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DESIGN, CONSTRUCTION AND TESTING OF A 5kg SMOKELESS FUEL MANUFACTURING REACTOR BY FORCED CONVECTION

Engr Christopher Zakariya, Dr Mary D Samuel, Engr Michael Alaku

Department of Mechanical Engineering, Faculty of Engineering and Technology, Nigerian Defence Academy, Kaduna, Nigeria

Email: chriszak2002@gmail.com

Abstract

This study presents the design, construction, and testing of a 5kg smokeless fuel manufacturing reactor by forced convection that converts locally available sub-bituminous coal and lignite into cleaner solid fuel (coke) via low-temperature carbonisation. The device was designed using locally sourced materials and incorporates a lagged steel reactor, a coal crucible, a combustion chamber, and a forced-air supply to achieve controlled heating in the range of 300–600 °C. Proximate and ultimate analyses were conducted on coal samples before and after carbonisation to evaluate changes in moisture content, volatile matter, ash content, fixed carbon, and elemental composition. Experimental tests were performed on different coal particle sizes (10 mm, 15 mm, and 20 mm) to assess temperature profiles, heating rates, and carbonisation efficiency. Results showed a significant reduction in volatile matter and sulphur content, increased fixed carbon, and improved calorific value, confirming the production of smokeless and cleaner fuel. The developed reactor offers a cost-effective and environmentally friendly solution for domestic and small-scale industrial energy needs, with strong potential for reducing indoor air pollution and dependence on firewood in rural communities.

Keywords— Smokeless fuel, Carbonisation, Coke production, Sub-bituminous coal, Reactor design, Coal carbonisation, clean fuel

I.0 INTRODUCTION

Energy remains one of the fundamental requirements for economic growth and sustainable development. Domestic cooking, industrial heating, electricity generation, and metallurgical processes depend heavily on reliable energy sources. Although renewable energy technologies continue to expand, solid fuels remain the dominant source of energy for millions of households, particularly in developing countries where access to cleaner fuels is limited. Coal constitutes one of the world's largest fossil energy resources because of its abundance, relatively low cost, and high calorific value. However, the direct combustion of raw coal produces considerable quantities of smoke, particulate matter, sulphur oxides, nitrogen oxides, and greenhouse gases, thereby contributing to environmental pollution, respiratory diseases, and climate change [1–7].

Nigeria possesses approximately 639 million tonnes of proven coal reserves and an estimated 2.75 billion tonnes of inferred reserves, consisting mainly of sub-bituminous, bituminous, and lignite coals. Despite these abundant resources, coal utilisation for domestic applications remains limited because raw coal combustion generates excessive smoke and harmful gaseous emissions. In many rural communities, households continue to depend on firewood and untreated coal for cooking and heating, exposing users to indoor air pollution while contributing to deforestation and environmental degradation [7].

Carbonisation provides an effective method for producing smokeless fuel by thermally decomposing coal under oxygen-deficient conditions. During the process, moisture and volatile compounds are removed, leaving behind a carbon-rich solid residue known as coke. Compared with raw coal, coke possesses higher fixed carbon content, lower volatile matter, reduced sulphur concentration, and burns with significantly less smoke. Consequently, it is considered a cleaner domestic and industrial fuel [8–12].

Conventional coke manufacturing technologies are generally designed for large-scale industrial production and require sophisticated infrastructure, continuous operation, and substantial capital investment. These requirements make them unsuitable for decentralised or rural applications. Therefore, there is a need for a compact, affordable, and locally fabricated carbonisation device capable of converting Nigerian sub-bituminous coal into smokeless fuel while maintaining acceptable thermal efficiency and product quality.

This study therefore focuses on the design, construction, and experimental evaluation of a smokeless fuel manufacturing device developed from locally available materials. The fabricated system incorporates a lagged steel reactor, combustion chamber, insulation layer, coal crucible, forced-air supply, and exhaust system to facilitate controlled carbonisation between 300 and 600 °C. The performance of the device was assessed through proximate and ultimate analyses of the produced coke together with temperature measurements obtained during experimental testing.

2.0 MATERIALS AND METHODS

2.1 Materials

Sub-bituminous coal obtained from a Nigerian coal deposit was used as the feedstock for the carbonisation process. Prior to experimentation, the coal samples were subjected to proximate and ultimate analyses to determine their moisture content, volatile matter, ash content, fixed carbon, and elemental composition. The coal was crushed and sieved to obtain particle sizes suitable for carbonisation, while representative samples were preserved according to standard coal sampling procedures to prevent oxidation before laboratory analysis [8], [23], [24].

The smokeless fuel manufacturing device was fabricated entirely from locally available engineering materials. Mild steel plates were used for the reactor body and combustion chamber because of their availability, ease of fabrication, and adequate mechanical strength. Angle irons provided structural support for the frame, while refractory insulation materials were incorporated between the inner and outer walls to minimise heat loss during carbonisation. Galvanised steel pipes and fittings were used for the air supply and exhaust systems, whereas bolts, nuts, hinges, handles, and welding electrodes were employed during fabrication.

