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Identification, Separation, and Characterization of Unburnt Carbon from Coal-Fired Power Plant Ash for Sustainable Resource Recovery

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Abstract

The increasing generation of coal combustion ash from thermal power plants presents significant challenges in waste management and resource utilization, particularly due to the presence of residual unburnt carbon. This study focuses on the identification, characterization, and efficient separation of carbon from power plant ash to improve ash quality and promote sustainable resource recovery. A systematic investigation was conducted to evaluate suitable analytical and separation techniques for the recovery of carbonaceous material from the ash matrix. Energy Dispersive Spectroscopy (EDS) and Thermogravimetric Analysis (TGA) were identified as effective techniques for detecting and quantifying the presence of unburnt carbon. Based on a comparative assessment of separation methods, dry cyclone separation and electrostatic separation demonstrated promising performance for the concentration and recovery of carbon-rich fractions. In addition, Computational Fluid Dynamics (CFD) analysis of a conventional cyclone separator was performed to investigate the flow characteristics and validate its separation efficiency. The study further examined the composition and forms of carbon present in carbon-rich ash and assessed the potential benefits of improved ash management strategies. The findings indicate that the integrated application of analytical characterization, dry separation techniques, electrostatic separation, and CFD-based process evaluation can provide a practical and scalable approach for carbon recovery from power plant

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ash. The proposed methodology can enhance the utilization potential of low-carbon ash in sectors such as construction and agriculture while enabling the recovery of carbonaceous material for potential industrial applications. The study therefore contributes to sustainable ash management, waste minimization, resource recovery, and improved economic value generation in coal-based power plant operations.

1. Introduction

Coal-fired thermal power plants generate substantial quantities of ash as a by-product of coal combustion. This ash is a complex heterogeneous material containing various inorganic constituents and residual unburnt carbon. The presence of carbon in ash can significantly influence its physicochemical properties and may limit its suitability for several value-added applications. Consequently, the effective identification and separation of carbon from power plant ash represent important challenges from both environmental and industrial perspectives. Carbon recovered from power plant ash has considerable potential as a secondary raw material for diverse industrial applications. Its effective separation can improve the quality and utilization potential of the remaining ash, thereby supporting its use in sectors such as construction, agriculture, and other material-based industries. At the same time, the recovery of carbon contributes to the conversion of an industrial waste stream into potentially valuable resources, thereby promoting the principles of resource recovery and a circular economy. The disposal and storage of coal ash also pose significant environmental concerns, including land consumption, particulate emissions, and the potential leaching of contaminants into soil and water. Effective separation of carbon prior to the utilization or final disposal of ash can improve ash management practices and reduce the environmental burden associated with coal combustion residues. Furthermore, the recovered carbon may be evaluated for potential use in other industrial processes, thereby enhancing the overall economic value of the waste stream. Therefore, the identification and separation of carbon from power plant ash represent a multifaceted approach that integrates waste minimization, resource recovery, environmental protection, and industrial sustainability. The development of an efficient and scalable separation methodology can contribute to improved ash utilization, reduced disposal requirements, and the creation of additional economic opportunities for coal-based power generation industries.

1.1 Aims and objectives: The main aim and objectives of identifying and separating unburnt carbon from ash extracted from a power plant are as follows:

a) Optimizing Combustion Efficiency: By identifying and separating unburnt carbon, power plants can optimize combustion processes to improve overall efficiency as non-combusted carbon in fly ash indicates wasted fuel. This contributes to better energy generation and resource utilization. b) Reducing Environmental Impact: Separating unburnt carbon helps in minimizing the environmental impact associated with ash disposal. Unburnt carbon particles can contribute to air pollution when released with the ash. Separation can minimize these emissions, improve air quality and reduce adverse health impacts. Fly ash might contain soluble salts that can harm plants if not managed properly. c) Improving Ash Utilization: Ash with reduced carbon content may be more suitable for certain applications, such as in construction materials. Separating unburnt carbon ensures that the remaining ash can be utilized in a manner that meets quality standards and application requirements. d) Enhancing Quality Control: The separation of unburnt carbon contributes to maintaining the quality of ash, ensuring it aligns with specified standards. This is particularly important for applications like cement production, where ash quality is a critical factor. e) Facilitating Research and Development: Analysis of unburnt carbon content provides valuable data for research and development purposes. Understanding the combustion characteristics helps in refining technologies and implementing improvements in power generation processes. f) Minimizing Capital Costs: This focuses on acquiring low-cost equipment and leveraging existing infrastructure whenever possible. It involves investigating the potential for repurposing or modifying readily available equipment within the plant to fulfil the separation function, potentially reducing the need for additional capital investment. g) Enhancing Plant Operation and Maintenance: Identifying unburnt carbon provides insights into the combustion conditions and overall plant performance. This information is valuable for maintenance planning and optimizing operational parameters for long-term efficiency.

