OPTIMIZATION OF HYBRID CYCLONE IN REDUCTION OF PARTICULATE FLY ASH IN SUGAR INDUSTRIES IN KENYA

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Thesis Submitted to the Department of Mechanical and Industrial Engineering in Partial Fulfillment of the requirement for the Award of the degree of Master of Science in Industrial Engineering and Management

2024

DECLARATION

This thesis is my original work prepared with no other than the indicated sources and has not been presented for a degree or any award in any other university or any other institution

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DEDICATION

I dedicate this thesis to my Mother, Alice Yalo, and my Father, Thomas, whose unwavering Support, encouragement and belief in my abilities have been invaluable throughout this journey. Their inspiration has been a Cornerstone of my success.

ACKNOWLEDGEMENT

I would like to express my deepest gratitude to my supervisors, Dr. E. Osore and Dr. J. Chirchir for invaluable support and encouragement throughout this research. Their expertise and insights have been instrumental in shaping this work.

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ABSTRACT

The sugar industry in Kenya faces growing environmental and regulatory pressure due to fly ash emissions from bagasse-fired boilers. Traditional single-stage cyclone separators currently employed in these facilities offer limited particulate collection efficiency—ranging between 50% and 60%—and often fail to capture fine ash particles, resulting in persistent air pollution and adverse health impacts on surrounding communities and industrial workers. This research investigates the design and performance of a hybrid cyclone separator, aiming to enhance particulate capture rates and reduce environmental degradation in Kenya's sugar belt regions. The study employed a factorial design approach, combining Computational Fluid Dynamics (CFD) simulations and experimental modeling to assess key design parameters, including inlet diameter (150 mm, 200 mm, 250 mm) and cyclone orientation (series vs. parallel). Temperature, pressure, velocity, and density profiles were analyzed across configurations to evaluate their influence on particle separation and gas dynamics. Results revealed a pronounced improvement in efficiency when using the hybrid cyclone in a series configuration, achieving rates between 81.26% and 81.95%—a substantial increase compared to conventional cyclones, which recorded a maximum of 63.69%. Notably, the hybrid design maintained stable gas velocities and operated with slightly lower fluid densities, reinforcing its capability to trap finer particles effectively. Among tested inlet diameters, the 200 mm configuration demonstrated optimal baseline efficiency and fluid dynamic stability. Orientation analysis showed that series connection outperformed parallel setups, with the latter achieving only 30.6% efficiency due to thermal instability and less synchronized vortex formation. The series arrangement enhanced flow regulation, leading to improved pressure gradients and particle capture. A regression-based mathematical model was derived to estimate efficiency using pressure, density, and relative pressure variables, yielding consistent predictive accuracy across all configurations. The model equation: Efficiency (%)} = -3303 + 0.05075P - 1441\rho - 0.05564P_r offers engineers a useful tool for real-time estimation and design optimization. The research concludes that hybrid cyclones configured in series offer a viable and energy-efficient alternative for particulate control in Kenyan sugar mills. Their implementation not only aligns with environmental standards but also enhances occupational safety, reduces equipment corrosion, and supports the industry's move toward sustainable practices. This thesis contributes a scalable and technically grounded solution to air quality challenges in agro-industrial settings, with implications for broader applications in biomass combustion and particulate-laden exhaust management.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

1.1 Background Information

The air around the cities is of serious environmental interest particularly in the developing areas of the world. In the industrially developing countries, there are augmented emissions of pollutants. The rapid economic growth, industrialization and rapid growth in energy demands in the developing regions of the world but more so in Africa and Asia are the causes of the increase in air pollution. It is because of this reason that the focus has been given on human health and exposure to these toxic emissions. It is estimated that about 4.2 million deaths occur annually due to the exposure to outdoor air pollution and 3.8 million deaths occur due to household exposure to smoke and dirty fuel (Hu et al., 2022). This leads to air pollution because the introduction of dust particles, gases, and smoke in the atmosphere surpasses the air quality levels.

Sugar industry is one of the most important sectors in the world agriculture, not only it produces sugar, but also some by-products such as bagasse, which is a fibrous product of sugarcane. The most common use of bagasse is in sugar mills where it is burned to generate steam and electricity, however, it produces a lot of particulate matter, especially fly ash. Fly ash is a fine particle which when not well managed may cause severe environmental and health hazards since it may be airborne and lead to air pollution. Such emissions need to be well managed to make sure that the sugar industry complies with the environmental standards and protects the air of the neighboring communities.

The sugar industry is one of the largest contributors of particulate emissions and is primarily in the form of fly ash when bagasse and other biomass are burned in a boiler. Fly ash has the form of fine particles and it is a threat to the environment and health as it is airborne. Particulate control is important in order to comply with the environmental standards and enhance the quality of air. The health issues that air pollutants cause are asthma, lung cancer, chronic obstructive pulmonary disease, respiratory diseases such as emphysema among others and even long term damages to nerves, brain, kidneys, liver and other organs of people, (Liu et al., 2016)

.

Kim et al. (2020) have examined the influence of different air pollutants ozone, PM2.5, and PM10 on the dry eye disease. Their study, published in Environmental Pollution, shows that the single pollutants have distinct adverse effects on the condition of dry eye that can be utilized to comprehend how these environmental factors contribute to the development and extent of the illness.

Altieri and Keen (2016) investigated the direct health consequences of pollution in South Africa and revealed that the air pollution was the cause of more than 21,000 premature deaths per year, which constituted 7.4 percent of all deaths. They approximated that these premature deaths cost the economy about US$ 20 billion. Mental health is also affected by air pollution to a significant extent. The study of the psychological impact of air pollution showed that the average concentrations of particulate matter (PM) were associated with an increased risk of scoring in the range of severe mental illness (Chen et al., 2024).

Air pollution is an inevitable by-product of the current industrial economy which cannot be eliminated fully but can be minimized through stern measures. Pollution may be minimized both collectively and individually. Air pollution has several sources and they include industries, fossil fuels, agro waste, and vehicular emissions.

Martin-Ortega and Gonzalez-Sanchez (2023) argue that two-quarters of greenhouse emissions are caused by industries. He says that factory emissions are a major contributor to green house gas emissions into the atmosphere and that factories are the major sources of air pollutants.

There is need therefore to have mitigations to curb the threat of air pollution. Some of the factors that can help in reducing the pollutants that cause the industrial air pollution include industrial processes, energy efficiency, control of burning agricultural wastes and conversion of fuels. According to (Munsif et al., 2021), the number of people that have been vaccinated with the COVID-19 vaccine is 7.5 billion.

