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Design of Industrial Carbon Black Recovery Plant For Incineration of Waste Tyres and Allied Products

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Abstract

The disposal of waste tyres poses a significant environmental challenge due to their non-biodegradable nature and potential for causing pollution. The non-existence of an industrial carbon recovery plant in Nigeria equally worsens the situation when compared with United States with up to one hundred and fifty (150) waste-to-energy combustion plants as well as counties in Europe and Asia (Switzerland incinerates about 70% of solid waste and Japan incinerates about 50%). In Nigeria, the accumulation of waste tyres has become a pressing issue, necessitating the development of sustainable solutions for their management. This work extrapolates linearly data for existing bench-scale experiment to estimate or an industrial carbon black recovery plant that utilizes the incineration of waste tyres as a means of waste management and resource recovery. The weights of waste tyres used ranges from 176kg–744kg while the maximum temperature for combustion ranged from 346–570^{0}C. Plant's daily capacity is 6,000 kilogram of incinerated waste tyres which produces 240 kilogram of Carbon black. The solid by-products of the operation are carbon black, ash and metal components. Results from this work can be used to determine the economic feasibility.

Keywords: waste tyre management, carbon black recovery, incineration, industrial plant

1.0 Introduction

The combustion of waste tyres (WT) and the recovery of carbon black (rCB) have emerged as a promising method for converting waste into a valuable resource. WT pose a significant environmental challenge due to their non-biodegradable nature and the difficulty in disposing of them. However, by incinerating WT, it is possible to rCB, a valuable industrial material with various applications (Frank, 2002). Although most developed economies have been working assiduously to valorize this waste (around 92% and 75.6% of the WTs generated in the European Union and the United States are recovered through different practices such as energy and material recovery and retreading (ETRMA, 2017; USTMA, 2019).

Carbon black is widely used in industries such as rubber manufacturing, ink production, and as a pigment in plastics and coatings. The market demand for carbon black is significant, approximately 281 million waste tyres (Oriaku et.al, 2013), creating economic opportunities for the recovery of this material from waste tyres. The size of the global rCB Market is expected to increase from USD 55 million in 2018 to USD 491 million by 2023 (Kamlesh, 2023).

Most states in Nigeria are facing a growing challenge of waste tyre accumulation, leading to environmental degradation and health hazards. The improper disposal of waste tyres not only poses a threat to public health but also contributes to air and soil pollution. In light of these concerns, there is a need for innovative solutions that can effectively manage waste tyres while also creating value from their disposal. One such solution is the incineration of waste tyres to recover carbon black, a valuable industrial material used in various applications. Traditional methods of tire disposal, such as land-filling or incineration, are not only unsustainable but also contribute to pollution and resource depletion. In response to this challenge, the recovery of carbon black from waste tires has gained traction as a promising solution that offers multiple environmental, economic, and social benefits.

The composition of scrap tyres typically includes rubber, steel, and fabric components. The combustion of waste tyres involves the thermal decomposition of these components, leading to the production of carbon black as a by-product. This process not only helps in reducing the amount of waste going to landfills but also enables the recovery of a valuable material, (RMA, 2002). The rCB was mainly composed of carbon (80.75 wt%) and sulfur (2.99 wt%), while virgin carbon black (vCB) exhibits a very high carbon content (98.80 wt%) and negligible contents of hydrogen, oxygen, and nitrogen. In rCB, volatile matter was more than twice (5.65 wt%) that found in vCB (2.73 wt%), while the ash content was remarkably higher in the former (13.45 wt%) than in the latter (0.00 wt%). Volatile matter suggests the presence of partially de-volatilized rubber and/or hydrocarbon compounds (Williams et.al, 2021).

This work presents a design proposal for an industrial carbon black recovery plant in Enugu State that aims to address the issue of waste tyre management through sustainable and environmentally friendly means. The proposed plant will utilize the process of incineration to convert waste tyres into carbon black, a high-demand material with a range of industrial applications. By implementing this innovative approach, the plant will not only help mitigate the environmental impact of waste tyres but also contribute to the local economy by producing a valuable commodity.

