



Effect of cyclone orientation on the collection efficiency of a hybrid cyclone for fly ash reduction in Kenyan sugar industries

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ABSTRACT

The sugar industry in Kenya continues to grapple with significant air pollution challenges due to the release of particulate fly ash from bagasse-fired boilers. Existing single-stage cyclone separators exhibit limited efficiency in capturing fine particles, prompting the need for improved dust collection technologies. This study investigates the impact of cyclone orientation—specifically series versus parallel configuration—on the collection efficiency of a hybrid cyclone system. Using a combination of Computational Fluid Dynamics (CFD) simulations and physical experiments, the study evaluates gas flow behavior, pressure differentials, and particulate capture performance under varying orientation setups. Results indicate that the series configuration significantly enhances particulate collection, achieving efficiency levels between 81.26% and 81.95%, compared to only 30.6% for the parallel setup. The superior performance of the series orientation is attributed to improved pressure gradients, stable vortex flow, and reduced thermal instability, which collectively enhance fine particle capture. The findings offer actionable insights into optimizing cyclone layout for sugar mill operations and contribute to the design of more effective air pollution control systems in biomass combustion environments.

Keywords: Cyclone, Emissions, Hybrid Cyclone, Orientation, Particulate Matter

I. INTRODUCTION

Air pollution has become a pressing environmental and public health issue, particularly in rapidly developing regions of the world such as Africa and Asia. Urbanization, industrialization, and increased energy consumption have significantly escalated emissions of pollutants in these regions (Lelieveld et al., 2015). Developing countries often experience weaker environmental regulations and enforcement, which exacerbates exposure to toxic air contaminants (Martin-Ortega & González-Sánchez, 2023). According to the World Health Organization (2021), approximately 4.2 million people die annually from outdoor air pollution, while 3.8 million deaths are linked to household air pollution from dirty fuels and smoke.

Air pollution is primarily caused by the release of particulate matter (PM), gases, and smoke into the atmosphere at levels that exceed safe air quality thresholds (Hu et al., 2022). Fine particles such as PM_{2.5} and fly ash are especially harmful due to their ability to penetrate deep into the lungs and bloodstream, leading to respiratory illnesses, cardiovascular disease, and even mental health deterioration (Chen et al., 2024; Liu et al., 2016; Kim et al., 2020). In South Africa, air pollution is attributed to more than 21,000 premature deaths annually, accounting for 7.4% of all deaths, with significant economic costs (Altieri & Keen, 2016). Mental health impacts have also been linked to high concentrations of PM in urban environments (Chen et al., 2024).

Industries are the largest contributors to greenhouse gas and particulate emissions globally, with manufacturing facilities, power generation, and agro-industrial processes playing dominant roles (Martin-Ortega & González-Sánchez, 2023). The sugar industry is particularly noteworthy in this context due to its extensive use of biomass fuels such as bagasse. Bagasse combustion in sugar mill boilers generates significant quantities of fly ash, which poses health and environmental risks if not adequately managed (Zhao & Zheng, 2019). Uncontrolled emissions can cause chronic illnesses such as asthma, COPD, and neurological damage (Liu et al., 2016).

To control emissions, many sugar mills use air pollution control devices (APCDs) such as cyclone separators, electrostatic precipitators (ESPs), scrubbers, and bag filters. Among these, cyclone separators are widely used as primary collectors due to their low cost, operational simplicity, and ability to handle large gas volumes (Kwiatkowski et al., 2021). Cyclones operate on the principle of centrifugal force, separating particles from flue gases in a spiral motion. However, traditional cyclones have limited efficiency when capturing fine particles like fly ash (Karagoz et al., 2013).

This shortfall has led to the development of hybrid cyclone systems that combine conventional cyclonic action with advanced collection technologies such as filtration or ESPs (Baharuddin et al., 2022). These systems enhance



overall efficiency and are increasingly used in sectors where fine particulate control is essential, including cement, food processing, tea production, and sugar manufacturing (Omondi et al., 2023). In Kenya, cyclone efficiency in sugar factories ranges from 60% to 80%, with improved designs achieving efficiencies of over 90% (Nyakundi, 2016).

Despite their widespread use, many cyclone systems in Kenyan sugar industries remain under-optimized. Field observations indicate heavy fly ash emissions, suggesting that current designs are inadequate or poorly maintained. Workers often experience direct exposure to ash-laden air, highlighting the urgent need to enhance particulate control systems (Meng et al., 2024). As noted by Sankar and Prasad (2015), performance modeling and simulation are essential tools in optimizing cyclone separator efficiency, particularly under varied operational conditions.

This study therefore investigates the performance of hybrid cyclone separators in sugar industries, with a specific focus on how cyclone orientation (e.g., series vs. parallel configurations) influences fly ash collection efficiency. Optimizing cyclone design and orientation is key to achieving compliance with environmental standards and protecting both worker health and community air quality.