The technologies applied in Sugar industries are cyclones, scrubbers and Electrostatic precipitators, cyclones are mostly used as primary collectors. Electrostatic precipitators and bag filters are applied in the secondary stage of collection (Kwiatkowski et al., 2021)
One of the most popular industrial gas-cleaning devices is the cyclone separators. They may be applied in certain industries like power generation, oil and gas, incineration plants, iron and steel industry, sand plants, cement plants, cooking plants, coal fired boilers and food industries. They are actually widely applied to the particle-controlling industries in the control of air pollution, aerosol sampling, and particulate matter control because of the ease of their construction, low cost of manufacturing, ease of maintenance and flexibility to a wide variety of operating conditions including high temperatures and pressures (Kwiatkowski et al., 2021)

The high volume of gases to be handled, low cost, and simplicity of cyclone separators make it popular in industrial applications of particulate control. Nevertheless, the conventional cyclone separators tend to perform poorly when it comes to capturing the fine particles such as fly ash. This has seen the creation and streamlining of hybrid cyclone systems, which integrate traditional cyclonic separation with other particulate removal technologies, e.g. electrostatic precipitation or filtration. Cyclone separators find application in a wide variety of areas to recover particles in a stream of gas due to their ease of operation, low cost, and ability to process a high volume of gas simultaneously. The devices operate by creating a vortex which forces the particles to the outer wall of the cyclone where they are collected and removed out of the gas stream.

Cyclonic devices by themselves cannot be used to meet stringent particle emission standards, but they have a place. Their low cost to purchase and no maintenance requirement makes them ideal to use as pre-cleaners to more costly control devices such as cloth filters or electrostatic precipitators. Cyclone separators are effective in capturing larger particles, but they are not effective in capturing smaller particles such as fly ash because they are small and do not possess a lot of mass and thus they can escape the vortex. Due to this issue, hybrid cyclone systems were developed. These systems enhance the basic cyclonic separation procedure with other technologies which assist in the collection of small particles.

Cyclones or cyclone separators are devices that utilize the principle of inertia to remove fine particles in exhaust gases. They contain no moving parts and operate on the principle of centrifugal separation to remove dust particles out of the polluted gaseous stream Cyclone separators are among many air pollution control devices called pre cleaners because they tend to remove larger particles of particulate matter.

They are the most common air pollution control technology and they are also referred to as pre-cleaners. They usually eliminate high range of particulate matter. This eliminates the need of the finer filtration techniques to cope with bigger and more abrasive particles in the future. It should be mentioned that cyclones may differ considerably in terms of their size.

The size of the cyclone is more or less dependent on the amount of flue gas that needs to be filtered and therefore the larger the operation the larger the cyclone may need to be. Cyclone separators are similar to a centrifuge except that they have a continuous flow of contaminated air. In a cyclone separator, the dirty flue gas is introduced into a chamber and then it is tangentially imparted on the wall of the cyclone cylinder by centrifugal force (figure 1.1).

The relative settling velocity is increased by this force, together with the difference in density of the fluid and the solid. The chamber interior forms a spiral vortex, like a tornado. The study by Baharuddin et al. (2022) is based on the idea that the number of people in the world is growing.

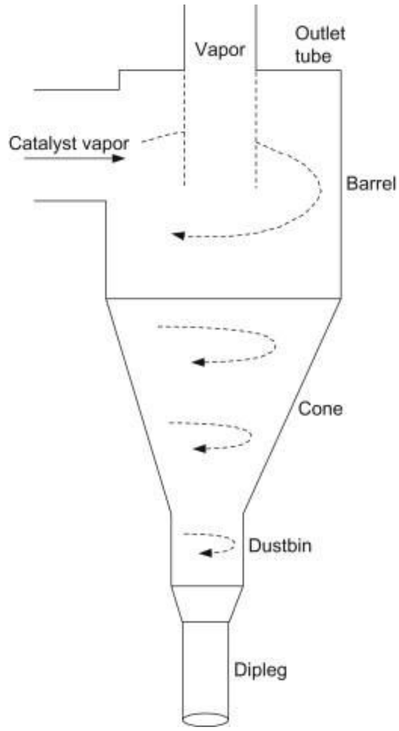


Figure 1-1-Typical principles of conventional cyclone operation (Baharuddin et al., 2022)

Comparing all the particulate-control devices, cyclone separators are one of the cheapest, and they are commonly applied as a pre-treatment prior to the flue gas passing through more efficient pollution control devices. Hence, the cyclone separators may be regarded as rough separators prior to the flue gas reaching the fine filtration systems.

The effectiveness with which the cyclone separators can, in reality, remove this matter is very much dependent on particle size. Sankar and Prasad (2015) discussed the modeling of processes and simulation of particle flow in cyclone separators that were applied in the separation of sand. Since the sugar industry is increasingly under pressure to minimize its environmental footprint, the implementation and streamlining of hybrid cyclone systems are essential. Such solutions will not only allow the business to comply with strict environmental regulations, but also will allow the air to be cleaner and people living close to sugar production to be healthier.

Cyclone separators are common in cement production, sugar processing, tea manufacturing and other industries in Kenya to effectively remove the small particles in the air or gas streams. The design of the cyclone, the size distribution of the particles, the velocity of the intake and the particular operating conditions influence the performance of these separators in Kenya.

General Efficiency Estimates

In Kenya, the traditional cyclone separators tend to operate at 50 to 80 percent efficiency, which is dependent on factors such as the size of the particles being captured and the design peculiarities of the cyclone (Nyakundi, 2016). More advanced or hybrid cyclone designs that are increasingly used in modern industrial processes can be over 90 percent efficient particularly with regard to small particles in the micrometer scale (Omondi et al., 2023)..

Industry-Specific Insights

The Kenyan cement industry requires cyclones separators very much to collect dust. The efficiency of these separators is approximately 70-85 percent in the Kenyan cement plants although it might change depending on the maintenance of the equipment and the design (Njoroge, 2020). The sugar business also uses cyclones separators to minimize the amount of particles that boilers emit. These separators have a tendency of working at a rate of 60-80 percent. The systems which use hybrid or multi-stage separators are better (Meng et al., 2024).

The tea processing industry uses cyclones separators to remove small dust particles. They tend to work at a rate of 60-75 percent (Kumar et al., 2023). Such variations between industries demonstrate the significance of cyclone design and operation optimization to the requirements of a specific industry.

Factors Affecting Efficiency

The design of the equipment, its maintenance and the size of the particles under processing all play a major role in the effectiveness of the cyclone separators in Kenya. In addition, weather and humidity in various regions of Kenya may significantly influence the effectiveness of cyclone separators (Karagoz et.al., 2013).

The largest problems of the cyclones utilized in sugar businesses can be recognized when you see them with your own eyes. A visit to our sugar factories reveals how poor is the management of pollution particularly in controlling fly ash that emanates in the bagasse-fed boilers. Workers are required to wear full protection because of the presence of a lot of fly ash in the air. The control system must be improved because the emissions to the environment are yet not satisfactory. It is due to this reason that the cyclone should be made to work in a better way by altering its design which will reduce the pollutants and make it more effective.

1.2 PROBLEM STATEMENT

Sugar industry which is major contributor in the global agriculture industry generates large quantities of fly ash through the burning of bagasse to generate energy. Being a fine particulate matter, this fly ash has the potential to cause air pollution and cause severe health problems, including respiratory and cardiovascular diseases, unless properly controlled. The conventional cyclone separators are effective in trapping large particles, but not the small ones such as fly ash. This indicates the necessity of coming up with improved technology of particle control.

In an attempt to control fly ash emissions in the sugar industry, the existing technologies often fail to effectively trap these minute particles thus increasing the number of pollutants in the air. Traditional cyclone separators find it difficult to remove smaller particles and this implies that not all the particles are removed and there are increased emissions. Due to this, there is a necessity of more contemporary hybrid cyclone systems that integrates traditional cyclonic separation with other capture technologies to make the process more effective.