2. Literature Review

Coal-fired thermal power plants remain one of the major sources of global electricity generation and produce large quantities of fly ash as a by-product of coal combustion [1]. Fly ash mainly contains silica, alumina, iron oxides, calcium compounds, and varying amounts of unburnt carbon [2]. The presence of unburnt carbon adversely affects the physical and chemical properties of fly ash, thereby limiting its use in high-value applications such as cement, concrete, ceramics, and geopolymers. Consequently, considerable research has been directed toward the identification, characterization, and separation of unburnt carbon from power plant ash in order to improve ash quality, enhance resource recovery, and reduce environmental impacts [3]. The amount of unburnt carbon in fly ash depends on several fuel-related and operational parameters [4]. Coal properties such as volatile matter, ash content, particle size, and calorific value significantly influence combustion efficiency [4]. Likewise, combustion conditions including furnace temperature, excess air, oxygen concentration, residence time, and burner configuration determine the extent of complete combustion [4,5]. Modern combustion systems such as fluidized bed combustors generally produce fly ash with lower residual carbon than conventional pulverized coal-fired boilers [5]. A clear understanding of these factors is essential for reducing carbon losses and improving the quality of fly ash generated in thermal power plants [4,5]. Accurate identification of carbon is the first step toward developing an efficient separation process [6]. Various analytical techniques have been employed for the qualitative and quantitative characterization of unburnt carbon in fly ash [6,7]. Thermogravimetric Analysis (TGA) is one of the most widely used techniques for determining carbon content [7]. It measures the weight loss of an ash sample as temperature increases under controlled atmospheric conditions. The oxidation of unburnt carbon within a specific temperature range provides a reliable estimate of carbon concentration [7]. Differential Scanning Calorimetry (DSC) is often used along with TGA to study the heat released during carbon oxidation and to improve the interpretation of thermal behaviour.

Scanning Electron Microscopy (SEM) has been extensively used to examine the morphology and surface characteristics of fly ash particles [8]. SEM images reveal porous and irregular carbon particles dispersed among spherical mineral particles [8]. When combined with Energy Dispersive Spectroscopy (EDS), SEM provides useful information on the elemental composition of individual particles. However, SEM mainly provides morphological information and requires considerable expertise for accurate interpretation. Energy Dispersive Spectroscopy (EDS) has emerged as one of the most practical techniques for elemental analysis of fly ash [9]. Based on characteristic X-ray emission from the sample, EDS rapidly identifies major elements such as carbon, oxygen, silicon, aluminium, iron, magnesium, potassium, and titanium. The technique provides qualitative and semi-quantitative information on carbon distribution and is particularly suitable for laboratory-scale investigations because of its simplicity, speed, and relatively low operating cost. X-ray Diffraction (XRD) has also been used for the mineralogical characterization of fly ash [10]. Although XRD accurately identifies crystalline phases present in ash, its sensitivity to amorphous or poorly crystalline carbon is limited [10]. Therefore, XRD is generally used as a complementary technique rather than a primary method for carbon identification. Comparative studies have shown that TGA and EDS provide a more practical and economical approach for identifying unburnt carbon than SEM and XRD. Several physical and physico-chemical separation techniques have been developed to recover unburnt carbon from fly ash [11]. The selection of a suitable method depends on particle size distribution, density difference, electrical conductivity, surface properties, moisture content, and the desired product purity [12]. Froth flotation is considered one of the most efficient techniques for carbon recovery. It exploits the hydrophobic nature of carbon particles by using collectors and frothing agents, allowing carbon to attach to air bubbles while hydrophilic ash particles remain suspended in water. Although the process offers excellent separation efficiency and high-purity carbon, it requires significant quantities of water and chemical reagents, which increases operational costs and environmental concerns. Magnetic separation has also been investigated for carbon recovery [13]. This method uses magnetic fields to separate magnetic constituents from fly ash. However, since elemental carbon exhibits very weak magnetic properties, magnetic separation alone provides limited efficiency and is generally used in combination with other techniques. Electrostatic separation has received considerable attention because it exploits differences in electrical conductivity and triboelectric charging behaviour of ash particles. Carbon particles generally acquire different charges from mineral ash, enabling their effective separation in a high-voltage electric field. The process is completely dry, environmentally friendly, and capable of producing relatively high-purity carbon at lower operating costs than froth flotation. In addition, electrostatic separation can be integrated with air classification or cyclone separation to improve recovery efficiency [15].