II. METHODOLOGY

2.1 Materials

The following materials and software tools were used for simulation and design: **CFD Software:** Fully subscribed ANSYS package for Computational Fluid Dynamics (CFD) simulation. **CAD Software:** For digital modeling of hybrid cyclone geometry. **Hardware:** Laptop computer with 6 GB RAM and 128 GB ROM, suitable for mid-level simulation tasks

2.2 Methods

Problem Definition and Objective Setting: The research began with a clear definition of the problem: inefficient capture of fine fly ash particles by conventional cyclone separators in sugar industries. The specific objective was to determine how cyclone orientation (series vs. parallel) affects the collection efficiency of a hybrid cyclone system. This guided the modeling, simulation, and experimental phases of the study.

Design and Geometry Specification: A hybrid cyclone model was developed and geometrically defined in line with industrial application requirements. Key design features included variations in inlet diameters (150 mm, 200 mm, 250 mm) and structural orientation. A Computer-Aided Design (CAD) software was used to digitally create the model geometry for input into the CFD environment.

Mesh Generation: The model geometry was discretized into computational elements using meshing tools within ANSYS. Fine mesh refinement was applied in critical zones—particularly around the inlet, vortex finder, and dust outlet to improve accuracy in regions with high velocity and pressure gradients.

Boundary Conditions and Initial Setup: Boundary conditions were specified to reflect realistic operating scenarios. These included: Inlet: Specified mass flow rate or velocity, Outlet: Pressure outlet, Wall Conditions: No-slip conditions applied to all solid boundaries, Particles: Defined by size distribution and density representing fly ash characteristics, Initial conditions were set to ensure flow field stability before simulation.

Turbulence and Particle Tracking Models: Turbulence was modeled using both the k- ϵ and Reynolds Stress Model (RSM) due to the rotational and swirling flow inside the cyclone. For particle behavior, a Lagrangian approach was applied to track individual particle trajectories, enabling precise calculation of particle capture efficiency.

Simulation Setup and Execution: Simulations were configured for steady-state analysis using an implicit solver. Convergence criteria were carefully monitored for pressure, velocity, and turbulence quantities. Where needed, transient simulations were performed to capture time-dependent phenomena. Results such as pressure drop, velocity fields, and particle dispersion were extracted post-simulation.

Optimization and Sensitivity Analysis: A factorial design approach was used to test combinations of inlet size and orientation. Sensitivity analysis was conducted by varying one design parameter at a time while holding others constant. This identified the orientation that yielded the highest efficiency with optimal pressure drop.

Data Analysis and Reporting: Results from each simulation run were analyzed for: Collection Efficiency (%), Pressure Drop (Pa), Flow Uniformity, Velocity Streamlines and Vortex Structure. All findings were documented and compiled to draw performance comparisons between series and parallel configurations. Insights were used to develop a mathematical regression model for efficiency prediction

Design Variables and Operating Conditions: Key parameters tested included: Cyclone Orientation: Series vs. Parallel, Inlet Diameter: 150 mm, 200 mm, 250 mm, Operating Conditions: Flow rate, pressure drop, and velocity profiles, Cyclone Geometry: Based on standard 2D2D cyclone model proportions

2.3 Experimental Set Up

The hybrid set up was arranged as below.