The necessity to strike a balance between the effectiveness of particle removal and energy consumption and operational costs makes the issue much more difficult. Sugar business needs solutions which are not only able to meet the requirements of the government, but also perform economically. The reason is that there are increasingly numerous regulations about the way to preserve the environment and clean up the production.

Therefore, the issue lies in developing and enhancing hybrid cyclone systems that are effective in the sugar industry to capture fly ash particles that are small in size. This implies developing cost and energy-efficient ways that do not violate environmental regulations. In order to address this issue we must look deeply into the way we design systems, optimize parameters and measure performance in order to achieve both effective particle control and long term operation.

Although vertical cyclones and in certain industries horizontal cyclones are present, it has been found out that the collection efficiency of particulate fly ash in sugar industries in Kenya remains low between 50-60%. This exposes the workers to these pollutants and hence affecting their productivity and this ultimately causes loss of revenue and rise in cost of production. It increases absenteeism among workers and reduces the productivity of the job by affecting the cognitive and physical ability of the worker hence causing corrosion of equipments, depreciation and hence high cost of maintenance.

Figure 1-2-Effect of fly ash corrosion on industrial equipment (Source: Mumias Sugar company, 2013)

The working conditions in the Kenyan sugar industry have major implications on the well-being and performance of employees. In a survey study conducted among 383 employees in sugar companies in Western Kenya, it was established that the state of occupational health and safety (OHS) was positively correlated with the performance of employees with a regression coefficient of 0.585. This implies that improved working conditions have a direct effect on productivity. In addition, top management support was found to moderate this relationship and the change of R 2 was 0.290 ($p = 0.000$), which means that the commitment of the top management to the safety policies can significantly enhance the results.

Even after the introduction of Occupational Safety and Health Act No. 15 of 2007, a number of sugar companies still subject their workers to dust, noise, heat, and chemical risks, which result in numerous injuries and long-term diseases. According to the International Labour Organization (ILO), it is estimated that 6,300 individuals die every day in the world as a result of accidents or diseases acquired at work and Kenya sugar industry is not an exception. Low morale, absenteeism and decreased efficiency among workers are caused by poor enforcement of safety procedures, poor protective equipment and training.

Therefore there is a need to have a more efficient hybrid cyclone in order to enhance efficiency in collection of particulate fly ash. This would not only enhance the health of the people working in the industries but also the environment adjacent to the industries which apparently accommodates a good percentage of the Kenyan population in the sugar belt region of western and Nyanza.

1.3 OBJECTIVE

1.3.1 Main Objective

To Model and simulate an improved cyclone for increased pre-collection efficiency of fly ash from bagasse fired boilers in Sugar industries.

1.3.2 Specific Objectives

1. To determine the effect of design parameters of a hybrid cyclone on the particulate fly ash collection efficiency
2. To determine the impact of cyclone orientation of hybrid cyclone on the collection efficiency of particulate fly ash
3. To develop a Mathematical model for the hybrid cyclone

1.4 HYPOTHESIS

1. H0-There is no effect of design variables of a hybrid cyclone on collection efficiency

   H1-There is effect of design variables of a hybrid cyclone on collection efficiency
2. H0 -There is no relationship between orientation and collection efficiency and pressure drop

   H1-There is relationship between orientation of the hybrid cyclone and collection efficiency
3. H0-Collection efficiency of a hybrid cyclone is the same as individual cyclone

   H1-Collection efficiency of a hybrid cyclone is not the same as individual cyclone

1.5 JUSTIFICATION OF STUDY

In Kenya, the cyclones are currently preferred pre collection technology in the sugar industries. In the particulate fly ash control, they employ vertical cyclones. It is clear that they are not efficient enough. This can be observed both physically and also experimentally by measuring the quantity of particulate fly ash that is discharged by the vertical cyclones. Physically, it is observable that the particulate fly ash is abundant in the vicinity of the industries and this compels the employees to wear protective gears on a constant basis to protect them against the impacts of the fly ash. This implies that the vertical cyclones by themselves are not effective enough in the management of particulate fly ash. Research indicates that they produce 50 to 60 percent efficiency, because of this, worker is subjected to these pollutants thus affecting his productivity and this ultimately results in loss of revenue and rise in cost of production. It increases work absenteeism and reduced productivity at work through the impairment of cognitive and physical performance of the worker. Inefficient collection, in our case a vertical cyclone causes corrosion of equipment, depreciation and hence high maintenance costs. Therefore, there should be an enhancement of collection efficiency to more than 60 percent in the case of the conventional cyclone.

Generally in Kenya, the sugar industry is crumbling and it is not competitive enough compared to the same industry in other developing industries. Its productivity of 85 percent is below the recommended productivity of 92 percent by the world industrial index and this can be blamed on ineffective industrial processes among them poor collection efficiency.

In order to achieve the suggested annual sugar productivity of 92 percent as per (Osore, 2020), it is necessary to guarantee the safety of workers in terms of their health, greater reliability of equipment.

1.6 SIGNIFICANCE OF STUDY

The study is significant since it is expected to play a great role in enhancing the efficiency of particulate control systems in the sugar industry, which is a crucial industry in the world agriculture. The study examines several significant issues by focusing on enhancing the hybrid cyclone systems to gather small particle fly ash.

Improved Adherence to Regulations: The research will facilitate easy disposal of particle matter which will make the sugar industry comply with strict environmental regulations. Fly ash emissions should be well controlled to reduce air pollution that impacts on the environment and the health of the people. The research assists the industry to adhere to the regulations and reduce its effects to the environment by designing superior hybrid systems.

Better Health to All: Fly ash contains fine particles that may not be good to your health when inhaled leading to heart and lung complications. The air becomes cleaner and reduces health risks associated with inhaling polluted air by better capturing of these particles. The study aims at reducing the quantity of fly ash entering the air, and this will save the health of people.

Better operating efficiency and reduced cost: Optimization of hybrid cyclone systems can enable you to increase the efficiency of the particle removal process and, at the same time, reduce energy consumption and operating costs. The aim of the research is to develop the methods which are effective in the reduction of emissions and affordable. This trade-off can assist the industry to remain profitable as it invests in cleaner technology.

Technological Innovation: The research assists in developing improved particulate control technologies through integrating cyclonic separation with other methods of particle capture, e.g. electrostatic precipitators, bag filters, or wet scrubbers. Other businesses with similar emission issues may use this new method of doing things as an example. It may also promote the use of new technology to control pollution.

Promotion of Sustainable Practices: With an increasing number of individuals around the globe getting conscious about the environment, there is enormous pressure on companies to employ greener processes. The study helps the sugar industry to be more sustainable by concentrating on the optimization of hybrid cyclone systems. Better particulate emission control technologies are in line with larger objectives of environmental management and sustainable growth.

In conclusion, the research is important since it considers the dire need of more effective and cost-efficient means of managing fine particulate fly ash in the sugar industry. Its results may be used to increase regulatory compliance, promote better health, lower operating costs, promote technological innovation, and promote sustainable industry practices.

1.7 SCOPE

Study was done at the Pre-collection stage of particulate fly ash from flue gas emitted from the bagasse fired boilers before the secondary collectors in sugar industries.

