



## Original Research Article

### Characterization of Coal-Iron Filings Pellets Combustion Parameters Using Thermogravimetric Analysis Techniques

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#### ABSTRACT

*The combustion of pure coal requires improvement of its temperature profile characteristics to enable thermal stability and sustainability through coal blending. The thermal degradation and temperature profile characteristics from combustion of coal-iron filings pellets have been evaluated using thermogravimetric analysis (TGA) and compared to 100% coal. This study explores the potential of enhancing coal combustion parameters by blending coal with iron filings to improve thermal performance. Thermogravimetric analyses were conducted on two samples of 100% coal pellets and coal-iron filings pellet prepared using hand-mixed process in ratios of 60%Coal:40%Iron filings using waste paper as binder to ensure high mechanical strength. Thermogravimetric analysis results of 100%coal and coal-iron filings pellets revealed temperature profile characteristics such as onset temperature, ignition temperature, mid-temperature, burnout temperature, mass loss and residual mass ranging from 125°C to 245°C, 300°C to 350°C, 400°C to 610°C, 700°C to 750°C, 89% to 81% and 11% to 19% respectively demonstrating the viability of coal blending with iron filings for improved combustion characteristics. These results suggest that coal-iron filings blend can significantly improve thermal stability and sustainability useful for energy source, aligning with Sustainable Development Goals 7.*

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## 1. INTRODUCTION

Coal is the largest fuel source for power generation in the world (Nihad *et al.*, 2016). Coal is originally from vegetal fragments formed in marshy layers to form compressional residue known as peat and is mainly derived from a variety of vegetal remnants consisting mainly of organic matters with associated

mineral constituents (Pajares and Diez, 2014). Coal is combustible black sedimentary rocks that are formed as a result of continuous exposure to high temperature and high pressure of ancient plants such as trees, fern and mosses which grew in swamps along the shoreline of the coastal region, the transitional stages to the formation of coal are peat, lignite, subbituminous coal, bituminous coal and anthracite which is the most carbon-rich, moisture-deficient form of coal and has the highest heating value (Ondari *et al.*, 2021). Coal was discovered in Enugu, Nigeria in 1909 and has large coal reserves, estimated to be at least 2 billion metric tonnes (Eneje *et al.*, 2012).

Iron filings (powder) is a very low carbon, high energy density energy carrier, fully recyclable energy carriers that can safely and efficiently store the surplus of energy generated by various renewable energy hubs around the world and then safely transfer the stored energy to energy consumption sites with high demand (Baigmohammadi *et al.*, 2023). The efficiency of solar and wind power generation is mainly determined by uncontrollable natural factors, resulting in a disparity between energy generation and consumption, metals, particularly iron, are promising energy carriers to overcome these challenges, hence, iron in powder form can be used as a high-energy-density, recyclable fuel that can be burned to generate electrical and heat power, with subsequent collection of iron oxide and reduction back to iron using renewable energy (Bergthorson *et al.*, 2015). Iron is well-known for its unique characteristics as a compact, recyclable, safe-to-store/shipment metal that is abundantly available on the earth's crust (4th most abundant element) and iron as a powder can be initially burned in a combustor after the combustion, the produced iron oxide would be recycled to metallic iron powder at renewable energy sites by reducing the iron oxide using electrolyzed hydrogen, then instead of direct transportation of hydrogen, which is more difficult, the recycled iron powder would be stored and shipped (Baigmohammadi *et al.*, 2023).

Thermogravimetric analysis (TGA) is one of the most important techniques used nowadays to rapidly evaluate the thermal degradation of solid fuels and it has the ability to measure the weight loss of a sample as a function of temperature and time. Thermogravimetric analysis involves the combustion of coal which is the process of heating coal in air or air mixtures to produce heat for steam raising and consequently power generation. Temperature profile from thermogravimetric analysis gives detailed information such as ignition temperature, mid temperature, peak temperature and burnout temperature of combustion characteristics starting from oxidation to complete burnout and the combustion behavior of coal samples indicates their type, grade and chemical composition (Mangs *et al.*, 2023). Information obtained from TGA decomposition profiles can provide insight into the understanding of combustion behaviour on industrial scale and broad knowledge of the thermal decomposition of coal combustion and kinetics is essential for clear understanding, design, optimization and fabrication of combustion furnaces on industrial scale (Garba *et al.*, 2016).