2.0 Conceptual Framework for the Carbon Recovery Plant

The Carbon Recovery Plant of the present study consists of the following:
i. Site Selection and Layout Planning: The selection of an appropriate site for the carbon black recovery plant is crucial, considering factors such as proximity to tire waste sources, transportation logistics, environmental regulations, and community acceptance. The layout planning should optimize space utilization, process flow efficiency, safety measures, and future expansion possibilities. ii. Process Engineering: The design of the combustion chamber system, gas scrubbing unit, carbon black recovery system, oil and gas refining facilities, and waste heat recovery systems requires a multidisciplinary approach encompassing chemical engineering principles, thermodynamics, heat transfer analysis, and material science considerations. Through pyrolysis, the Natural Rubber (NR) and the Synthetic Rubber (SR) contained in WTs are separated from the solid carbon matrix. These rubbers are transformed into hydrocarbon vapours, thus giving rise to condensable and non-condensable products known as Tire Pyrolysis Oil (TPO) and Tire Pyrolysis Gas (TPG), respectively. The remained solid fraction concentrates all the Carbon Black (CB) content and the inorganic compounds used in tire manufacture. iii. Technology Integration: Incorporating state-of-the-art pyrolysis technology, gas cleaning techniques, carbon black separation methods, and energy recovery systems is essential for maximizing the plant's efficiency, product quality, and environmental performance.
iv. Environmental Management: Implementing emission control measures, waste minimization strategies, water conservation practices, and noise abatement measures are integral to ensuring compliance with environmental regulations and minimizing the plant's ecological footprint.
v. Economic Viability: Conducting cost-benefit analysis, market research, feasibility studies, and financial modelling is critical for assessing the economic viability of the carbon black

2.1 Viability of Industrial Carbon Black Recovery Plant

The viability of Industrial Carbon Black Recovery Plants are as follows:
i. The conversion of waste into a valuable resource and the creation of economic opportunities.
ii. Environmental Sustainability, the reduction of landfill waste and minimize the environmental impact of tire waste on land, water, and air quality.
iii. Resource Conservation from waste tires reduces the demand for virgin carbon black production, which helps conserve natural resources and reduce energy consumption.
iv. Economic Opportunities as carbon black is sold as a valuable commodity to industries that use it as a raw material, creating economic opportunities and contributing to a circular economy model.
v. Energy Recovery from the incineration process can be used as alternative fuels, reducing reliance on fossil fuels and promoting energy efficiency.

2.1.1 Industries that make use Carbon Black

Carbon black has wide range of uses across an array of applications in three markets, such as:
(i) Speciality Blacks:
- Carbon black play important role as pigment to impart jetness
- In ink and coatings as well as blackness
- Ultraviolet (UV) protection
- Conductivity of plastics;
- For Niche applications including: adhesives, sealants, ceramics and glass.

(ii) Mechanical Rubber Goods
(iii) Tires

2.2. Measures in Industrial Carbon Black Recovery Plant for effectiveness

Necessary measures for effectiveness in Industrial Carbon Black Recovery Plant include the following:
i. Potential air pollution and emissions of harmful gases if proper emission control measures are not implemented.
ii. Regulatory Compliance: Industrial carbon black recovery plants must comply with environmental regulations to ensure safe operations and minimal environmental impact.
iii. Technology and Infrastructure: Advanced combustion technology and efficient processing systems is needed for maximizing carbon black recovery and plant performance.
iv. Stakeholder Engagement: Collaboration with government agencies, industry partners, and local communities is important for promoting awareness of the benefits of carbon black recovery from waste tires.

3.0 Materials and Methods

3.1 Description of the Industrial Carbon Black Recovery Plant

The 3-D design drawing for the industrial carbon recovery incineration plant was done using SOLIDWORKS 2016 SP4.0 (2016195), are presented in Fig. 4.5 and Fig. 4.6. The snapshot of the bench scale experiment is shown in Fig 4.7 and samples of recovered carbon-black from the spent waste tyres are shown in Fig 4.8 respectively.