Dry cyclone separation is another promising mechanical technique widely studied for preliminary carbon recovery. The separator uses centrifugal forces generated by tangential airflow to separate lighter carbon particles from denser mineral ash. Although cyclone separators may not achieve the very high purity obtained through flotation, they are simple, economical, require minimal maintenance, and operate without water, making them suitable for large-scale industrial implementation [15]. Recent research has increasingly incorporated

Computational Fluid Dynamics (CFD) to understand particle motion and optimize separator performance. CFD simulations using ANSYS Fluent and Discrete Phase Modeling (DPM) enable visualization of gas flow patterns, particle trajectories, pressure distribution, and separation efficiency within cyclone separators. These numerical studies facilitate the optimization of cyclone geometry and operating conditions while reducing the need for expensive experimental trials. CFD has therefore become an effective design tool for improving carbon recovery efficiency and minimizing operational costs. Although numerous studies have investigated identification and separation methods individually, comparatively fewer studies integrate carbon characterization, selection of suitable analytical techniques, evaluation of multiple dry separation methods, and CFD validation within a single framework. In addition, industrial implementation requires economical, water-free, and scalable separation processes capable of producing high-quality fly ash while recovering carbon efficiently. Therefore, there is a need to develop an integrated methodology combining reliable identification techniques such as EDS and TGA with cost-effective separation methods such as dry cyclone and electrostatic separation. The literature indicates that recovery of unburnt carbon from power plant ash is essential for improving ash utilization, reducing environmental impacts, and enhancing economic value [11]. Among the available characterization techniques, Energy Dispersive Spectroscopy (EDS) and Thermogravimetric Analysis (TGA) provide reliable and practical identification of carbon [7,9]. Among separation technologies, dry cyclone separation and electrostatic separation offer environmentally friendly, economical, and scalable alternatives to conventional wet processes [15]. Furthermore, CFD-based analysis has proven to be a valuable tool for optimizing separator performance before industrial implementation [16]. These findings provide the technical basis for the present study, which focuses on the identification, separation, and recovery of carbon from power plant ash using integrated analytical, experimental, and computational approaches.

3. Materials and Methods

3.1 Methods of UC Determination: Several methods have been used to determine UC content in ash, including loss on ignition (LOI), X-ray diffraction (XRD), and scanning electron microscopy (SEM). LOI is a commonly used method that involves heating the ash to a high temperature and measuring the weight loss due to the combustion of UC. XRD can be used to identify the mineral phases present in the ash, which can provide information on the UC content. SEM can be used to visualize the UC particles in the ash and provide information on their size and morphology.

3.2 UC Separation Techniques: Several techniques have been developed to separate UC from ash, including froth flotation, gravity separation, and magnetic separation. Froth flotation is a commonly used technique that involves the use of surfactants to selectively separate UC from the ash. Gravity separation involves the use of differences in density to separate UC from the ash. Magnetic separation involves the use of magnetic properties to separate UC from the ash.

3.3 Different Approaches in Studying UC:

Different approaches have been used to study UC, including experimental studies, mathematical modeling, and statistical analysis. Experimental studies involve the use of laboratory-scale equipment to investigate the factors that affect UC content and the effectiveness of UC separation techniques. Mathematical modeling involves the development of models to predict UC content and the effectiveness of UC separation techniques. Statistical analysis involves the use of statistical methods to analyze large datasets and identify correlations between UC content and other variables. Overall, UC content in ash is a major concern in the combustion of coal and other solid fuels. Several factors can affect UC content in ash, and several methods have been developed to determine UC content and separate UC from ash. Different approaches have been used to study UC, and a combination of experimental studies, mathematical modeling, and statistical analysis can provide a comprehensive understanding of UC in ash.