2.2 Design Concept

The design of the smokeless fuel manufacturing device was based on the operating principle of the traditional beehive coke oven. The beehive oven operates by carbonising coal under oxygen-deficient conditions, allowing volatile compounds to escape while retaining the fixed carbon required for smokeless fuel production [20], [21].

Unlike conventional industrial coke ovens that require continuous external heating and sophisticated process controls, the developed device was designed as a compact batch reactor suitable for laboratory investigations and small-scale fuel production. The reactor incorporates thermal insulation, controlled air supply, and an enclosed heating chamber to maintain the temperatures necessary for carbonisation while preventing complete combustion of the coal.

The design philosophy emphasised:

i. Utilisation of locally available materials;
ii. Simplicity of fabrication and operation;
iii. Low production cost;
iv. Adequate thermal insulation;
v. Controlled oxygen supply;
vi. Ease of maintenance; and
vii. Safe handling during carbonisation.

These considerations enabled the fabrication of an economical device capable of producing smokeless fuel suitable for domestic and small-scale industrial applications.

2.3 Description of the Smokeless Fuel Manufacturing Device

The developed smokeless fuel manufacturing device consists of six principal components:

i. Carbonisation reactor
ii. Combustion chamber
iii. Coal crucible
iv. Thermal insulation layer
v. Forced-air supply system
vi. Exhaust/flue system

The reactor serves as the principal carbonisation chamber in which coal is heated under limited oxygen conditions. The combustion chamber provides thermal energy by burning coal beneath the reactor. Heat generated is transferred through the reactor walls to initiate pyrolysis within the coal charge. The lagging material surrounding the reactor reduces heat losses and improves thermal efficiency by maintaining a nearly uniform temperature throughout the carbonisation period. Controlled airflow supplied through the blower regulates combustion intensity, while the exhaust system allows volatile gases generated during carbonisation to escape safely from the reactor [20–22].

The completed reactor was designed to carbonise approximately 5 kg of sub-bituminous coal per batch at operating temperatures between 300 and 600 °C, consistent with the design specifications established for the study.

2.4 Design Methodology

The design procedure consisted of the following stages:

i. Characterisation of the selected sub-bituminous coal through proximate and ultimate analyses.
ii. Development of a three-dimensional computer model of the reactor using SolidWorks software.
iii. Determination of reactor dimensions based on the desired coal capacity.
iv. Selection of suitable construction materials considering thermal resistance, strength, availability, and fabrication requirements.
v. Determination of heat transfer characteristics and insulation requirements.
vi. Fabrication and assembly of the reactor.
vii. Experimental testing and performance evaluation.

The reactor dimensions were selected to provide adequate space for the coal charge while allowing uniform heat distribution during carbonisation. Material selection considered resistance to thermal deformation, corrosion, mechanical loading, and repeated heating cycles.

2.5 Fabrication Procedure

Fabrication commenced with the cutting of mild steel plates according to the design dimensions generated from the SolidWorks model. Individual components were machined and assembled through electric arc welding to form the combustion chamber, reactor body, supporting frame, and exhaust system. Openings were provided for coal charging, temperature measurement, combustion air supply, and product discharge.

Thermal insulation materials were installed between the inner and outer reactor walls to reduce conductive heat losses and improve thermal efficiency. The reactor cover was designed to minimise air leakage during carbonisation while permitting controlled release of volatile gases through the exhaust pipe. After fabrication, dimensional inspection and leak tests were conducted before experimental evaluation.

2.6 Experimental Procedure

Performance testing was conducted using prepared sub-bituminous coal samples of different particle sizes. Measured quantities of coal were loaded into the reactor crucible before sealing the reactor. Coal placed within the combustion chamber was ignited to provide the heat required for carbonisation.

Forced air was supplied continuously to maintain combustion and achieve the desired reactor temperature. Reactor temperature was monitored throughout the carbonisation process using thermocouples positioned at designated locations within the system. Carbonisation continued until the desired operating temperature and residence time had been attained.

After completion of heating, the reactor was allowed to cool naturally before the carbonised product was removed for laboratory analysis.

2.7 Performance Evaluation

The performance of the developed smokeless fuel manufacturing device was evaluated using both laboratory analyses and operational observations.

Proximate analysis was carried out to determine moisture content, ash content, volatile matter, and fixed carbon of the raw coal and the carbonised product using standard laboratory procedures [23]. Ultimate analysis was also conducted to determine changes in carbon, hydrogen, nitrogen, sulphur, and oxygen contents after carbonisation.

The thermal performance of the reactor was evaluated by monitoring temperature variation with time throughout the carbonisation process. Heating rate and temperature distribution were used to assess the effectiveness of heat transfer within the reactor. The quality of the produced smokeless fuel was determined by comparing the physicochemical properties of the raw coal and the carbonised product.

The overall performance of the reactor was assessed based on:

i. Temperature stability during carbonisation;
ii. Effectiveness of volatile matter removal;
iii. Increase in fixed carbon content;

iv. Reduction in sulphur concentration;
v. Quality of the produced smokeless fuel; and
vi. Operational reliability of the fabricated device.