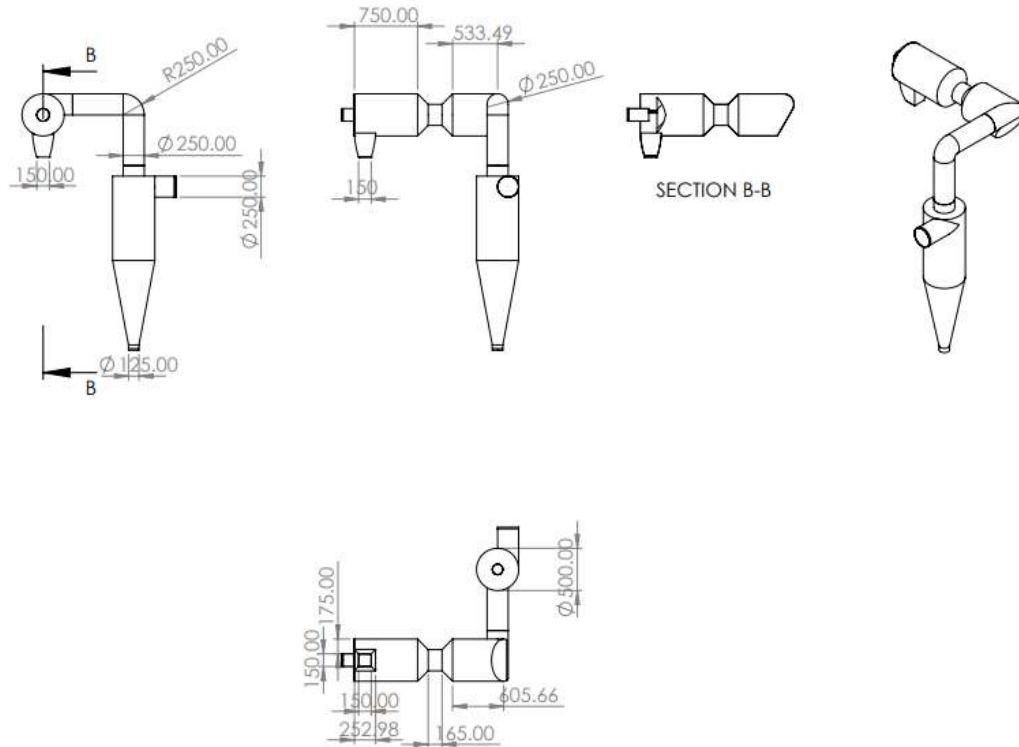


Figure 1
Experimental Set Up

The design was arranged as seen in Figure 1 above. The experiment was analyzed on CFD. The design parameters that were considered in the experiment were the flow rate, Pressure drop and the geometrical parameters. The parameters were considered under 2D2D model. Under geometrical parameters, diameter D, was varied from 150 to 200 to 250 and results obtained in order to study the most efficient.

III. FINDINGS & DISCUSSION

3.1 Findings

Considering the efficiency levels achieved on the series orientation, Analysis was done on the most efficient parameter of inlet diameter of 250mm on the parallel orientation. The result were as below
Temperature

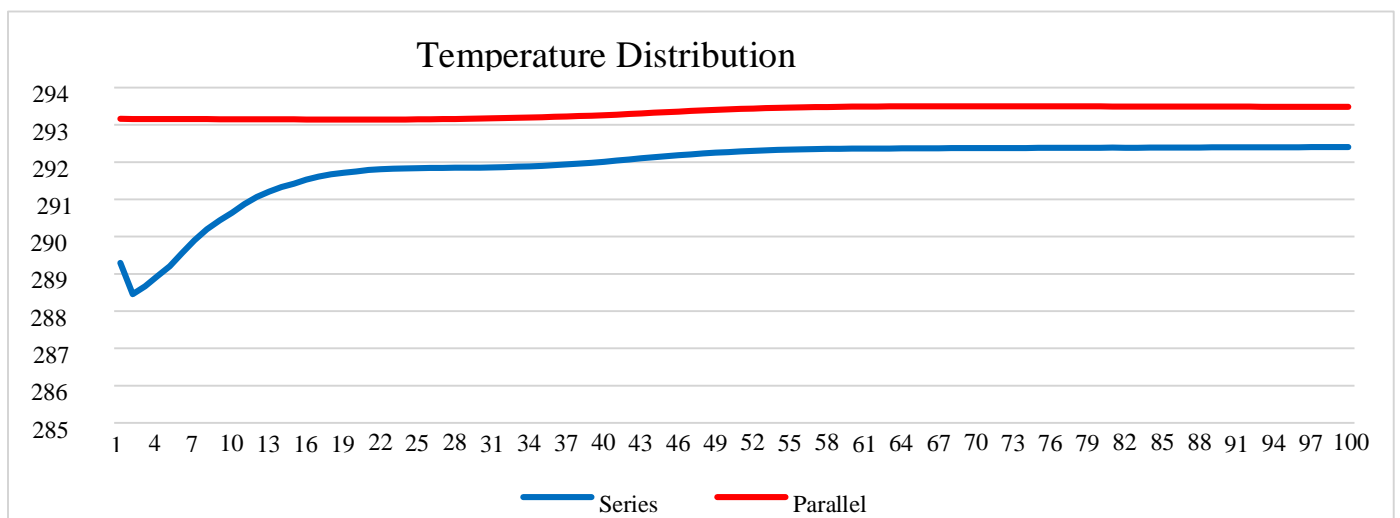


Figure 2
Temperature Distribution



Figure 2 - Graph for temperature distribution in the hybrid cyclone Diameter 250 mm. It was observed that under parallel orientation, the system, rapid temperature loss is recorded as seen from the graph. The temperature was recorded as 293.725. It is maintained at that after 215 iterations. The trend is that the temperature loss is rapid which is significant in the study.