3.4 Methodology:

3.4.1 Sampling and Collection:

The first step is often the collection of fly ash samples from the coal fired thermal power plant. This involves obtaining representative samples of the ash generated during combustion.

3.4.2 Characterization and Analysis:

Identification usually begins with the characterization of the ash. This involves analyzing the composition, particle size distribution, and other relevant properties of the ash. Various analytical techniques are to be used to identify the components present in the ash.

3.4.3 Identification of Carbon Content:

Once the ash is characterized, specific methods are employed to identify the carbon content. Techniques like energy dispersive spectroscopy (EDS) or elemental analysis can be used to quantify the amount of carbon present on a microscopic level.

3.4.4 Separation Techniques:

After identifying the carbon content, the next step is the actual separation of carbon from the ash. This can be achieved through various separation techniques, such as froth flotation, gravity separation, electrostatic separation, or chemical treatments. The choice of method depends on the properties of the ash and the specific requirements of the project.

3.4.5 Post-Separation Analysis:

Following the separation process, it's common to conduct additional analyses to verify the effectiveness of the separation (efficiency) and to ensure that the separated carbon meets the desired specifications.

3.4.6 Final Product Handling:

The separated carbon, once obtained, may be processed further or used for specific applications. The remaining ash may also undergo additional treatments or be disposed of in an environmentally friendly manner.

4 Experimental Approach:

4.1 Thermogravimetric Analysis (TGA) for Fly Ash Characterization

This section outlines the key steps involved in Thermogravimetric Analysis (TGA) for the characterization of carbon content in ash samples

a. Sample Preparation:

Sample Acquisition: Collect a representative fly ash sample following established protocols to ensure its homogeneity and representativeness of the bulk material.
Sample Drying: Pre-dry the fly ash sample at a low temperature (typically below 110°C) under controlled conditions to remove any surface moisture that might interfere with the subsequent analysis.
Sample Grinding and Sieving: To ensure uniform particle size and improve measurement accuracy, grind the dried sample using a suitable mortar and pestle or grinder. Subsequently, sieve the ground sample to obtain a specific particle size fraction appropriate for the TGA instrument.

Instrument Setup and Calibration:

Instrument Preparation: Set up the TGA instrument according to the manufacturer's instructions, ensuring proper functionality and cleanliness of the sample crucible and weighing system.
Calibration: Perform regular calibration of the TGA instrument using reference materials with well-defined weight and thermal properties to ensure accurate mass measurements throughout the analysis.[15]

5. Sample Loading and Experimental Setup:

5.1 Sample Weighing: Accurately weigh a known amount of the prepared fly ash sample and carefully transfer it into the pre-cleaned TGA crucible.

5.2 Experimental Parameters: Define the desired experimental parameters for the TGA analysis, including:

Heating rate: The rate at which the temperature increases within the furnace.

Temperature range: The minimum and maximum temperatures encompassing the region of interest for the analysis (e.g., typically room temperature to 900°C for fly ash).

Atmosphere: The gas environment surrounding the sample during the analysis (e.g., inert gas like nitrogen, air, or oxidizing atmosphere).

6. TGA Analysis and Data Acquisition:

6.1 Experiment Initiation: Start the TGA experiment according to the defined program, allowing the instrument to automatically control the heating profile and continuously record the sample's weight change as a function of temperature.

6.2 Data Acquisition: The TGA instrument continuously monitors and records the sample's weight throughout the experiment, generating a thermogram depicting the change in mass (weight loss) as a function of temperature.

7. Data Analysis and Interpretation:

7.1 Qualitative Analysis: Analyze the obtained thermogram to identify critical features such as: On-set and end-set temperatures of significant weight loss events and the overall weight loss percentage across the defined temperature range.

7.2 Quantitative Analysis: If applicable, utilize established relationships or reference materials to correlate the observed weight loss events with specific components decomposing within the fly ash sample during the analysis (e.g., moisture loss, volatile organic compound (VOC) release, unburnt carbon combustion).