The set-up for the industrial CB Plant consists of the following components namely:

1. Combustion chamber
2. Harvesting chamber
3. Scrubber unit
4. Waste treatment tank
5. Water tank
6. Suction blower
7. Water pump
8. Stand

An industrial recovery plant for the incineration of waste tyres to recover carbon black typically consists of several components for efficient operation, such as: combustion chamber; heat recovery system; carbon black collection system; and emission control technologies.

3.2 Principle of Operation

The principles of operation involve feeding waste tyres into the combustion chamber, where they are subjected to high temperatures to facilitate thermal decomposition. The resulting gases are then cooled and condensed to rCB, which is collected using a filtration system. Tire Shredding System is the first step in the process involves shredding waste tires into smaller pieces to facilitate further processing. The second phase is Pyrolysis Reactor, the shredded tires are then fed into a pyrolysis reactor, where they are heated in the absence of oxygen to break down the rubber into its constituent components, including carbon black, oil, and gas. Third phase is the Gas Scrubbing System. The gas produced during the incineration process is scrubbed to remove impurities and pollutants before being released into the atmosphere. The fourth phase involves Carbon Black Recovery System: The carbon black is separated from the other pyrolysis products and collected for further processing and refinement. Then a final phase for Oil and Gas Recovery: The oil and gas by-products from the pyrolysis process can be further refined or used as fuel for the plant's operations.

3.3. Analytical Method for Estimating Industrial Operation from Bench Scale Experiments

The method used for analysis in this work is the extrapolation method. Extrapolation is the prediction or the estimation of a variable beyond the given data set by observing its relation with other variable in the existing data set (Souvik et. al, 2023). Statistical analysis techniques for the work involved the linear extrapolation. The data points are plotted on a graph and a linear equation is used to best represent the data. A tangent line is drawn with the concerned value of the dependent variable calculated. From previous Bench-scale experiment, (Oriaku, et. al, 2013), data of weight of tyres combusted versus weights of carbon black, weight of metal components and weight of ash batch produced forms equations which is linearly extrapolated.

First, the equation for weight of tyres used against weight of carbon-black produced during bench-scale experiment is given by;

$$Y = -0.000X^2 + 0.092X - 1.189 \qquad (3.1)$$

Where,

Y = Weight of Carbon-black produced

X = Weight of waste tyres used for the incineration

For the equation for weight of tyres used against weight of metal components obtained during bench-scale experiment is;

$$Y = -0.151x^2 + 0.448 \qquad (3.2)$$

Where,

Y = Weight of metal components produced

X = Weight of waste tyres used for the incineration

Then for equation of weight of tyres used against weight of Ash produced is given by;

$$Y = -0.000x^2 + 0.167x - 1.210 \qquad (3.3)$$

Where,

Y = Weight of Ash batch produced

X = Weight of waste tyres used for the incineration

Application of Extrapolation Method, (Nedoseka, 2012); Linear extrapolation was done using the equations 3.1 to 3.3, within the two known values (weight of tyres during bench-scale (x1) and weight of tyre for industrial scale (x2), having a ratio of 1: 8) will produce the predicted values for industrial scale products based on the formula;

$y(x) = y1 + \frac{x-x1}{x2-x1}(y2 - y1)$ .... (3.4)

4.0 Results and Discussion

The data obtained from the table experiment shown in the Table 1, we extrapolate for the designed industrial plant to determine carbon black recovery, using a ration of (1: 8). Since the loading bay of the industrial large-scale plant can accommodate 8 times that of the bench-scale experiment. From the data graphs can be plotted to show relationship between weight of tyres used for the industrial scale and the products obtained. This is shown in Fig. 4 to Fig.6.This implies that per hour, one production line will discharge 400 kg of recycled carbon black from the ash — which accounts for 2500 tons annually. As part of the final expansion stage, the plant, on the whole, will have a yearly capacity of about 30,000 tons. There is need to build a fully integrated, continuous tire combustion plant to recover carbon black, metal components and ash batch in high tyre waste centres in Nigeria.