Researchers such as Chukwu *et al.*, (2016); Garba *et al.*, (2016); Oboirien *et al.*, (2018); Nyakuma, (2019); Benedict *et al.*, (2022); Msheilla *et al.*, (2022); and Mangs *et al.*, (2023) studied on thermal degradation of solid fuel decomposition during combustion are focused on 100% coal using thermogravimetric analysis. However, none reported the potential of evaluating combustion characteristics of composite fuel such as coal-iron filings pellets. The aim of this work is to investigate a comparative study of TGA of 100% coal and its composite 60%coal : 40%iron filings.

## 2. MATERIALS AND METHODS

### 2.1. Materials Preparation

Coal samples were collected from coal mines in Obomkpa, Delta State, Nigeria, and left to dry in the sun for 10 days to reduce their moisture content and make them easier to pulverize. Iron filings, on the other hand, were sourced from the fabrication workshop at the National Engineering Design Development Institute (NEDDI) in Nnewi, Anambra State, Nigeria, using a magnet to ensure only iron filings were collected. A grinding machine then pulverized the samples to a particle size between 250  $\mu\text{m}$  and 300  $\mu\text{m}$ . To achieve the best mixture of coal and iron filings optimized mixing ratios of 60%coal

: 40% iron filings was used (Ajiboye *et al.*, 2016). The pulverized samples were combined and formed into pellets using a screw press pelleting machine capable of handling 5 kg per hour at an average pressure of  $1.2 \times 10^3$  N/m<sup>2</sup>. Additionally, 100% coal pellets was produced to compare with the mixed ratio, resulting in two different categories of pellet samples. The coal grains and iron filings were measured, weighed, and thoroughly mixed in a ratio of 60% Coal: 40% Iron filings to obtain optimal mix pellets. These pellets are illustrated in Figure 1a and 1b. They were naturally dried at temperatures ranging from 28°C to 32°C over 48 hours. After drying, the pellets were characterized using thermogravimetric techniques.



Figure 1a: 100% coal pellets



Figure 1b: 60% coal: 40% iron filings pellets

## 2.2. Combustion Characteristics Analysis

The burning (combustion) characteristics and thermal degradation behaviour were examined by thermogravimetric analysis (TGA). The thermogravimetric runs were performed under mild oxidative conditions and controlled by an air flow/purge rate at 20 mL/min through the non-isothermal heating programme of the Thermogravimetric analyser (Model: Shimadzu TG-50 analyser, Japan). For each test, approximately 10 mg of coal-iron filings sample was weighed and placed in an alumina crucible before the samples were heated at 20 °C/min from 30°C to 800°C. At the end, the thermogravimetric analyser was cooled down, the raw data retrieved and processed on the Shimadzu Workstation (Version: TA-60WS). Next, the mass loss (%) and derivative mass loss (%/min) were plotted against temperature to obtain TG-DTG plots for the oxidative thermal analysis of the 100% coal pellet and optimal mix pellet (60%C: 40%IF). The plots were then analysed to examine the burning characteristics through their degradation behaviour, thermal reactivity, and temperature profile characteristics (TPC), according to the procedures in the literature ( Donahue and Rais, 2009). The TPCs examined in this study are onset temperature ( $T_{ons}$ ), ignition ( $T_{ons}$ ), midpoint temperature ( $T_{mid}$ ), offset temperature ( $T_{off}$ ), and burnout ( $T_{out}$ ) temperatures, along with mass loss (%) and residual mass ( $RM$ , %). The experiments were duplicated for each test in order to ascertain the reproducibility of the results.

## 3. Results and Discussion

### 3.1. Thermogravimetric Analysis Results of 100% Coal Pellet

The thermogravimetric analysis for the coal pellet was done at heat rate of 25°C/min to determine the combustion characteristics and profile. As shown in Figure 2, the 100% coal pellet sample experienced progressive mass loss. The thermogravimetric plots showed that the increase in temperature from room temperature (RT) of 24.35°C to 886.2°C significantly decomposed the sample during TGA which is in agreement with the report of Ondari et al, (2021); Akinyemi et al, (2020); Nyakuma, (2019) and Garba *et al.*, (2016). Basically, the thermal degradation of coal is due to the breakdown of the organic matter or macerals such as inertinite, vitrinite and liptinite in its structure (Zou, *et al.*, 2017). The TG plot in figure 2, showed the downward sloping weight loss curves for thermally decomposition coals as reported by Mang *et al.*, (2023), Nyakuma, (2019); and Akinyemi *et al.*, (2020) which indicated that temperature significantly affected the devolatilization of the coal pellets under the conditions investigated.