8. Reporting:

8.1 Summarize the methodology: Briefly describe the sample preparation, instrument settings, and analysis parameters employed in the TGA experiment.

8.2 Present the results: Include the obtained thermogram and any relevant quantitative data (e.g., total weight loss, estimated component contributions).

8.3 Discuss the findings: Interpret the observed weight loss events in the context of fly ash composition and potential implications for its properties or applications.

9 Energy-dispersive x-ray spectroscopy (eds) analysis for carbon in ash samples

This section outlines the key steps involved in utilizing Energy-Dispersive X-ray Spectroscopy (EDS) for the characterization of carbon content in ash samples:

a. Sample Preparation:

Sample Acquisition: Collect a representative ash sample following established protocols to ensure its homogeneity and integrity.

Sample Preparation: To minimize the influence of surface roughness on the experimental results, polishing is essential for the specimens. This preparatory step closely resembles the procedures employed for reflected light microscopy. However, a crucial distinction lies in the materials utilized. For this specific analysis, only vacuum-compatible materials are permissible to ensure compatibility within the analysis environment.

b. Instrument Setup: Instrument Calibration: Perform regular calibration of the EDS instrument using appropriate standards to ensure accurate elemental quantification. **Analysis Condition Optimization:** Establish appropriate operating parameters for the EDS analysis, such as accelerating voltage, beam current, and acquisition time, based on the expected sample composition and desired detection limits.

c. Sample Loading and Initial Analysis:

Sample Positioning: Mount the prepared ash sample onto the dedicated sample stage within the EDS instrument, ensuring proper alignment and electrical grounding.

Initial Elemental Scan: Conduct a preliminary elemental analysis to identify the major elements present in the sample.

Carbon Detection: Analyze the initial X-ray spectrum to identify the presence of carbon peaks based on their characteristic energy levels.

Carbon-Specific Analysis:

Setting Adjustment: Refine the EDS analysis conditions to optimize the detection and quantification of carbon. This might involve adjusting the acquisition time, focusing the beam on regions suspected to contain carbon, or employing specific filter settings.

Spectral Acquisition: Collect high-resolution X-ray spectra with a focus on the energy range corresponding to carbon (approximately 0.2 - 0.3 keV).

Spectral Analysis and Interpretation:

Peak Identification: Analyze the acquired spectra to identify and confirm the presence of characteristic carbon peaks based on their specific energy positions in the spectrum.

Background Corrections: Account for and remove any background noise or interferences from other elements that might overlap with the carbon peaks.

Quantitative Analysis:

- **Calibration Standards:** Use well-characterized reference materials with known carbon content to establish the relationship between peak intensity and carbon concentration.
- **Quantification:** Employ the established calibration curve to quantify the carbon content in the ash sample based on the intensity of its corresponding peak(s) in the collected spectrum.

Data Interpretation and Reporting:

- **Data Review:** Analyze and interpret the obtained results considering the overall elemental composition of the ash, potential limitations of the technique, and any uncertainties associated with the measurements.
- **Report Generation:** Prepare a comprehensive report summarizing the results, and interpretation of the EDS analysis, including the identified elements and the quantified carbon content in the ash sample [22].

10 Carbon Separation Methods

Separating carbon from fly ash is an effective method for enhancing the efficiency of utilizing waste fly ash and maximizing the associated economic and environmental advantages.

Types of Separation Methods

Several methods are employed for the separation of unburnt carbon from ash in power plants:

10.1 Froth Flotation:

Principle: Relies on differences in the wettability of particles. Air bubbles are introduced, and hydrophobic particles attach to the bubbles, forming a froth on the water's surface. **Application**: Effective for separating carbon from ash based on differences in hydrophobicity, with carbon particles adhering to the air bubbles. Froth flotation is a widely used separation process that exploits the differences in the surface properties of particles to achieve selective separation. The process involves the introduction of air bubbles into a slurry containing finely ground particles. The particles to be separated, in this case, unburnt carbon and ash, interact with the introduced air bubbles based on their hydrophobic or hydrophilic nature.