3.0 RESULTS AND DISCUSSION

3.1 Chemical Characterisation of Coal Before Carbonisation

The chemical properties of the sub-bituminous coal were first determined before carbonisation to establish its suitability as a feedstock for smokeless fuel production. Both proximate and ultimate analyses were conducted using standard laboratory procedures. The results serve as the baseline for evaluating the effectiveness of the carbonisation process.

Table 3.1 Proximate analysis of coal before carbonisation

Proximate analysis	Coal sample
Moisture content (%)	5.15
Ash content (%)	12.65
Volatile matter (%)	35.43
Fixed carbon (%)	46.07
Sulphur (%)	0.70
Net calorie value (kcal/kg)	5257.56
Gross calorie value (kcal/kg)	5570.02

The relatively high volatile matter (35.43%) indicates that the raw coal would generate considerable smoke during combustion if used directly as a domestic fuel. The fixed carbon content of 46.07% is typical of Nigerian sub-bituminous coal and confirms that the coal possesses sufficient carbon to produce quality coke after carbonisation. Furthermore, the sulphur content of 0.70% suggests that sulphur emissions can be significantly reduced through the carbonisation process, thereby producing a cleaner fuel for domestic and small-scale industrial applications. These observations agree with the characteristics of sub-bituminous coal reported by Loison et al. [8] and subsequent studies on coal carbonisation [9–12].

3.2 Ultimate Analysis Before Carbonisation

Ultimate analysis was conducted to determine the elemental composition of the raw coal before carbonisation. Carbon is the dominant constituent, while hydrogen, oxygen, nitrogen, and sulphur occur in smaller proportions.

Table 4.2 ultimate analysis of coal before carbonisation

Ultimate analysis	Coal sample
Carbon (%)	80.7716
Hydrogen (%)	5.6726
Oxygen (%)	10.9744
Nitrogen (%)	1.8814
Sulphur (%)	0.70

The high carbon content confirms the suitability of the selected coal for coke production, while the elemental composition provides the basis for evaluating chemical transformations occurring during carbonisation.

3.3 Chemical Properties After Carbonisation

Following carbonisation, proximate and ultimate analyses were repeated on the coke samples produced from 10 mm, 15 mm, and 20 mm coal particle sizes.

Table 4.3 proximate analysis of coke after carbonisation

Coke samples / **Proximate analysis**	**10mm Coal**	**15mm Coal**	**20mm Coal**
Moisture content (%)	1.20	0.75	1.15
Ash content (%)	11.16	12.60	12.01
Volatile matter (%)	9.28	9.30	9.27
Fixed carbon (%)	77.56	76.55	76.87
Sulphur (%)	0.80	0.80	0.70
Net calorie value (kcal/kg)	5221.46	5134.24	4861.29
Gross calorie value (kcal/kg)	5504.10	5411.78	5141.91

Table 4.4 ultimate analysis of coke after carbonisation

Coke samples / **Ultimate analysis**	**10mm Coal**	**15mm Coal**	**20mm Coal**
Carbon (%)	90.3548	89.7511	89.7668
Hydrogen (%)	3.2442	3.1972	3.2112
Oxygen (%)	4.3866	5.0377	5.1074
Nitrogen (%)	1.2144	1.2140	1.2146
Sulphur (%)	0.80	0.80	0.70

The laboratory analyses revealed that carbonisation significantly modified the physicochemical properties of the coal. Moisture content and volatile matter decreased considerably, while fixed carbon increased substantially. Sulphur concentration was also reduced, indicating successful removal of volatile sulphur-containing compounds during pyrolysis. Similar behaviour has been reported for low-temperature carbonisation of sub-bituminous coal and is characteristic of efficient coke production [39–42].

3.4 Discussion of Proximate Analysis Results

Comparison of the proximate analyses before and after carbonisation demonstrates that the fabricated reactor effectively converted raw coal into smokeless fuel.

The reduction in moisture content indicates efficient drying of the coal during heating. Removal of inherent moisture improves combustion efficiency because less energy is consumed in evaporating water during fuel utilisation.

The most significant improvement is observed in the reduction of volatile matter. Volatile compounds are primarily responsible for dense smoke, tar formation, and harmful gaseous emissions produced during raw coal combustion. Their removal during carbonisation confirms that the reactor successfully achieved pyrolysis under oxygen-limited conditions.

A corresponding increase in fixed carbon content demonstrates that carbonisation concentrated the combustible carbon remaining after volatile components had been driven off. Higher fixed carbon improves fuel quality by increasing burning duration, combustion stability, and thermal efficiency.

Although ash content changed slightly following carbonisation, the values remained within acceptable limits for domestic and small-scale industrial fuel applications. The reduction in sulphur content further indicates that the produced coke is environmentally preferable to untreated coal because lower sulphur concentrations reduce sulphur oxide emissions during combustion.

Overall, the proximate analysis confirms that the developed reactor successfully produced a cleaner-burning smokeless fuel with improved combustion characteristics.