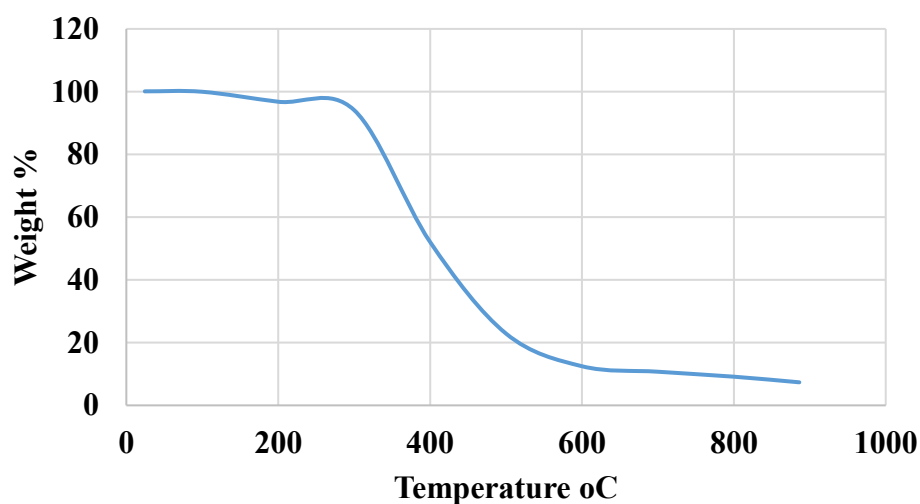


Figure 2: TGA plot of 100% coal pellets

As shown in Figure 3, the thermal decomposition generated three major endothermic peaks. The first peaks were observed at 100°C, which can be ascribed to drying or the loss of moisture. The second and third major peaks occurred at 250 °C and 450 °C; the mass loss at these peaks could be ascribed to the loss of volatile matter and fixed carbon content of 100% coal pellets through devolatilization in line with the submission of Mang et al. (2023) and Akinyemi et al. (2020).

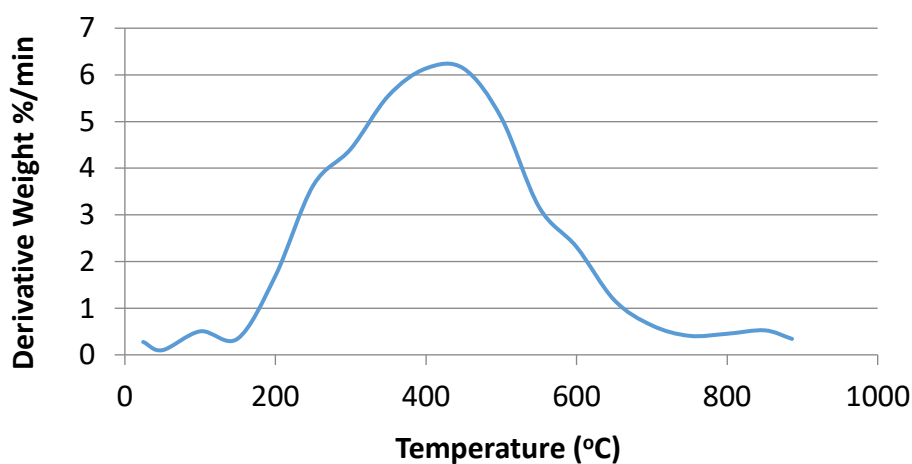


Figure 3: DTG plot of 100% coal pellet

The magnitude of the mass loss for the coals was examined from the temperature profile characteristics (TPCs). The TPCs for the coal pellet deduced from the TG plots in Figure 2 are presented in Table 1. As observed from Table 1, the ignition temperature for the 100% coal pellet is 300°C which is consistent with the report of Nyakuma (2019) and fairly close to value obtained by Ondari *et al.*, (2021). The onset temperature is the lowest temperature in which a sample undergoing thermal analysis begins to decompose or experience mass loss. The midpoint temperature, offset temperature or burnout temperature, mass loss and residual mass of 100% coal pellet are 407°C, 700°C, 89% and 11% respectively which are fairly in agreement with the reports of Mang *et al.*, (2023), Akinyemi *et al.*, (2020), Nyakuma (2019) and Chukwu *et al.*, (2016). It can be concluded that higher temperatures