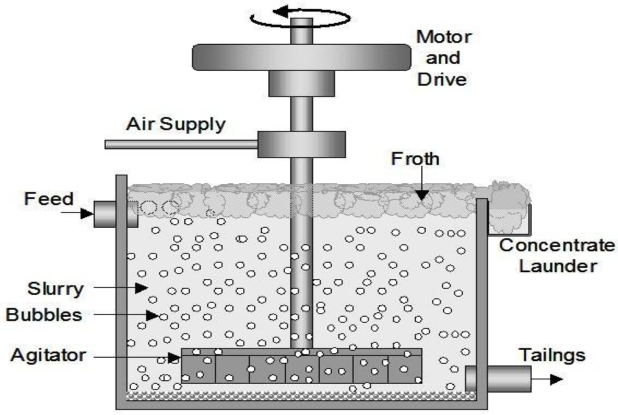

Fig. 1. Froth flotation

In this process, finely ground fly ash is suspended in water, forming a slurry. To initiate separation, collectors are introduced, which selectively coat the carbon particles, rendering them hydrophobic. Air bubbles are then injected into the slurry, and the hydrophobic carbon particles selectively adhere to the air bubbles, creating a froth at the liquid surface. The froth, enriched with hydrophobic carbon, can be physically separated from the rest of the slurry. This separation is particularly effective due to the intrinsic hydrophobic nature of carbon, in contrast to the hydrophilic nature of ash particles. The froth containing the attached carbon is collected and further processed, resulting in a concentrated carbon fraction. This method is advantageous for power plants seeking to recover unburnt carbon from fly ash for reuse or resource recovery. Froth flotation's versatility, efficiency, and selectivity in separating particles based on their surface properties make it a valuable technique in the context of managing and utilizing fly ash in an environmentally friendly and economically viable manner [17].

10.2 Magnetic Separation:

Principle: Utilizes a neodymium magnet to perform magnetic separation in a dry state, without the need for a liquid medium. **Application**: Efficient for magnetic separation of carbon from ash in a dry environment. Magnetic separation is a widely employed technique for separating materials based on their magnetic properties. In the context of separating unburnt carbon from ash in power plants, this method is particularly effective due to the distinct magnetic characteristics of carbon and other ash components. The process involves the use of a magnetic separator, typically equipped with a strong neodymium magnet.

10.3 Electrostatic Separation:

Principle: Exploits the differences in electrical conductivity or charge of particles. Charged particles are attracted or repelled by an electric field, leading to their separation. **Application**: Useful for separating carbon from ash by taking advantage of differences in the electrical properties of the components. Electrostatic separation is a separation technique that exploits the differences in the electrical charges of particles to achieve effective isolation. In the context of separating carbon from ash in power plants, this method proves valuable due to the contrasting electrical properties of carbon and ash components. The process involves introducing the ash mixture into an electrostatic separator, where the particles are subjected to an electric field.

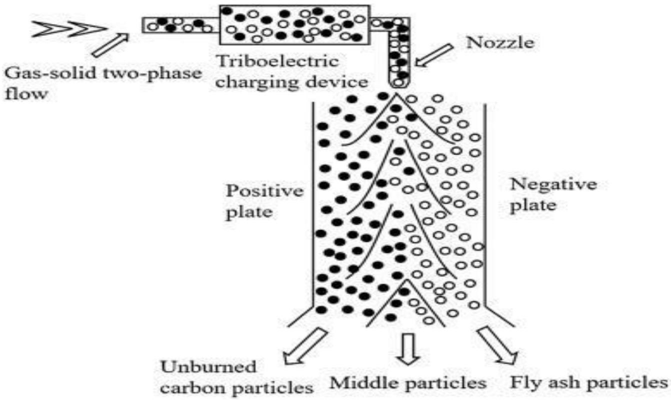

Fig. 2. Electrostatic Separation

During electrostatic separation, particles become charged either positively or negatively based on their electron affinity. The charged particles experience attraction or repulsion forces, depending on their charge polarity. In the case of unburnt carbon and ash, which may have different affinities for gaining or losing electrons, the electrostatic forces induce separation. Particles with opposite charges are attracted to each other, leading to their separation from the mixture [19]. Electrostatic separation and magnetic separation are complementary techniques employed for the separation of carbon from ash in power plants, each capitalizing on distinct physical properties for effective isolation. Combining these techniques allows for a comprehensive approach to separation, addressing both electrical and magnetic characteristics of the particles [20].