3.5 Discussion of Ultimate Analysis Results

The ultimate analysis further confirms the effectiveness of the carbonisation process. Carbon remained the predominant constituent after carbonisation and showed an increase relative to the untreated coal because volatile hydrocarbons and oxygenated compounds were removed during heating. Hydrogen and oxygen contents decreased considerably, reflecting thermal decomposition of organic compounds and release of gaseous products such as methane, carbon monoxide, carbon dioxide, and water vapour during pyrolysis. Nitrogen exhibited only minor variation, whereas sulphur content decreased after carbonisation, demonstrating the removal of sulphur-bearing volatile compounds. The reduction of sulphur is particularly important because it contributes to lower emissions of sulphur dioxide during combustion, thereby improving environmental performance.

The increase in carbon concentration together with reductions in hydrogen, oxygen, and sulphur confirms successful conversion of raw sub-bituminous coal into high-carbon smokeless fuel suitable for domestic and industrial heating applications.

3.6 Temperature Profile During Carbonisation

The thermal behaviour of the reactor was investigated by monitoring reactor temperature throughout the carbonisation process for coal particle sizes of 10 mm, 15 mm, and 20 mm.

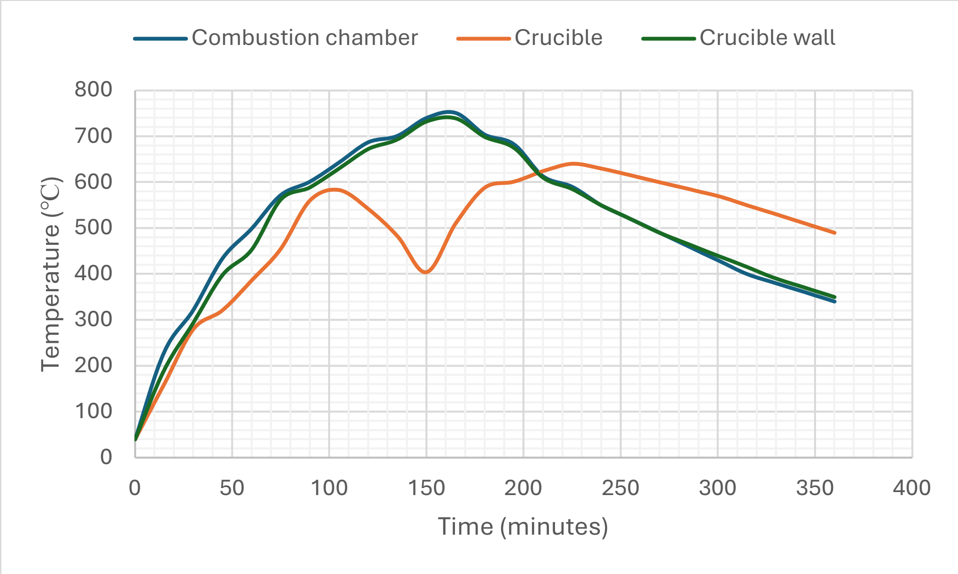

Figure 3.1 temperature-time relationship for 10mm coal

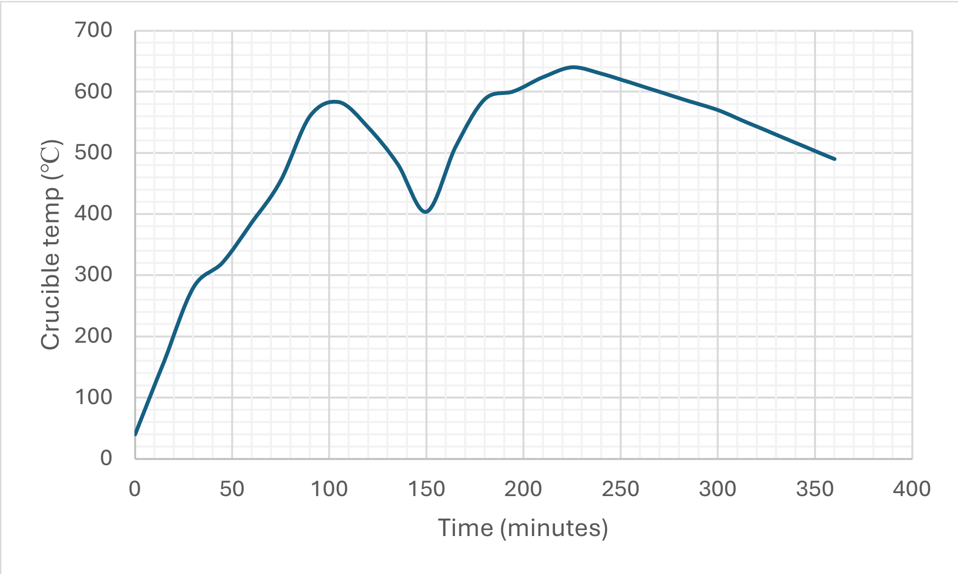

Figure 3.2 crucible temp–time relationship for 10mm coal

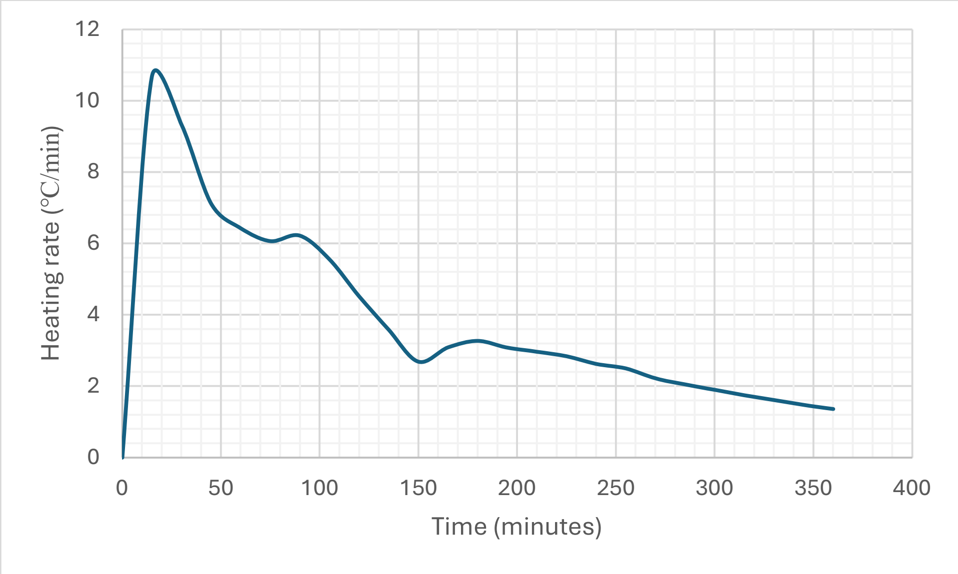

Figure 3.3 heating rate-time relationship for 10mm coal

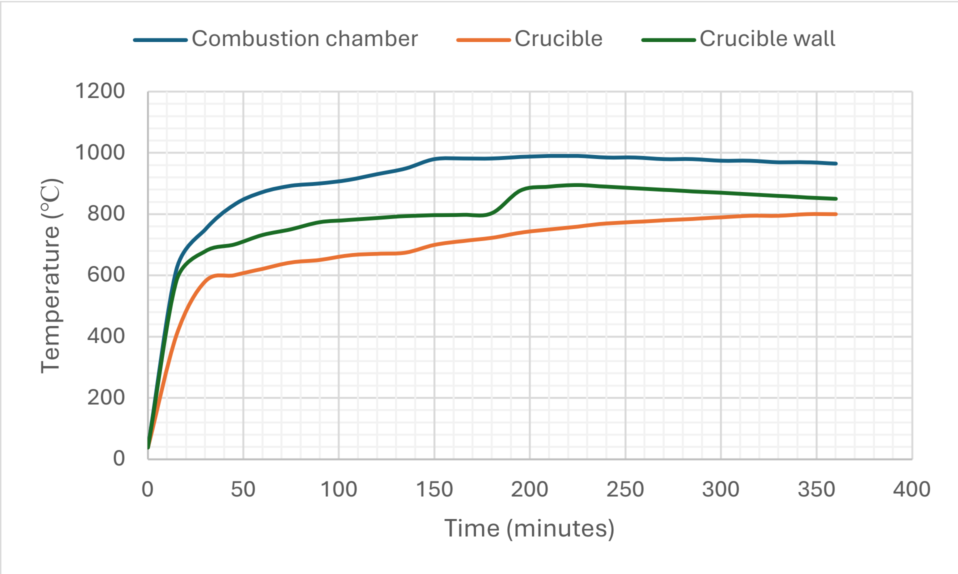

Figure 3.4 temperature-time relationship for 15mm coal

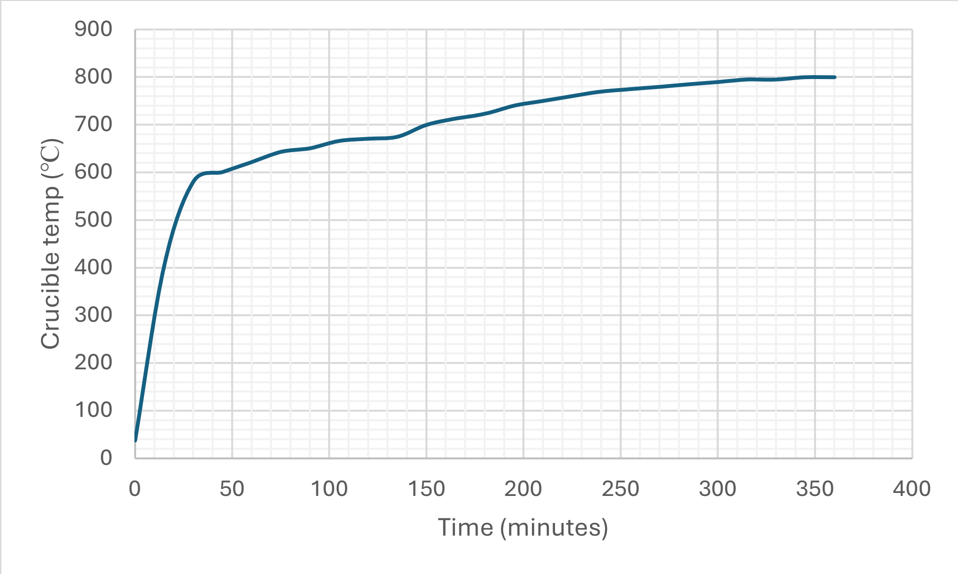

Figure 3.5 crucible temp–time relationship for 15mm coal

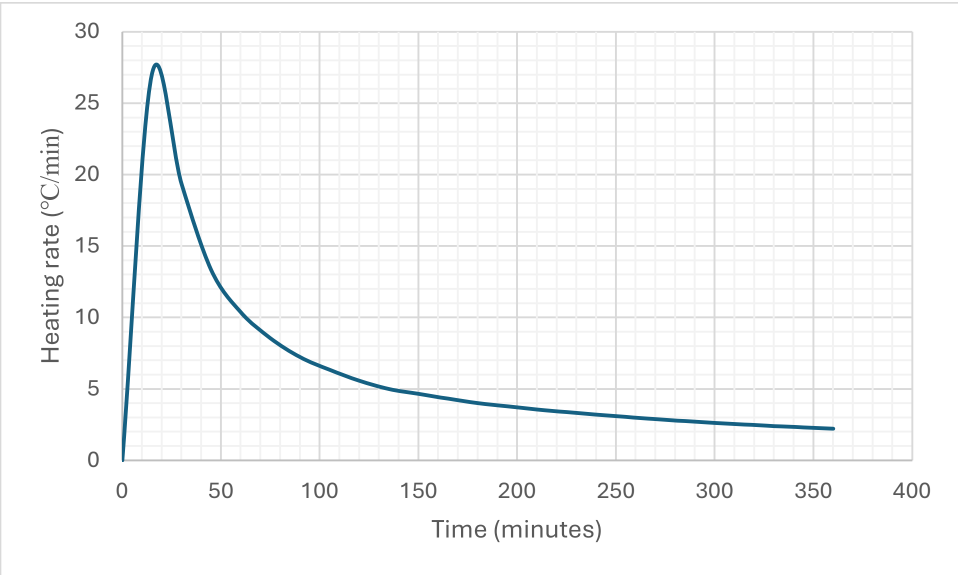

Figure 3.6 heating rate-time relationship for 15mm coal

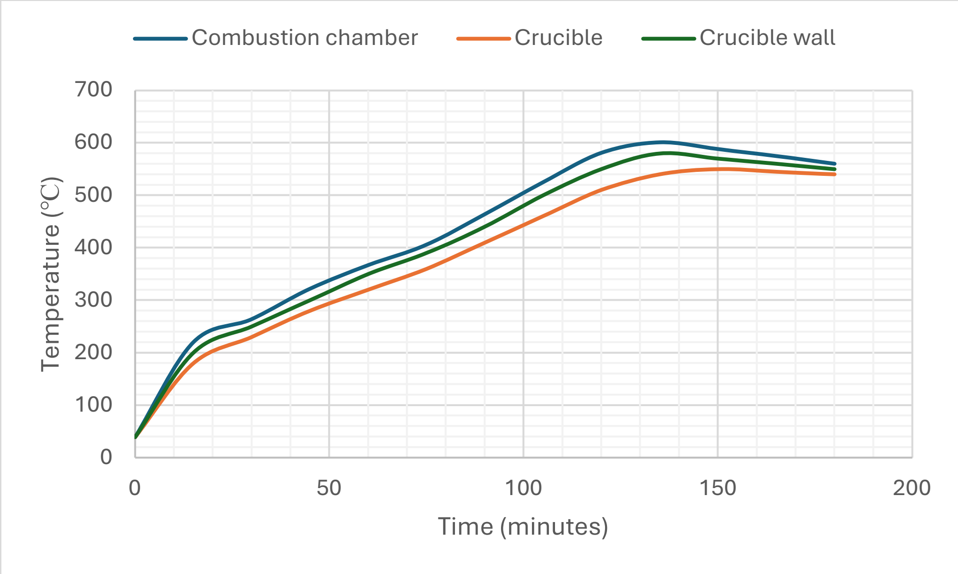

Figure 3.7 temperature-time relationship for 20mm coal