1.8 CONCEPTUAL FRAME WORK

The concept of this study revolves around the independent variable, interdependent variables and Dependent variables. Under independent variables we have the hybrid cyclone. The dependent variables vary depending on the orientation of the hybrid cyclone and the inlet diameter of the hybrid cyclone

Intermediate variables

1. Inlet diameter
2. Orientation

Figure 1-3 Conceptual framework

CHAPTER 2: LITERATURE REVIEW

2.1 Principle of operation of a conventional cyclone separator

A cyclone separator uses centrifugal force to separate particles on the basis of size. It acts by creating a swirling turbulent flow that segregates phases of different densities. The principle of operation of a typical cyclone separator is that the centrifugal force is used to separate particles in a gas or air stream. The air or gas stream is introduced into the cyclone at an intake which is usually angled or tangential to the cyclone. It is possible to think of a situation where the information is not provided (Caliskan et al., 2019a).

This design is rather important as it makes the cyclone rotate which is a significant part of the separation process. Once the gas is introduced into the cyclone, it is compelled to move in a spiral fashion along the inner wall of the separator. The injection is done at an angle or tangentially thus giving the flow angular momentum and rotating it. The vortex that is formed due to this spin is very important in the separation of the particles with the gas (Ray et al., 2000) The centrifugal force formed by the spinning process pushes the larger and heavier particles against the outer wall of the cyclone. These particles experience a lot of force as compared to the lighter and smaller particles because they are heavy and possess more mass. This separation occurs since the centrifugal force is proportional to the square of the velocity of the gas hence it is effective in separating particles of various sizes. The walls of the cyclone push the larger particles against them and this slows them down and eventually makes them settle at the bottom. These separated particles are collected in this bottom part that is typically cone-shaped or cylindrical. The collected material, also referred to as the dust or concentration of the cyclone is then discharged via a hopper or outlet. The remaining gas with reduced number of particles moves up through the center core of the cyclone. This core is the exit of the cleansed gas. In this upward direction, the gas stream that is escaping takes with it any small particles that were not trapped by the cyclone. (Lapple, 1950)

The performance of the cyclone separator is greatly affected by the design and shape of the cyclone separator. The vortex and the centrifugal force it produces are based on the diameter of the cyclone, its height and the shape of the intake and outflow. These design features are rather important in defining the success of the cyclone in separating the particles. The performance of the cyclone separator is greatly affected by the quality of tuning of these design parameters. An effective cyclone guarantees that the spinning effect is robust to dislodge larger particles and discharge the cleaned gas with the least number of residual particles. The same applies to the time of the day spent (Karagoz et al., 2013)

The use of cyclones separators is widely used in the industries to remove the particles of the gases or air streams by the centrifugal forces. The idea of these machines is that a swirling or vortex is created by injecting a stream of gas with particles into the separator at an angle (Oh et al., 2014). This centrifugal force movement makes the more dense particles than the gas to be pushed to the sides of the separator. People use cyclone separators very much because their operation is simple and the costs of using them in removing the particles in the streams of gases are low (Asadullah, 2014).

The cyclone separator is used by creating a vortex in a cylindrical or conical chamber. The gas stream entering the separator at an angle acquires angular momentum, and the swirling movement necessary to separate the gas stream is achieved (Zandie et al., 2021). The design of the cyclone ensures that the gas takes the downward spiral path around the external walls of the separator. This forces larger particles to the exterior because they are more inert. This rotational movement plays a very significant role in initiating the process of separation.

The centrifugal force produced by the spinning gas separates the particles. The force increases with the square of the speed of the gas, hence it is effective in separating the particles of different sizes (Svarovsky, 2000). The effect of this force is greater on larger, denser particles which are forced towards the outer walls where they slow down and drop into a collection chamber at the bottom of the cyclone (Dirgo & Leith, 1985). The smaller ones are less affected by the centrifugal force, and thus remain suspended in the gas stream and may escape the separator unless they are removed by filtering.

The cyclone separator is designed to capture the larger particles at the bottom which is typically in a dust collecting chamber or hopper. This lower section is typically in the form of a cone to allow the separated material to settle down by gravitational settling. When the particles have been collected, they are discharged out through an outlet at the bottom of the separator. The effectiveness of this collecting procedure depends on the particles size and weight, separator design, and many others, and this is only a small list (Oh et al., 2014).

The separated particles are separated and the cleaned gas stream is flowing up the center core of the cyclone. The nearer the vortex is to the bottom of the separator, the more the gas swirls around and moves up the central axis, through the outlet on the top (Vahedi et al., 2018). This upward flow is very essential so as to remove the now-cleaned gas. Other small particles may however be left floating in the gas and be swept away by the gas stream.

A cyclone separator performance is affected by its design. The strength of the vortex and the centrifugal forces that are produced by the latter depend on the diameter and height of the cyclone, size and shape of the intake and outlet (Svarovsky, 2000). The bigger the diameter, the weaker the centrifugal forces and hence the small particles cannot be separated easily. The smaller cyclones on the other hand can generate greater forces, however they may have greater pressure dips and this may make them less efficient (Dirgo & Leith, 1985).

The primary benefit of cyclone separators is that it has the ability to handle large gas volumes with little maintenance. Cyclones lack moving parts, which minimizes wear and tear and their durable structure makes them work in severe industrial conditions (Nakhaei et al., 2020). They however do not always work well in capturing small particles and therefore you may have to employ other filtering systems like the baghouses or the electrostatic precipitators to filter all the particles (Boysan et al., 1982).

A cyclone separator is optimized best when it has been optimized in design. By adjusting the operating conditions of the cyclone such as the input velocity and the cyclone shape, you will have a better cyclone that will separate the particles with the gas stream (Su et al., 2011). To make sure that the cyclone is efficient in the intended use, the designers ought to balance between efficiency of the cyclone in capturing particles and the pressure that the cyclone loses as it moves through the system (Zandie et al., 2021).

A conventional cyclone separator operates by generating a rotating vortex that generates centrifugal forces which push the particles to the walls of the separator where they are captured. The purified gas is exhausted via a central core and occasionally small particles require re-filtering. The design of the cyclone like the shape of the intake and the size of the cyclone is very crucial in determining the effectiveness of the cyclone and its effectiveness in an industrial context (Svarovsky, 2000).

Finally, the conventional cyclone separator employs the centrifugal force to separate the gas stream. The initial tangential entry of the gas creates a rotating vortex which forces larger particles to the outer wall of the cyclone. The cleaned gas is then drained out through the center core and the particles collected at the bottom. Overall, the cyclone separator is a low cost and commonly used method of controlling the particles in various industrial processes. Its effectiveness is based on the way it is designed and the way it is used and therefore these should be well established so as to achieve the best outcomes.

Theoretically, a conventional cyclone separator is an efficient device that can be used to control particulate emissions in diverse industrial processes because it uses the combination of centrifugal force and gas flow dynamics to achieve excellent separation of particles.