Table 4.1: Experimental results from the Bench-Scale Combustion of waste tyres

s/n	Wt. loading tyre Bench-Scale(kg)	Time (mins)	Max. Temp (°C)	Wt. loading tyres large Scale (kg)
1	22	65	359	180
2	31	78	379	250
3	43	92	404	340
4	51	110	431	410
5	60	129	461	480
6	72	151	496	580
7	80	175	536	640
8	93	198	586	740

Table 4.2: Experimental result of industrial-scale combustion of waste tyres

S/N	Wt. Loading large Scale (kg)	Wt. of carbon black (kg)	Wt. of metal component (kg)	Wt. of ash batch (kg)	Time (mins)	Max temp (°C)
1	180	6.43	26.25	26.24	58	346
2	250	9.02	36.25	36.26	76	375
3	340	12.48	53.95	53.95	99	413
4	410	14.78	61.70	61.74	114	440
5	480	18.35	72.75	72.75	132	468
6	580	20.83	88.40	88.40	155	506
7	640	23.13	98.20	98.23	170	532
8	740	28.88	115.15	115.15	195	573

Table 4.3: Composition of typical carbon black

Type	Carbon (%)	Oxygen (%)	Hydrogen (%)	Volume content (%)
High Colour Channel	88.4	11.2	0.4	18
Long flow channel	90.0	8.7	0.8	12
Reinforcing channel	95.2	3.6	0.6	5
Semi-reinforcing furnace	99.2	0.4	0.3	1.2
Reinforcing oil furnace	98.0	0.8	0.3	1.4
Thermal acetylene	99.5	0.8	0.05	0.06

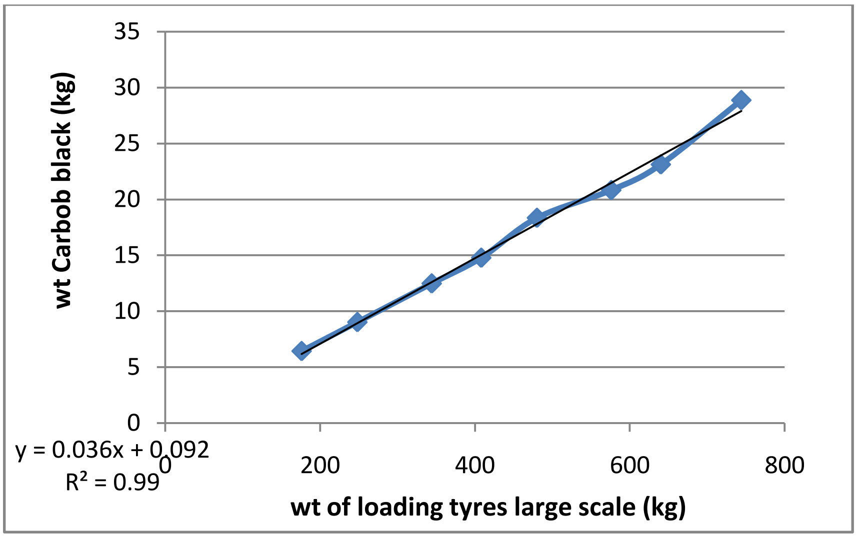

Fig 4.1: Plot of Carbon-Black Industrial Recovery against quantity of tyres incinerated

From the plot above, current equation for weight of tyres used against weight of carbon-black produced during industrial scale operation becomes;
y = 0.036x + 0.092 …………………………….. (4.1). Data gives, $R^2 = 0.99$