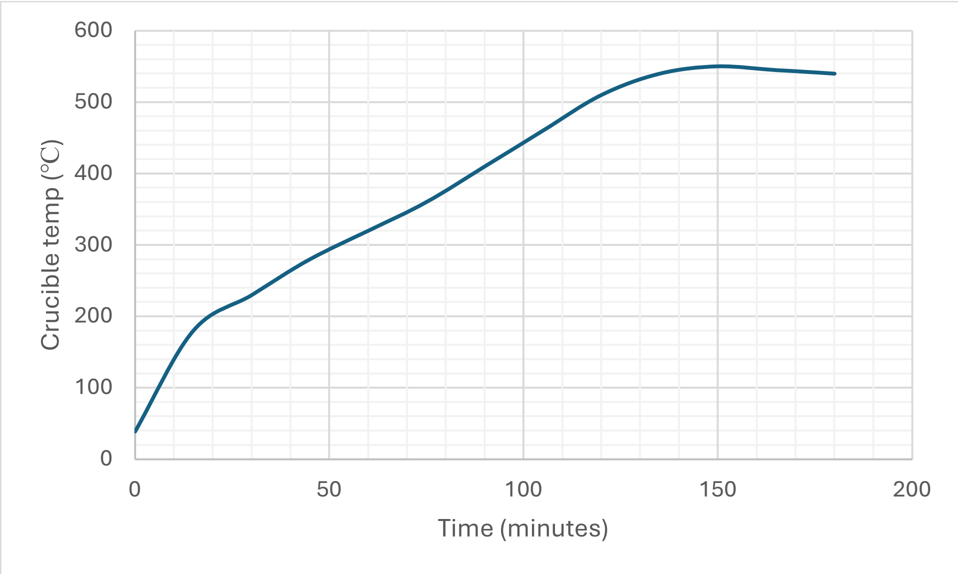

Figure 3.8 crucible temp-time relationship for 20mm coal

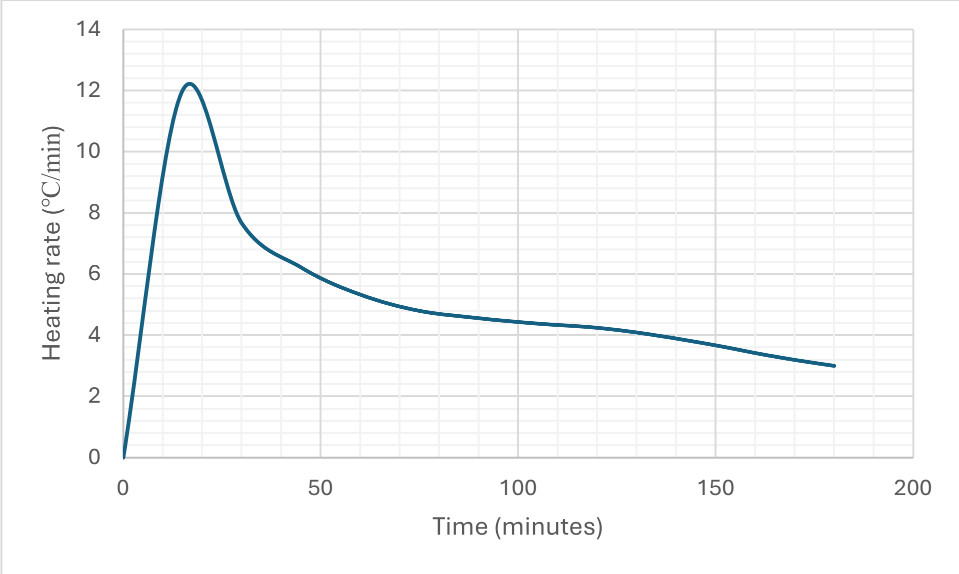

Figure 3.9 heating rate-time relationship for 20mm coal

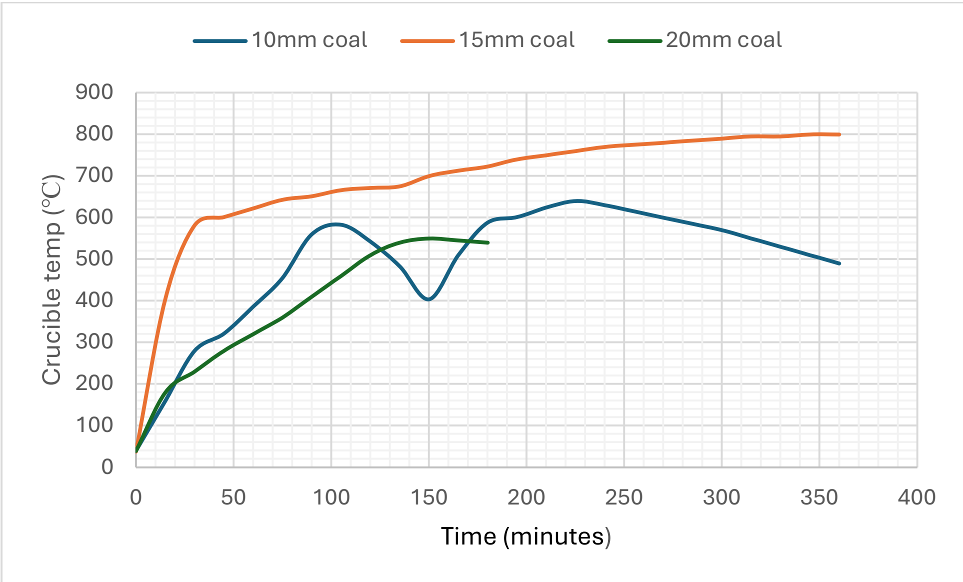

Figure 3.10 Comparison of crucible temperature for the three coal samples

The temperature–time curves show that reactor temperature increased steadily following ignition until the desired carbonisation temperature was attained. Heat supplied from the combustion chamber was effectively transferred through the reactor walls into the coal crucible, indicating good thermal contact between the combustion chamber and the carbonisation chamber.