A gas cyclone used to remove particles in a gas stream, e.g. the high-efficiency cyclone of Stairmand, Figure 1.2, usually has a tangential inlet to generate swirling motion. This movement causes the particles to move towards the outer wall of the cyclone where they move downwards spirally and are deposited in a dustbin at the bottom of the conical part. In the meantime the cleaned gas is released through a pipe at the top. Two important factors affect the separation process, namely swirl which exerts a centrifugal force to separate the solids and turbulence which disperses the particles and enhances the possibility of the particles being swept away with the exit gas. Swirl and turbulence are both a function of the particle size and the flow conditions in the cyclone. (Elsayed & Lacor, 2011)

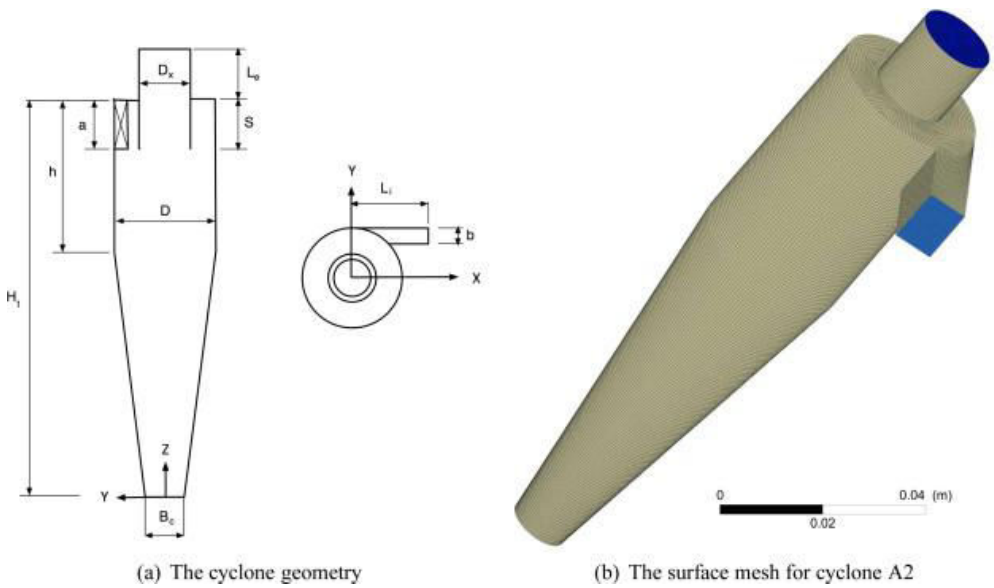


Figure 2-1 Typical Cyclone dimensions (Elsayed & Lacor, 2011)

Cyclone separators provide a method of removing particulate matter from air streams at low cost and low maintenance. In general, a cyclone consists of an upper cylindrical part referred to as the barrel and a lower conical part referred to as cone (see figure 3 below)

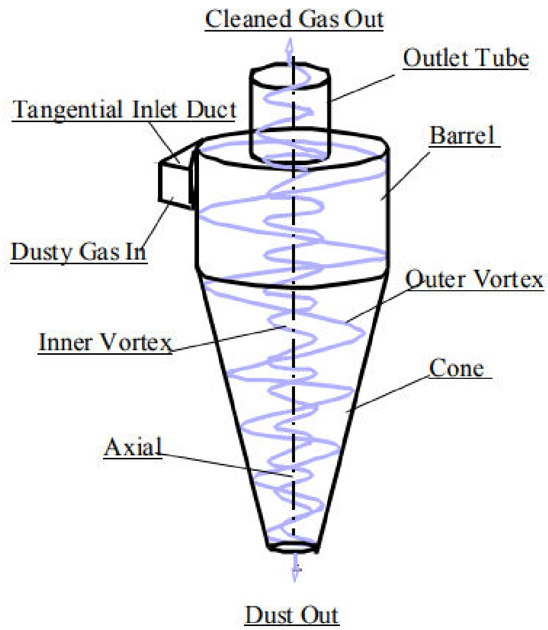
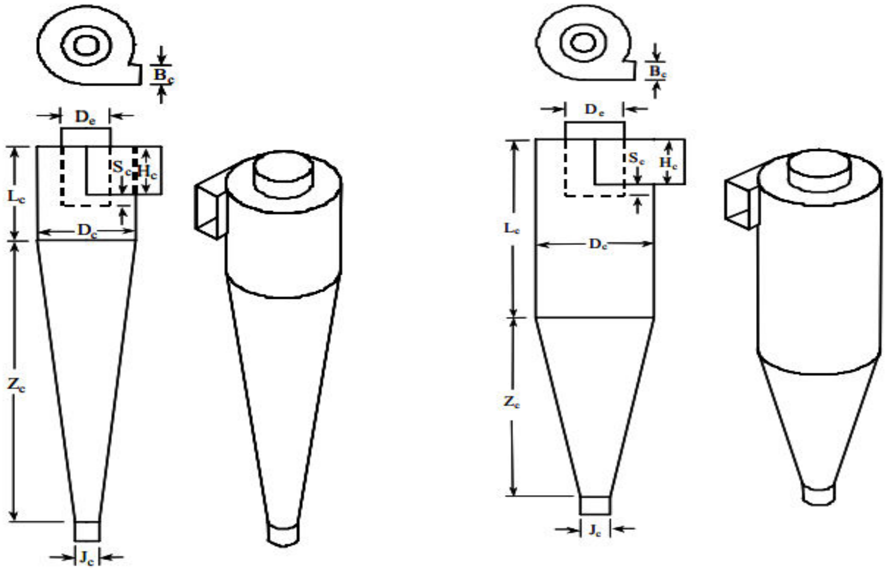


Figure 2-2-Schematic diagram of a cyclone Source (Wang et al., 2006)

The air flow flows into the cyclone tangentially at the top and flows downward into the cone forming an outer vortex. The accelerating speed in this vortex creates a centrifugal force, which causes the particles to become detached to the air stream. When the air reaches the bottom of the cone, an inner vortex is created, which turns and comes out as clean air at the top and the particles are deposited in the dust chamber at the bottom. The 2D2D (Lapple & Shepherd, 1940) and 1D3D (Mohammed et al., 2019) cyclone types are usually applied to particulate control in agricultural processing. The 2D2D designation is made up of the letters D which signify the barrel diameter and the numbers which signify the lengths of the barrel and cone sections in relation to the barrel diameter. In particular, a 2D2D cyclone has a barrel length and cone length two times the barrel diameter, and a 1D3D cyclone has barrel length equal to the diameter and cone length three times the diameter.