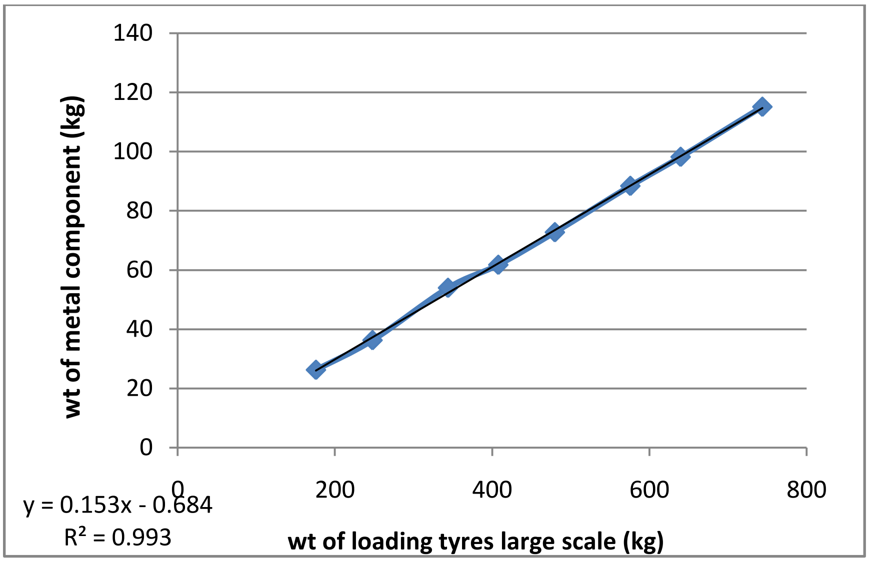

Fig 4.2: Plot of metal components against quantity of tyres incinerated

The plot above presents new equation for weight of tyres used against quantity of metal component for industrial scale operation as;

y=0.153x-0.684………………………………….. (4.2). Having an $R^2 = 0.993$

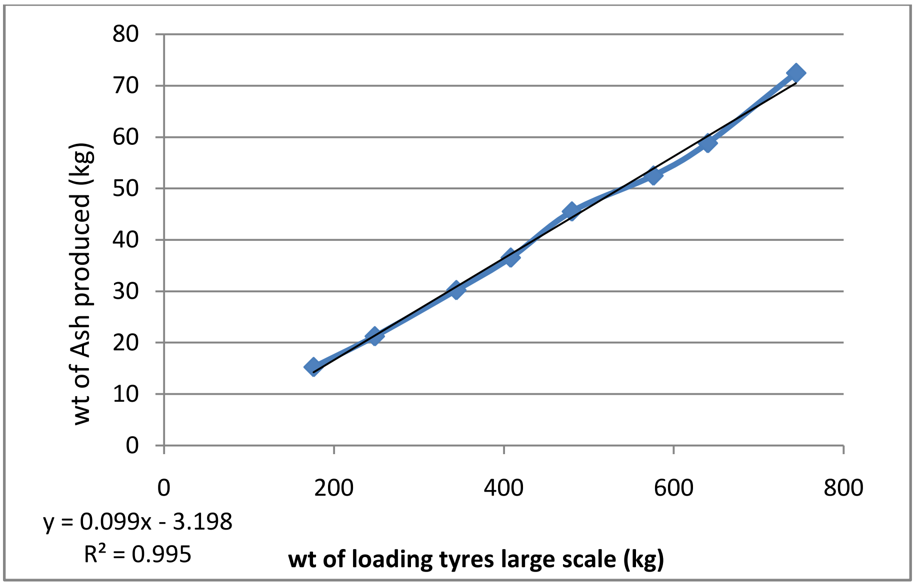

Fig 4.3: Plot of Ash batch produced against quantity of tyres incinerated

New equation derived for quantity of waste tyres used against quantity of ash produced.