10.4 Dry Cyclone Separation Method:

Principle: Dry cyclone separation is a mechanical technique employed to separate unburnt carbon particles from fly ash generated in power plants. It utilizes centrifugal forces to achieve separation based on the differences in density between unburnt carbon and fly ash particles. **Application**: Dry cyclone separation is primarily used in power plants as a preliminary separation stage to remove a portion of the unburnt carbon from fly ash. This improves the quality of fly ash for further processing or utilization in applications like construction materials. The process involves introducing the fly ash mixture into a cylindrical chamber with a tangential inlet. This creates a cyclonic flow, forcing the heavier fly ash particles outwards due to their greater inertia. These particles then spiral downwards and exit through the bottom outlet of the cyclone. Conversely, the lighter unburnt carbon particles, having lower inertia, remain suspended in the inner core of the swirling air flow and exit through the upper outlet. The effectiveness of dry cyclone separation depends on several factors, including:
Particle size distribution: Smaller unburnt carbon particles are more challenging to separate efficiently. **Density difference:** A larger difference in density between unburnt carbon and fly ash components improves separation efficiency. **Airflow rate:** Controlling the airflow rate is crucial for maintaining the desired separation performance. While dry cyclone separation offers a simple and cost-effective approach for unburnt carbon removal, it typically achieves

moderate separation efficiency. For more demanding applications requiring higher purity, other techniques like triboelectric separation or density-based methods may be necessary [21].

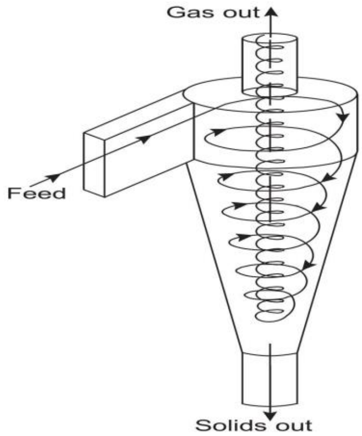

Fig. 3. Cyclone Separation process

11 Discrete Phase Modeling (DPM):

Discrete Phase Modeling (DPM) is a computational technique used to simulate the separation of unburnt carbon particles from fly ash in power plants. CFD software treats the gas flow (carrier for fly ash) as a continuous phase (Eulerian framework) and the unburnt carbon particles as a discrete phase (Lagrangian framework). Each particle is tracked individually, considering its properties like size, density, and shape. **Simulating Separation:** The model accounts for the following factors that influence separation:

- **Drag Force**: The resistance experienced by the particle due to the gas flow.
- **Buoyancy**: The upward force due to the density difference between the particle and gas.
- **Particle-Particle Interactions**: Collisions between particles can affect their trajectories.

DPM offers several advantages over traditional design methods:

- **Optimization**: It allows simulating various separation device configurations (e.g., cyclone separators) and operating conditions (gas flow rate) to optimize separation efficiency.
- **Understanding Particle Behavior**: The model helps visualize the movement of particles within the separator, providing insights into factors limiting separation performance.
- **Reduced Costs**: By optimizing designs virtually, DPM can reduce the need for physical prototypes and pilot testing, leading to cost savings.
- **Improved Efficiency**: An optimized separation process translates to cleaner fly ash with reduced unburnt carbon content. This can have environmental benefits by minimizing the amount of unburnt carbon landfilled and potentially even enabling its reuse as a fuel source.

Pre-processing: Desiccation: To prevent complications arising from electrical conductivity and potential arcing within the separator, the fly ash must be completely dry, **Electrostatic separation process: Feed System:** A controlled feeding system is necessary to introduce the dry fly ash into the electrostatic separator. This system could involve either a screw feeder for

a continuous process or a pneumatic conveying system utilizing compressed air for a batch process. **Charging:** As the fly ash particles traverse a high-voltage charging zone, they acquire an electrical charge. This zone can employ various techniques, due to its ease of employment. including corona chargers.
Tribochargers: In this method, the fly ash particles collide with a grounded surface, acquiring a charge through frictional contact and the triboelectric effect.
Separation: The charged particles then enter a separation zone permeated by an electric field. Due to the disparity in electrical properties, the unburned carbon particles (generally exhibiting higher conductivity) will experience a stronger force towards the collection electrode with the opposing polarity. The fly ash particles, with lower conductivity, will be collected on a different electrode or remain entrained in the gas stream.[24]
Cleaning: The collected fractions (unburned carbon and fly ash) necessitate periodic removal from the electrodes for further processing or utilization.