1D3D

$B_c = D_c/4$ $J_c = D_c/4$

$D_e = D_c/2$ $S_c = D_c/8$

$H_c = D_c/2$ $L_c = 1 \times D_c$

$Z_c = 3 \times D_c$

2D2D

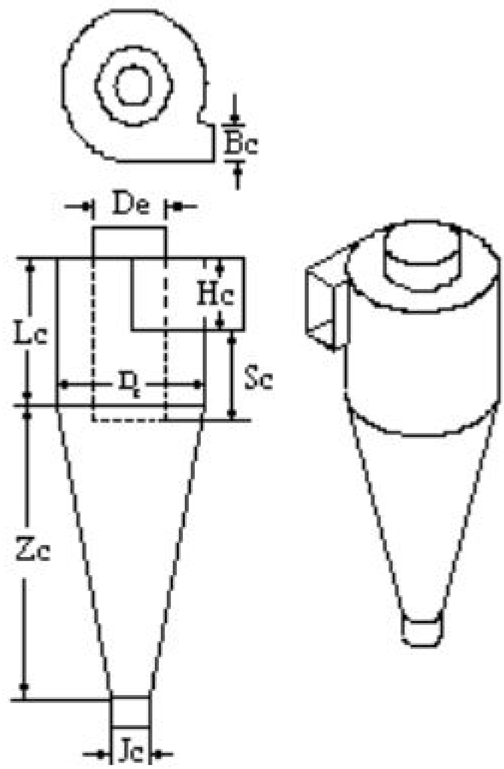
$B_c = D_c/4$ $J_c = D_c/4$

$D_e = D_c/2$ $S_c = D_c/8$

$H_c = D_c/2$ $L_c = 2 \times D_c$

$Z_c = 2 \times D_c$

Figure 2-3-1D3D and 2D2D Cyclone configuration Source (Wang et al., 2006)



1D2D

$B_c = D_c/4$ $\qquad$ $J_c = D_c/2$

$D_e = D_c/1.6$ $\qquad$ $S_c = 5D_c/8$

$H_c = D_c/2$ $\qquad$ $L_c = 1 \times D_c$

$Z_c = 2 \times D_c$

Figure 2-4-1D2D cyclone configuration Source (Wang et al., 2006)

The most popular type of cyclone separator is the tangential inflow cyclone separator. Industrial cyclone separators are normally applied to separate solid or liquid particles with gas because they are inexpensive to operate and maintain.

The efficiency of cyclone separators has been the subject of much research. One of the most crucial things that define their effectiveness is the design of the intake. Even a small variation in the angle or the size of the entrance, e.g., can produce an enormous impact on the ability of the cyclone to create a strong vortex (Su et al., 2011). The tangential entry enhances the angular velocity of the gas flow that aids in separation of the particles. It has also been found that through smooth transition of the intake and the cylindrical body of the cyclone, the turbulence is minimized hence separation increases (Zandie et al., 2021).

The interaction between the speed of the gas stream and the size of the particle is quite significant as regards the cyclones operation. Dirgo and Leith (1985) also say that larger particles experience more centrifugal forces and hence are effectively pushed against the walls of the cyclone. These forces are not so strong always on the small particles and hence there is a likelihood of them being suspended in the gaseous flow. To solve this, other scientists have considered the idea of multi-cyclone systems, in which numerous small cyclones are employed, which act in unison to trap smaller particles more efficiently (Ramachandran, 2018). These techniques will assist in handling the separation of particles in a better way without reducing the velocity of gas.

Cyclones separators also have much to do with the industrial environment in as far as the reduction of the level of particle pollutants is concerned. According to the research conducted by Setoodeh Jahromy (2019), the cyclone separators can reduce the volume of particulate matter (PM) emissions by 80 percent in certain configurations. However, they do not work too well in trapping particles that are less than 10 microns (PM10). In order to collect these minute particles and make them meet the environmental standards, other filtration procedures like bag houses have been integrated by some companies (Topmiller & Dunn, 2013). Cyclones and secondary filters have also been found to be an effective way of controlling the particles in a process that produces a lot of particles.

The reduced operating pressure is the other factor that should be considered in an endeavor to maximize the utilization of a cyclone separator. Su et al. (2011) stated that the pressure drop is proportional to the cyclone effectiveness and the energy consumption. Higher pressure drops enhance separation and consume more energy that may be expensive to businesses that undertake a lot of work. The scholars have been trying to find a balance between the two things. In other systems, the size of the cyclone and the inflow rate are varied by optimization algorithms to produce optimal performance with the minimum energy. These results show the importance of taking into consideration the performance as well as the cost of operation when constructing the cyclone separators.

Other than the removal of the particles, cyclone separators play a major role in environmental sustainability. Cyclones are used in many businesses, especially those involving chemicals and heat, to recover valuable by-products, e.g. unburned carbon or catalyst particles. The fact that cyclones do not only manage pollution but also recover resources has also necessitated the need to enhance the design of cyclones as Nakhaei et al. (2020) noted. The further development of the cyclone technology may lead to the systems which not only reduce the amount of the emissions but also maximize the amount of the resources which can be extracted and this makes them a considerable part of the sustainable industrial processes. The reason is that it is an emerging type of technology (Ma et al., 2020).

2.2 Performance of a cyclone separator

There are many applications of cyclone separators. The majority of vacuum cleaners in the market today have the cyclone separators to collect fine particles. They are applied as an instrument to gather a wide range of particles, including indoor and outdoor fine dust, allergies, and bio aerosol, besides household appliances. When better cyclone separators are produced, there are high chances that they will be applied in more regions. According to (Noh et al., 2018), the researcher was able to determine the type of experience that the participants had. The researcher also managed to determine the kind of experience the participants lacked.

Kumar and Jha (2018) investigated the cyclones performance in the aspects of the cone length of the tangential inlet cyclone and the changes in the internal and external diameters of the vortex finder. They used experimental data of 15 cyclones of varying cone lengths and vortex finders and obtained non-dimensional equations to correlate the effects of flow rate to cut-off size and pressure drop.

Noh et al. (2018) describe a cyclone separator as a device that is applied to separate particles in terms of size with the help of centrifugal force. Tangential inlet cyclone separator is the most popular cyclone separator among others. The cyclones separators are widely used in the separation of solid or liquid particles in the gas because of several advantages such as low operating cost and easy maintenance Cyclone separators have been used in different industries and in different forms. The cyclone separators are found in most of the vacuum cleaners in the market today to trap the fine dust and clean appliances. They are also applied in sampling the samples of the various types of particles such as the fine dust in the indoor and outdoor environment.

Kumar and Jha (2018) addressed the efficiency of cyclones through the cone length of the tangential inflow cyclone and variation of the inner and outer diameters of the vortex finder. They have applied experimental data of 15 cyclones with varying cone lengths and vortex finder diameters to develop non-dimensional equations that indicate the influence of flow rate on cut-off size and pressure drop.

The paper by Liu et al. (2019) addressed the work of an inverse two-stage dynamic cyclone separator. The findings indicated that the inverted two-stage system was much more effective in separation as compared to the traditional single-stage systems. This was well witnessed in the aspect of handling small particles. There was improved collection of the particles in the system with little loss of pressure. It was also observed in the study that the changes of the design assisted the evenness of the flow distribution and this enhanced the overall performance of the cyclone separator.

In the present research (Yuan et al., 2020), the authors examined whether it is possible to enhance the work of the cyclone separators in various industrial environments with the help of the computational optimization method. The research established that optimized customized cyclones to a specific working condition were superior to the conventional ones. The article emphasized the relevance of the tailoring of cyclone shape to meet personal separation requirements. This is more efficient and energy saving.

Zhang et al. (2024) investigated the long-term process of cyclone separators. The paper has discussed the problem of wear and tear on efficiency. The researchers discovered that material selection is extremely important in making sure that separators work efficiently especially in severe conditions. They encouraged regular service and wear resistant materials so that efficiency could be attained in the long term.