$y = 0.099x - 3.198$ ……………………………… (4.3). $R^2 = 0.995$

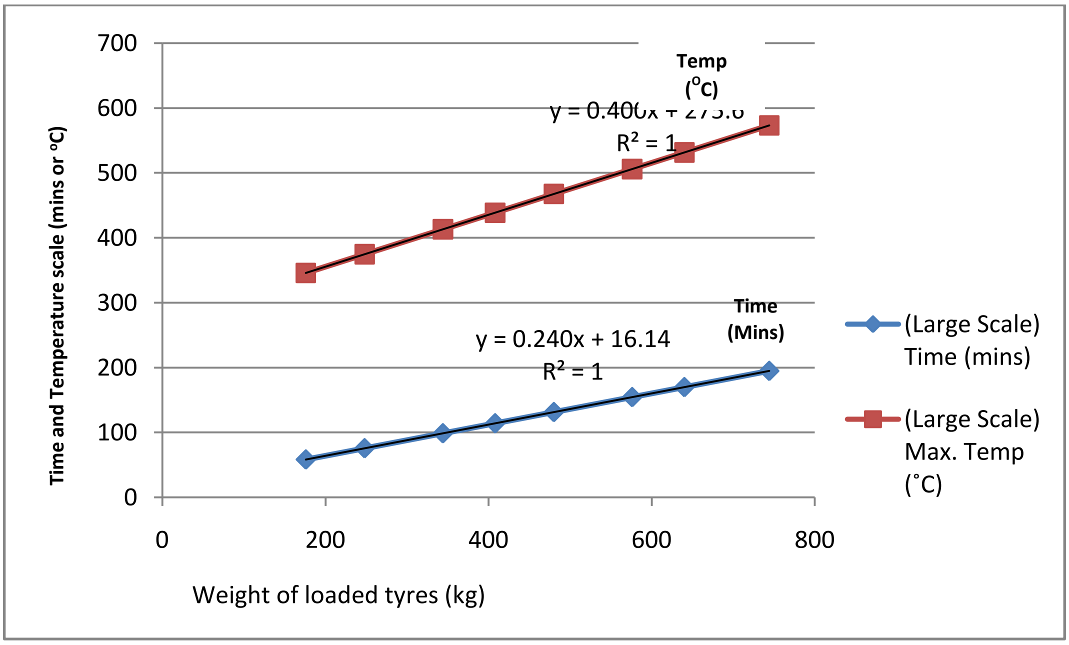

Fig 4.2: Plot of weight of loaded tyres against (Time and Temperature) scales

4.2 Capacity of the Carbon Recovery Industrial Plant

Based on the results obtained from the bench scale Carbon Black recovery experiment, we can derive that in three (3) hours approximately 740 kilogram of waste tyres incinerated in the combustion plant will produce 30 kilograms of Carbon Black. Therefore it will be safe to set the daily capacity of the industrial carbon black recovery plant at 6,000 kilogram of incinerated waste tyres to produce 240 kilogram of Carbon black.