12 Experimental Analysis

TGA Testing: Sample: Fly Ash (Paras Power Plant), sample Type: Solid Sample Result Table:

Table 1. TGA Results

SN	Parameters	Result	Unit
1	pH 5% solution	8.68	-
2	LOD	0.046	%
3	Volatile Carbon	0.474	%
4	Fixed Carbon	0.09	%

Interpretation of Results: Based on the table showing the results of the experiment, it could be interpreted as follows: The pH of the 5% solution is 8.68, which is slightly alkaline. The loss on drying (LOD) is 0.046%, which is a very small amount of mass loss. This suggests that the sample is very dry or has very low moisture content. The volatile carbon content is 0.474%. Volatile carbon is the portion of the material that vaporizes without combustion when heated in an inert atmosphere. This value is relatively low, indicating that the sample does not contain a high number of volatile components.

Limitations:

1. **Sampling:** The sample size may not be large enough to be representative of the entire population.
2. **Measurement:** The instrument used to make the measurements may not be properly calibrated.
3. **Human error:** The person conducting the experiment may make mistakes.

13 Conclusion

It is found that various methods exist for identifying and separating unburnt carbon from power plant fly ash, with some approaches showing greater promise in terms of feasibility and potential benefits. Energy-dispersive X-ray spectroscopy (EDS) stands out as a reliable method for identification, high accuracy, and widespread availability. This makes EDS a viable and easily accessible option for quantifying unburnt carbon content in fly ash. On the other hand, electrostatic separators offer a promising avenue for separation. These separators utilize electrostatic forces to efficiently separate particles, making them well-suited for managing large-scale volumes of fly ash. Noteworthy technologies such as STET's triboelectric separator, although still in development, exhibit significant potential in this area. Continual advancements aim to enhance the efficiency and feasibility of both identification and separation techniques. MECONTROL UBC's in-situ microwave analysis simplifies the identification process, while ongoing exploration into alternative separation methods, like triboelectric separators and size-selective techniques, seeks to address specific challenges and improve overall effectiveness. By focusing on the advancement of established methods like EDS and electrostatic separators, alongside the development and refinement of promising technologies such as MECONTROL UBC and alternative separation techniques, researchers and developers can work towards an efficient, cost-effective, and scalable solution for identifying and separating unburnt carbon from fly ash. This endeavor will significantly contribute to cleaner power generation and pave the way for a more sustainable future.

13.1 Key areas for improvement in identifying and measuring carbon from ash

- **Large-scale deployment and data collection:** Implementing MECONTROL UBC in a wider range of power plants and collecting comprehensive data on its performance under various operating conditions would be crucial. This data can be used to validate its accuracy, identify potential limitations, and inform further improvement.
- **Advanced data analysis and filtering techniques:** Developing and employing sophisticated data analysis and filtering algorithms could help mitigate the influence of interfering materials and improve the accuracy of carbon identification.
- **Cost optimization:** Exploring alternative materials, streamlining the manufacturing process, and potentially offering different service tiers with varying levels of complexity could help reduce the overall cost of the technology and make it more accessible to a wider range of power plants.

13.2 Key areas for improvement in separation of carbon from ash

- **Pre-processing:** Implementing pre-processing techniques like size reduction or selective feeding based on particle size fractions could improve separation efficiency for smaller particles.
- **Moisture control:** Investigating and potentially incorporating moisture control measures, such as drying or conditioning, could mitigate the negative effects of moisture on separation performance.
- **Advanced electrode materials:** Researching and developing advanced electrode materials with improved durability and resistance to wear and tear can extend their lifespan and reduce maintenance requirements.

- **Optimization of operating parameters:** Exploring and optimizing operational parameters, such as belt speed, electrode voltage, and feed rate, could potentially improve separation efficiency and energy consumption.
- **Integration with renewable energy sources:** Exploring the possibility of integrating the separator with renewable energy sources, like solar or wind power, could contribute to a more sustainable overall solution

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