The lagging material significantly reduced heat losses to the surroundings, allowing relatively stable operating temperatures throughout the carbonisation period. Temperature fluctuations observed during testing were primarily associated with variations in combustion intensity and volatile gas evolution.

3.7 Effect of Coal Particle Size

Coal particle size influenced both heating rate and carbonisation duration. The 10 mm coal particles reached carbonisation temperature more rapidly because of their larger surface-area-to-volume ratio, allowing faster heat penetration. The 15 mm particles exhibited intermediate heating characteristics and provided relatively uniform temperature distribution throughout the carbonisation process. The 20 mm particles required longer heating periods because heat had to penetrate deeper into the coal before complete carbonisation occurred. Despite these differences, all three particle sizes were successfully carbonised, demonstrating the operational flexibility of the developed reactor.

3.8 Overall Performance of the Developed Device

Experimental evaluation demonstrated that the fabricated smokeless fuel manufacturing device performed satisfactorily under laboratory operating conditions. The reactor successfully maintained the temperature required for carbonisation while minimising heat loss through effective insulation. Controlled airflow supplied by the radial blower ensured sufficient combustion within the heating chamber while preventing excessive oxygen from entering the carbonisation chamber. Laboratory analyses confirmed that the produced coke possessed lower volatile matter, lower sulphur content, and higher fixed carbon than the original coal. These improvements indicate successful production of smokeless fuel with better combustion characteristics and reduced environmental impact. The successful operation of the fabricated reactor demonstrates that locally available materials can be effectively utilised to develop an affordable smokeless fuel manufacturing system capable of producing cleaner solid fuel for domestic and small-scale industrial applications.

4.0 CONCLUSION

The design, construction, and performance evaluation of a smokeless fuel manufacturing device have been successfully accomplished. The study demonstrated the feasibility of developing a compact and cost-effective carbonisation system using locally available engineering materials for the production of smokeless fuel from Nigerian sub-bituminous coal. The fabricated device was designed to operate under controlled oxygen-deficient conditions, enabling efficient carbonisation within the temperature range of 300–600 °C.

Experimental evaluation confirmed that the developed reactor effectively converted raw coal into smokeless fuel through the removal of moisture and volatile compounds while increasing the fixed carbon content. Proximate and ultimate analyses revealed significant reductions in volatile matter and sulphur concentration after carbonisation, accompanied by improvements in the fixed carbon content and fuel quality. These changes indicate that the produced coke possesses superior combustion characteristics compared with untreated coal and is capable of burning with considerably less smoke and lower emissions.

Temperature measurements obtained during the carbonisation process showed that the reactor maintained stable operating conditions throughout the heating period. The incorporation of thermal insulation effectively reduced heat losses, while the forced-air supply system ensured adequate combustion within the heating chamber. The device successfully carbonised coal samples of different particle sizes, demonstrating its operational flexibility and suitability for batch production.

The study further established that the use of locally sourced materials and conventional fabrication techniques can significantly reduce the cost of smokeless fuel production equipment without compromising operational performance. Consequently, the developed device offers a practical alternative for small-scale smokeless fuel production, particularly in developing countries where access to cleaner domestic fuels remains limited.

The successful production of smokeless fuel using the developed reactor contributes to cleaner energy utilisation by reducing smoke generation, sulphur emissions, and indoor air pollution associated with the direct combustion of raw coal. The technology therefore has considerable potential for domestic cooking, small-scale industrial heating, educational demonstrations, and further research into coal carbonisation and clean solid fuel production.

5.0 RECOMMENDATIONS

Based on the findings of this study, the following recommendations are proposed:

i. Future work should investigate the influence of higher carbonisation temperatures and longer residence times on the quality and yield of smokeless fuel.
ii. An automatic temperature control system should be incorporated into the reactor to improve process stability and ensure more precise thermal regulation during carbonisation.
iii. The reactor should be modified to enable continuous rather than batch operation, thereby increasing production capacity and improving industrial applicability.
iv. Further studies should evaluate the thermal efficiency, energy consumption, and economic feasibility of the device under different operating conditions.
v. Emission monitoring should be carried out during carbonisation and subsequent fuel combustion to quantify reductions in particulate matter, sulphur oxides, carbon monoxide, and other pollutants.
vi. Additional investigations should be conducted using different Nigerian coal deposits and biomass blends to assess the versatility of the developed device and optimise smokeless fuel quality.
vii. Scale-up studies should be undertaken to adapt the developed technology for commercial and community-level smokeless fuel production.

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