Wang and Zhang (2025) developed another type of cyclone, a hybrid of the conventional cyclone separation and the electrostatic precipitation. The hybrid system was more efficient especially when it came to sub-micron particles, which cannot be separated with the regular cyclone designs alone. The study proved that the hybrid systems might be used in the business where a great number of particles are to be removed.

Li et al. (2022) explored the effect of temperature on cyclones performance. They showed that viscosity of a gas can be minimized through elevation of temperatures and this works in separation, especially in the case of small particles. The study also looked into the effects of changes in temperature on the stability of the overall operations of cyclones. This means that when it comes to critical situations, temperature has to be regulated.

In their study, Wang et al. (2023) focused on the interaction of the gas and the liquid phases and discussed the multi-phase flows in cyclone separators. The researchers noted that the liquid droplets might alter the flow patterns in the cyclone entirely. This may enhance or deteriorate the performance of separation depending on the operating conditions. The study indicated that the designs will be adjusted in a way that it will consider the operation of multi-phase flow.

El-Emam et al. (2024) examined the response of cyclone separators to the variations of the working conditions. In this paper, the sophisticated modeling techniques were employed to demonstrate that cyclones must be formulated in a manner that they are able to resist transient variations, i.e. when the flow rate or the particle loading varies suddenly. The results proved the importance of good design as an instrument of stable performance in dynamic conditions.

Bartz-Beielstein et al. (2018) applied evolutionary algorithms to find the optimal designs of cyclone separators in a manner that they would be capable of being effective and simultaneously possessing a low pressure drop. They discovered that the evolutionary algorithms can be used in the selection of the most optimum design parameters that would improve efficiency of separation and energy saving in a substantial manner.

Guo et al. (2023) examined the influence of operating noise and vibrations on the cyclones separator performance. The researchers reached a conclusion that high level of noise and vibration might lead to structural fatigue and reduce the life of the separator and lower its efficiency. The hypothesis of the study was that the cyclones designs ought to incorporate the vibration-damping materials and noise-reducing strategies.

Yao et al. (2022) analyzed the influence of the form of the entrance on the cyclone performance. The experiment has revealed that a small alteration in the structure of the inlet such as the angle or shape of the intake can be significant in the quality of particle separation. The findings indicate that inlet geometry plays a significant role in the process of maximizing the performance of a cyclone in some activities.

Zhao et al. (2021) discussed a novel dual-inlet cyclone and demonstrated that dual inlets could enhance the efficiency of separation through the enhancement of flow distributions in the cyclone. The researchers discovered that dual-inlet designs would be the most helpful in those instances when a broad range of particle sizes must be exceptionally efficient.

Zhang et al. (2020) examined the influence of the size distribution of particles on the efficiency of cyclone separators. The researchers found out that cyclones are more efficient in separating particles of a certain range of sizes and that outside the range, separation is highly inefficient.

Zhang et al. (2022) considered the influence of the working conditions on the work of the cyclone separator. They found out that a significant difference can be made to the efficiency of separation of particles by varying the temperature and pressure and that the greater the temperature the better it works.

The influence of gas viscosity on the performance of cyclone separators was discussed by Chen et al. (2023). The findings revealed that high viscosity of gas hinders separation particularly that of small sized particles. This indicates the significance of considering the gas properties in cyclones design.

Sardar et al. (2023) investigated the effect of the inlet shape of the cyclone on the decrease in pressure and separation efficiency. The research also revealed that the alteration of the shape and size of the intake would assist in the minimization of the pressure drop without the sacrifice of the separation efficiency. This enhances the entire system to be energy efficient.

The approach of implementing the design of a vortex detector in cyclone separators was considered by Gao et al. (2019). The researchers noted that the length and the diameter of the vortex finder can be varied to provide significant increases in separation efficiency due to the decreased short-circuiting and altered flow pattern within the cyclone.

Zhang et al. (2019) have examined the influence of the speed of the input on the effectiveness of the cyclone separators to collect the particles. The researchers discovered that the faster the rate of the intake the easier it becomes to trap the larger particles but this may lead to re-entry of the smaller particles into the system hence reducing efficiency.

Zhang et al. (2022) study took into account the use of computational fluid dynamics (CFD) in predicting the work of cyclone separators. The paper demonstrated that CFD is quite an excellent method of estimating the fluid flow and the extent to which they can be separated and you can optimize the design of a cyclone before you go to the extent of constructing a real one.

Guo et al. (2022) applied machine learning to predict the behavior of cyclone separators in various conditions. It was revealed in the analysis that the machine learning models were able to predict the effectiveness of the separation sufficiently and this would enable optimization and control of the cyclone operations.

M. Wang et al. (2023) considered the impact of multi-phase flow on cyclone separators and their ability to separate solid-liquid mixtures in particular. It was concluded that the traditional cyclone designs must be subjected to numerous changes in order to accommodate multi-phase flows and in order to ensure high separation efficiency.

Gao et al. (2020) considered the importance of the shape of a cyclone in the quality of separation of things. The researchers found out that the height-to-diameter ratio of the cyclone (aspect ratio) is a strong factor that determines the effectiveness of the particles separation process and that some ratios are more effective than others.

Gao et al. (2020) investigated the size of the cut-off of the cyclone in terms of the area of the input, the height of the cylinder, and the change in the flow rate. They developed a theory whereby the pattern of the flow of a cyclone is used to make an estimation of the cut-off size.

Sun et al. (2020) have taken into account the effectiveness of cyclones through the analysis of the ratios of the diameter of the cyclone body and the vortex finder. They found that efficiency of collection increased with cyclone body size and pressure drop decreased with vortex finder diameter provided that the other size parameters were identical.

Caliskan et al. (2019b) examined the effectiveness of cyclones under the change of the size of the body of the cyclone. They found out that the cut-off size decreased when the diameter of the cyclone body and the vortex finder diameter decreased. Sakin et al. (2019) tested the effectiveness of cyclones in regard to the area of the bottom of the cone. They found that the collection efficiency increased with the decrease in size of the cone when the cone aperture was larger than the diameter of the vortex finder. In most of these studies, the design of the cyclone separator was changed or a new one was introduced so that it could collect better

Karagoz et al. (2013) have designed a novel internal geometry of a cyclone with the help of a spiral guide, a vertical groove and a circumferential groove. They found out that the spiral guide was more effective in low flow rates collections, though the grooves were not so useful. Noh et al. (2018) tested the effectiveness of a cyclone with the application of two cyclone inlets. They found out that pure air twin intake cyclone was preferable to collect than a single entrance cyclone.

Fu et al. (2021)performed a comparison of the cyclones with different designs of the vortex finder regarding the efficiency of collection and pressure drop. They came to the conclusion that cone shaped vortex finder design was useful in reducing the pressure drop per unit of flow rate. They placed a scroll inlet into a cyclone and compared the performance of a cyclone with the angle of cyclone inlet. They got to know that the angle of inlet section was 45 and it enhanced the collection efficiency more than the normal angle of the inlet section. In the meantime a process was invented that would make collection more efficient with the use of multiple cyclones.