Pressure

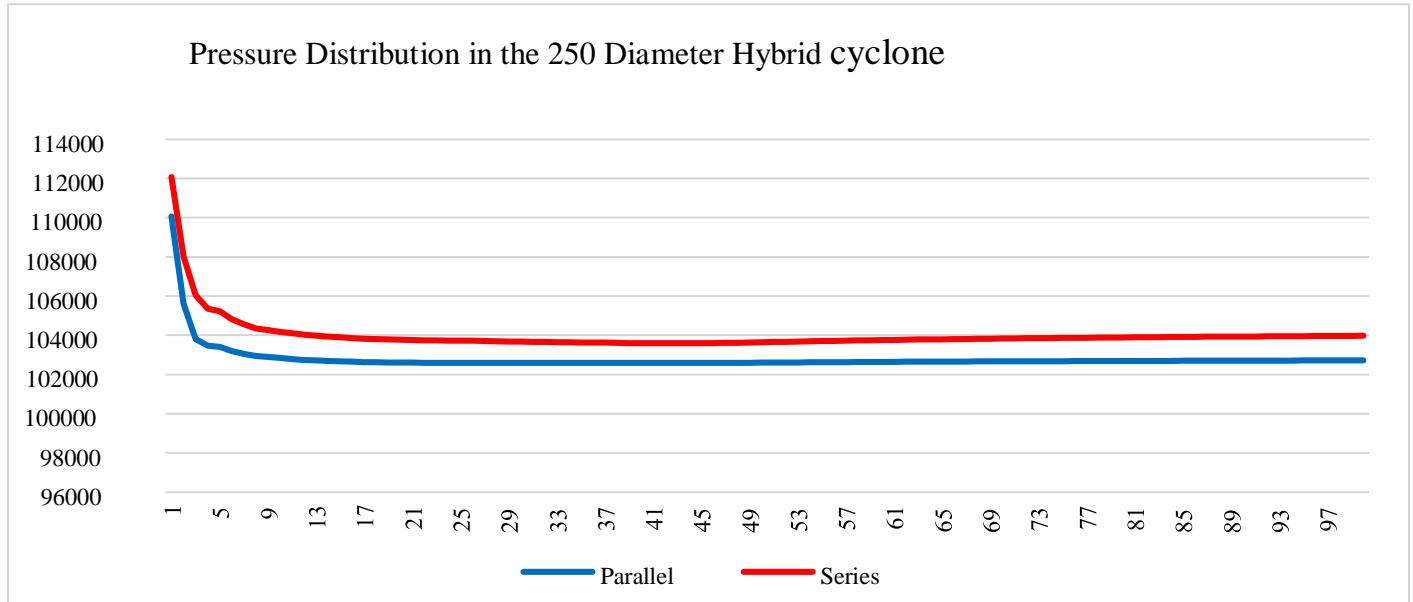


Figure 3
Graph for pressure distribution in the hybrid cyclone Diameter 250 mm

Table 1
Summary of the Average Data of 250 mm Diameter Hybrid Cyclone Orientations

Orientation	Pressure, Pa	Density, Kg/m3	Temperature	Efficiency
Series	103952.37	1.22	292.43	81.95%
Parallel	101949.0149	1.21	293.725	30.6%

3.2 Discussion

3.2.1 Observations and Comparison

Table 2
Observations and Comparison

Parameter	Series Orientation	Parallel Orientation	Insights
Pressure (Pa)	103952.37	101,949.01	Parallel system operates at a known higher pressure. If Series pressure is atmospheric (~101,325 Pa), Parallel is slightly higher.
Density (kg/m³)	1.22	1.21	Very close; Series slightly denser, which could imply lower temperature or higher pressure.
Temperature (K)	292.43	293.725	Parallel is hotter, which often correlates with lower efficiency in some thermodynamic cycles.
Efficiency (%)	81.95	30.6	Series performs significantly better, possibly due to better thermal regulation or component synergy.

3.2.2 Engineering Interpretation

Series Configuration: High efficiency likely stems from streamlined flow path, reduced losses, or cooperative component behavior. Slightly higher density and lower temperature may enhance thermodynamic performance, possibly via better heat exchange. Parallel Configuration: Considerably lower efficiency could result from flow imbalance, greater pressure drops, or thermal mismatches across parallel paths. Elevated temperature with slightly lower density may point to reduced heat exchange effectiveness or higher energy dissipation.

The Series orientation appears superior in this setup, delivering almost triple the efficiency of its parallel counterpart. This points toward an optimized interaction between system components and more effective thermal



management. In contrast, the Parallel system, while operating at a slightly higher pressure and temperature, suffers from lower energy conversion efficiency—likely due to flow distribution issues or diminished thermodynamic synergy.

IV. CONCLUSION

The orientation of cyclone configuration—series versus parallel—substantially affected performance. The series-oriented hybrid cyclone demonstrated superior efficiency at 81.95%, while the parallel configuration lagged behind at 30.6%, despite operating at slightly higher pressure and temperature. This stark contrast highlights that orientation controls thermodynamic synergy, vortex formation, and flow path stability. Series orientation promotes particulate capture by minimizing flow separation and allowing consistent pressure drops, while parallel flow may suffer from uneven distribution and weakened separation zones.

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