enhanced the conversion of the coal components due to the increase in the bond breaking reactions of the coal components during TGA, and the findings indicate that 100% coal pellet bond-breaking is thermally reactive and can be effectively utilized for efficient thermal energy recovery.

Table 1: TG Temperature profile characteristics of 100% coal pellet

TPC parameters	Symbol/ unit	100% coal pellet
Onset temperature	$T_{on}$ °C	125
Ignition temperature	$T_{ig}$ °C	300
Midpoint temperature	$T_{mid}$ °C	400
Burnout temperature	$T_{out}$ °C	700
Mass loss	$M_l$ %	89
Residual mass	$R_m$ %	11

The DTG temperature profile characteristics as shown in Figure 2, revealed three major peaks, namely drying peak at 100 °C, devolatilization peak 1 at 250 °C and devolatilization peak 2 at 450 °C which are presented in Table 2.

Table 2: DTG temperature profile characteristics

Parameter	Symbol/ unit	100% coal pellet
Drying Peak	DyP, °C	100
Devolatilization Peak 1	DvP1 °C	250
Devolatilization Peak 2	DvP2 °C	450

### 3.2. Thermogravimetric Analysis Results of Optimal Mix Pellet (60%C: 40%IF)

The thermogravimetric analysis for the optimal mix pellet was done at a heat rate of 25 °C/min to determine the combustion characteristics and profile. As shown in Figure 4, the optimal mix pellet sample experienced less progressive mass loss. The TG plots showed that the increase in temperature from room temperature (RT) of 27 °C to 889.49°C gradually decomposed the sample during TGA.

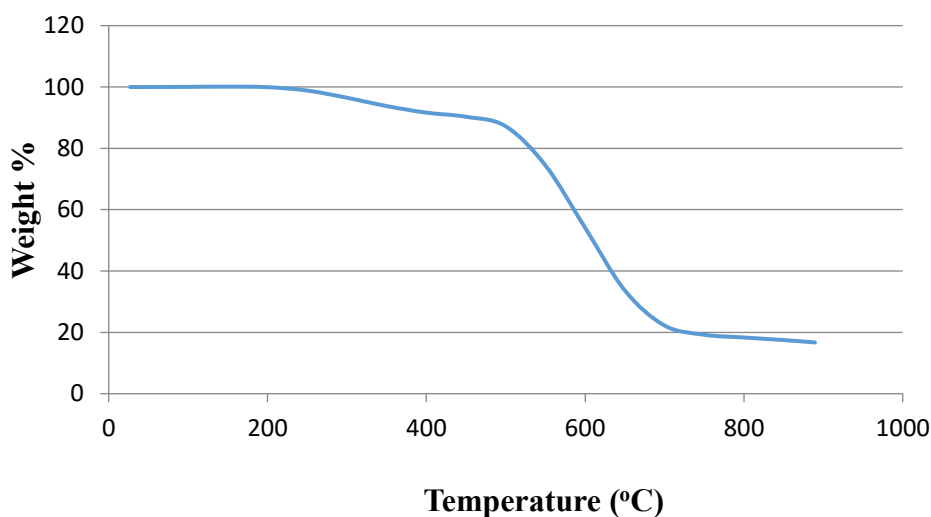


Figure 4: TGA plot of optimal mix of pellet (60%C: 40%IF)

As shown in Figure 5, the thermal decomposition generated two major endothermic peaks. The first peaks were observed at 280°C, which can be ascribed to drying or the loss of moisture. The second and major peak occurred at 600 °C, the mass loss at this peak could be ascribed to the loss of volatile matter or organic matter content of optimal mix pellets through devolatilization, which is consistent with the report of Mang *et al.* (2023); Garba *et al.* (2016).