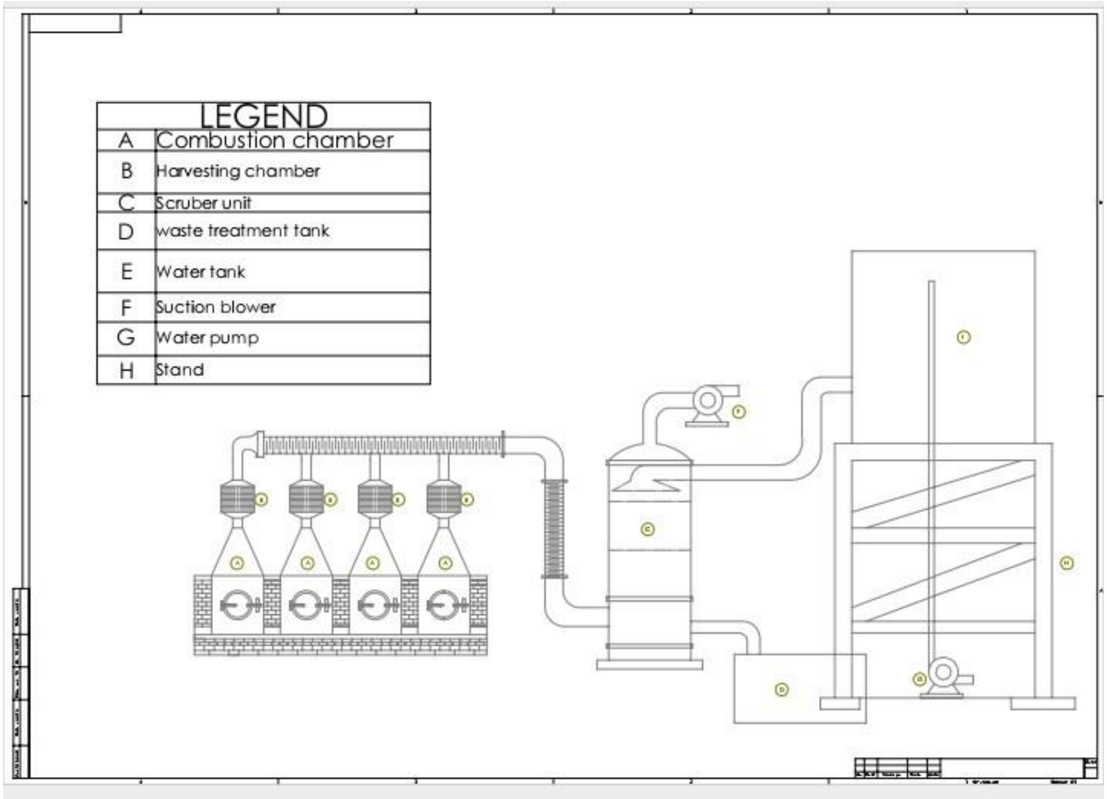

Fig 4.5: Solid Work of the Industrial Carbon-Black Plant

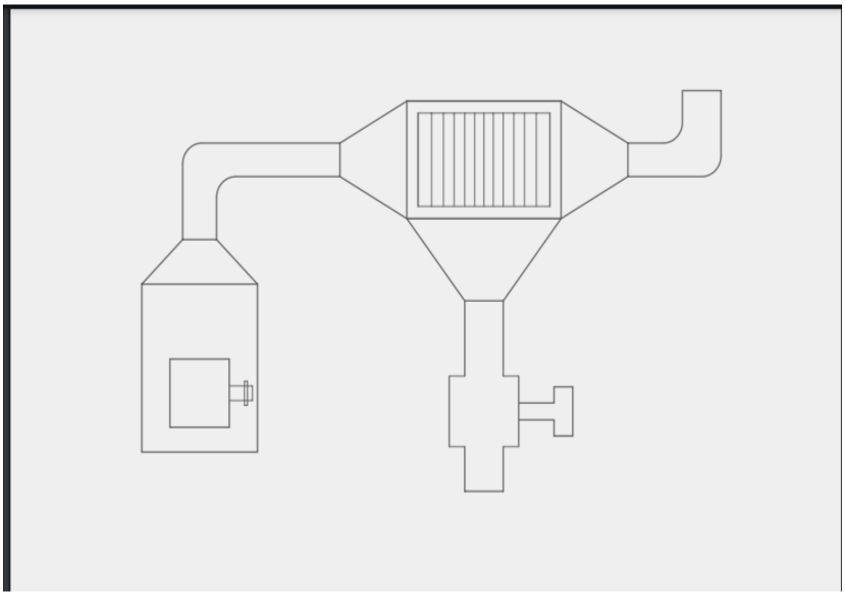

Fig 4.6: Single Combustion Chamber

Fig 4.7: Snapshot of Carbon Black Recovery Pilot Plant (Research work, 2024)

Fig 4.8: Snapshot of Carbon Black Recovered Carbon-black samples (Research work, 2024)

5.0 Conclusion

Deduction from the results obtained for large-scale design of combustion plant and products gained, gave the following:

- Higher amount of carbon black was recovered from the industrial scale combustion of waste tyres with daily capacity of 6,000kg waste tyres to produce 640 kg Carbon black
- The linear extrapolation helped to predict the large scale weight of tyres required for industrial operations under similar conditions with bench-scale experiments.
- The industrial design developed worked appreciably for the large scale production of carbon-black, metal components and ash-batch.
- We were able to obtain appreciable amount of ash batch, and metal components with the content of the former being an important material in road construction (Mohammed, 2019).

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