameters. The operating parameters used were the flue gas temperature and combustion percentage excess air. The percentage excess air was varied from 0.05 (5%) to 1.2 (120%) to determine their effects on the C_p of the gases considering both wet and dry basis analysis. That of CO_2 and N_2 shown decreasing and increasing trend respectively as the percentage excess air increase. Both intercepted at 0.43 (43%) excess air. The behavior of oxygen and water vapour from the combustion also shows the same trend but had their intercept at 0.39 (39%) excess air. The percentage of flue gases difference for wet and dry case was also investigated against the percentage excess air. The N_2 and CO_2 curves intercepted at the point of 0.44 (44%). This implies that the maximum of 45% (with range of 30% - 45%) excess air is required for the real balanced combustion in the furnace to give the system specified output without the dissociation of the gases and as well as the system's metallurgical consideration. With these models, other similar thermal system (furnace) excess air requirement can be predicted for optimum system output.

Acknowledgement-The authors of this research paper wish to express their profound gratitude to the workers of cupola furnace at the Nigeria Railway Corporation, Enugu, Enugu State, Nigeria for the facilities used to carry out the experiments.

Disclosure statement: *Conflict of Interest:* The authors declare that there are no conflicts of interest.
Compliance with Ethical Standards: This article does not contain any studies involving human or animal subjects.

References

[1] E. D. Larsen, D. E. Clark, K. L. Moore, and P. E. King, *Intelligent Control of Cupola Melting*, University of North Texas Libraries, Digital library, 1997. https://www.osti.gov/biblio/484517-intelligent-control

[2] J. Meredith, *The Cupola Furnace*, Atlas Foundry Company Publications, 2016. http://www.atlasfdry.com/cupolafurnace.html

[3] H. M. Raymond, *Cupola Furnace, Modern Shop Practice*, Part 1-3, 2011. http://chestofbooks.com/crafts/machinery/shop-practice-v2/cupola-furnace.html

[4] Sengerandu's *Tutorials, Cupola Furnace*, Worldpress blog, 2013. https://sengerandu.wordpress.com/tutorials/basic-manufacturing-process/foundry-practice/cupola-furnace

[5] K. Rathod, S. Gupta, A. Sharma and S. Prakash, "*Energy-Efficient Melting Technologies in Foundry Industry*". Indian foundry journal. 62 (2016) 39-46.

[6] T. Niehoff, H. Struning, M. *Lemperle, Oxy-fuel Burner Technology for Cupola Melting*, 2nd International Cupola Conference, Trier 18, Lecture No. 2-4, 2004.

[7] Wikipedia: *Fuel – coke*, (2016). https://en.m.wikipedia.org/wiki/coke

[8] J. Carvill, *Mechanical Engineer's Data Handbook*. Butterworth-Heinemann publishers, Jordan Hill, Oxford, 2003.

[9] R. S. Khurmi and J. K. Gupta, *A Textbook of Machine Design*. S. Chand and Company Ltd., Eurasia Publishing House (PVT.) Ltd., 2008, pp16 – 50.

[10] R. B. John, Foseco *Ferrous Foundryman's Handbook*. Butterworth-Heinemann, 2000.

[11] C. Norwood, A. Noble and S. Williams, *Iron Melting Cupola Furnace with Heat Recuperating System*, MSE/ME 499 Project – University of Alabama, Birmingham. 2010, pp 1-91.

[12] D. S. Chastain, *Iron Melting Cupola Furnaces for the Small Foundry*. Jacksonville, FL; U.S.A., 2000.

[13] Pal, Prosanto and Nath, Abhishek. *Energy Efficien/t and Environmentally Friendly Cupola Furnace*. Tata Energy Research Institute Publication, 2002. http://www.teriin.org/upfiles/pub/papers/ft4.pdf, accessed May 26, 2016.

[14] H.U. Ugwu and E. A. Ogbonnaya, "*Design and Testing of a Cupola Furnace for Michael Opara University of Agriculture, Umudike*", Nigerian Journal of Technology, 32 (1) (2013) 22-29.

[15] A. G. Olorunnishola and S. A. Anjorin, "*Design, Construction and Testing of an Erythrophleum Suaveolens Charcoal-fired Cupola Furnace for Foundry Industries in Nigeria*", Scientia Agriculturae, 12 (1) (2015) 1-12.

[16] K. Ramaswamy, *Foundry Air Pollution: Hazards, Measurements and Control*. (2015) 10.1007/978-3-319-11906-9_9

(2021); http://www.jmaterenvironsci.com