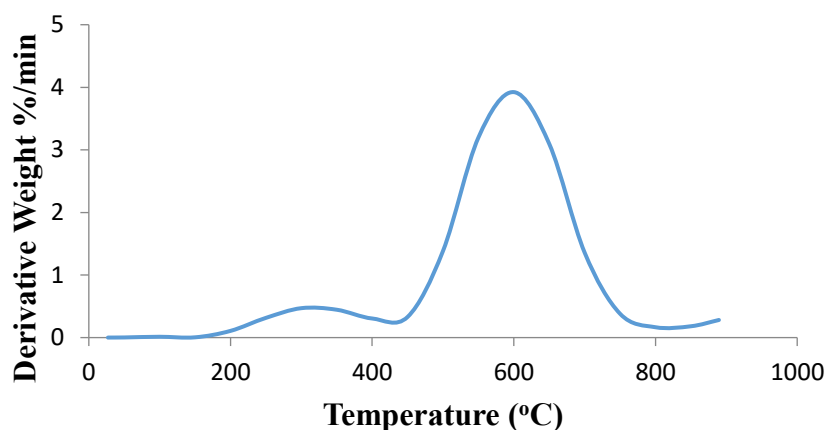


Figure 5: DTG plot of optimal mix of pellet (60%C:40%IF)

The magnitude of the mass loss for the coals was examined from the temperature profile characteristics (TPCs). The TPCs for the optimal mix pellet deduced from the TG plots in Figure 4. are presented in Table 3. As observed from Table 3, the onset and ignition temperature for the optimal mix pellet are 245°C and 350°C. The result of the ignition temperature is consistent with the conclusion of Kizgut *et al.*, (2003) that the ignition temperature of coal increases with decreasing volatile matter. The onset temperature is the lowest temperature in which a sample undergoing thermal analysis begins to decompose or experience mass loss. The midpoint temperature, offset temperature or burnout temperature, mass loss and residual mass of optimal mix pellet are 610°C, 750°C, 81% and 19% respectively showing a more thermally stable pellets than 100% coal pellet and a thermally improved fuel than the reports of Mang *et al.* (2023), Akinyemi *et al.* (2020), Nyakuma *et al.* (2019).

Table 3: TG temperature profile characteristics of optimal mix pellet (60%C:40%IF)

TPC parameters	Symbol/ Unit	100% Coal Pellet
Onset temperature	T <sub>on</sub> °C	245
Ignition temperature	T <sub>ig</sub> °C	350
Midpoint temperature	T <sub>mid</sub> °C	610
Burnout temperature	T <sub>out</sub> °C	750
Mass loss	M <sub>l</sub> %	81
Residual mass	R <sub>m</sub> %	19

The DTG Temperature Profile Characteristics were higher than those of 100% coal pellets as shown in Figure 5, which revealed two major peaks, namely drying peak at 280 °C, devolatilization peak at 600 °C which are presented in Table 4.

Table 4: DTG temperature profile characteristics of optimal mix pellet (60%C:40%IF)

Parameter	Symbol/ Unit	100% coal pellet
Drying peak	DyP, °C	280
Devolatilization peak	DvP1 °C	600

#### 4. CONCLUSION

The combustion characteristics of 100% coal pellet and optimal mix pellet (60%C: 40%IF) revealed that the latter exhibited higher thermal stability and sustainability from a higher onset temperature and midpoint temperature. From the combustion parameters, 100% coal pellet thermal degradation started at 125 °C, while for the optimal mix pellet thermal degradation commenced at 245°C, also mid temperature for 100% coal was 407°C while the optimal mix pellet is 610 °C. mass loss for 100% coal and optimal mix pellet are 89% and 81%, and their respective residual mass are 11% and 19%. Hence, iron filings showed great potential in enhancing thermal stability of coal pellets which is in agreement with the efficacy of fine metal particles as potential fuel additives as reported by Berghorson *et al.*,

(2015) and Khan *et al.*, (2020) The findings from this study suggest that coal-iron filings blend can significantly improve thermal stability and sustainability of pure coal combustion as energy source, aligning with Sustainable Development Goals 7.

## 5. ACKNOWLEDGEMENT

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## 6. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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