Noh et al. (2018), tried to optimize the work of separation by cross-connecting five cyclones in series and optimized its performance at different conditions of the flow rate, gas viscosity, and particle density. They tried the effectiveness of the double cyclone where a countercurrent cyclone design was placed inside a cyclone. They discovered that the double cyclone had a greater collection efficiency, sharper collection efficiency curve and a lower pressure drop than the conventional cyclones

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Cyclone separators performance is determined by collection efficiency and pressure drop. Overall, the earlier studies tried to enhance the collection efficiency by reducing the cone bottom diameter, enhancing the flow rate and enhancing the inlet height or inlet width and the earlier studies assumed that the pressure drop was negative to the collection efficiency. That is, by raising the pressure drop the collection efficiency is enhanced or the converse is true, the collection efficiency is decreased by reducing the pressure drop. This study was aimed at enhancing the overall deficiencies of these cyclone separators and to come up with a cyclone separator that would enhance the collection efficiency and a low pressure drop. The proposed study is based on tangential inlet cyclone which is conventional and it suggests a new type of cyclone separator in which a number of subsidiary cyclones are mounted on a central cyclone. Elsayed and Lacor (2013) investigated the cyclones performance in accordance to the ratio between the diameter of the cyclone body and the vortex finder diameter. They discovered that the efficiency of collection rose as the size of the cyclone body rose and the pressure drop fell as the diameter of the vortex finder rose with other size parameters held constant. Brar et al. (2015) monitored the cyclones performance with regard to the variations in the size of the cyclone body. They discovered that cut-off size was reduced when the diameter of cyclone body and vortex finder were reduced.

Honda et al. (2021) conducted an experiment of the performance of a cyclone scrubber in the removal of fine particulate matter and discovered that an increase in the inlet air velocity enhanced the collection of larger particles and reduced the separation of smaller particles. They also added that in order to calculate efficiency as a total equation 1 is appropriate

$$n_{overal} = \frac{C_{in} - C_{out}}{C_{in}} \quad \text{..equation 1}$$

Where C_{in} and C_{out} are the mass concentration of particles at the inlet and upper outlet of the cyclone respectively

Misiulia et al. (2020), used a scroll inlet on a cyclone, and measured the performance of a cyclone depending on the cyclone inlet angle. They discovered that the 45 angle of the inlet section was efficient in collection than the normal inlet section angle. In the meantime, a technique was created to enhance efficiency of collection with multiple cyclones. Tang et al. (2023) tried to enhance the performance of the separation by crossing and connecting five cyclones in series and calibrated its performance at different flow rate, gas viscosity, and particle density. They designed a dual-cyclone in which two cyclones were linked by a single case and they tested its collection efficiency at various temperatures and flow rates and they also analyzed the performance of a double cyclone where a countercurrent cyclone design was fitted within a cyclone. He discovered that the double cyclone had greater collection efficiency, steeper collection efficiency curve and less pressure drop, than the conventional cyclones.

Elsayed and Lacor (2013) conducted an experiment of how the cyclone inlet dimensions affect the performance and flow field pattern. They discovered that the highest tangential velocity in the cyclone reduces as the cyclone inlet width and height increases, there is no acceleration in the cyclone space (the maximum tangential velocity is almost constant in the cyclone). The change of the static pressure and the axial velocity along the axial direction is also very small. They also found out that by increasing the width or the height of the cyclone inlet, the pressure drop is reduced at the expense of the cut-off diameter.

In the research of the impact of vortex finder diameter on the performance and flow pattern of a cyclone separator by means of CFD analysis, Chetiwal and Jhamnani (2018) discovered that the maximum tangential velocity in the cyclone is enhanced by reducing the vortex finder diameter and vice versa. The fact that the reduction of the vortex finder diameter will gradually increase the axial velocity through the cyclone and vice versa. The fact that the larger the vortex finder diameter, the less is the pressure drop in the cyclone. They also found out that when the diameter of the vortex finder is increased the collection efficiency of particulate matter is decreased. That as the inlet velocity is increased the collection efficiency of cyclone separator of the particulate matter is increased. They also came to a conclusion that a cyclone separator model can be optimized with the help of numerical technology of CFD approach

Taiwo et al. (2016) Cyclone separator is a process of particulate removal of an air, gas or liquid stream without filters, using vortex separation. Solid-fluid mixtures are separated by rotational effects and gravity. It is also possible to use the method to separate fine drops of liquid in a gaseous stream. The flow is made high speed rotating (air) in a cylindrical or conical containers known as a cyclone. The air moves in a helical manner starting at the top (wide end) of the cyclone and ends at the bottom (narrow) end of the cyclone before exiting the cyclone in a straight stream through the center of this cyclone and out the top. The larger (dense) particles in rotating stream possess too much inertia to trace the narrow arc of descent to the bottom of the cyclone where they can descent to the bottom of the stream, and collide with the outside wall, then descent to the bottom of the cyclone where they can be removed. In a conical system, the cyclone being the rotational radius of the stream is minimized hence separating smaller particles. The cut point of the cyclone was determined by the cyclone geometry along with flow rate. This is the size of particle which will be extracted out of the stream with 50 percent efficiency. The larger particles than the cut point will be removed more efficiently and smaller particles less efficiently.

They also add that another design of the cyclone involved a secondary air flow inside the cyclone to prevent the particles collected to hit the Walls, to avoid abrasion of the Walls. The primate air flow with the details in it flows in at the bottom of the cyclone and is forced into spiral rotation by the fixed Spinner vanes. The secondary air flow gets in through the top of the cyclone and flows down the bottom, catching the particulate in the primary air. The secondary air flow also enables the collector to be mounted horizontally optionally since it directs the particulate to the collection region and does not depend entirely on the force of gravity to accomplish this. Sawmills use large scale cyclones to eliminate sawdust that is extracted in the air. Oil refineries also use cyclones to separate oils and gases and in the cement industry as part of the kiln pre-heaters. Industry and professional kitchen ventilation also employ those cyclones in separating the grease in the exhaust air of extractions hoods.

The use of cyclones in the house hold is on the increase, as the core technology in bag-less. Although the cyclone separator works in a simple way, the fluid dynamics and flow structures in a cyclone separator are very complex. This apparatus is a vertical cylindrical setting chamber so arranged that the particles laden air spirals round the cylinder to the outer wall. The popularity of cyclones is due to the fact that they have no moving parts that can wear out or break, the moving part is non-existent and it is mostly a drum with a funnels on the bottom and inlet including export. In agricultural processing business,

Salehyar et al. (2023), studied the influence of rotating the body of the cyclone on its efficiency. They found that rotating the cyclone body increased the performance significantly, by approximately 10-13 percent over a stationary cyclone, at the same flow rate and particle size. This observation was confirmed by experimental and numerical tests. The faster rotation speed led to the increased impacts of the rotation speed on the cyclone efficiency. That when the cyclone body is rotated at the same speed of 1900 rpm in opposite direction of the inlet flow, the cyclone performance reduces by approximately 48%. This is because of internal flow and increase in pressure drop at the cyclone, increased inlet mixing air currents and a variation in the centrifugal force relative to the stationary body at the same flow rate and particle size. Consequently, it is possible to note that the rotational direction of the cyclone affects the cyclone efficiency. They also observed that the rotation of cyclone in the direction of inlet flow results to a more even distribution of pressure and volume fraction of particles, which generates the tangential velocity and enhances the centrifugal force, thus the tendency of the particle to be closer to the cyclone wall and the cyclone efficiency.

In the research of performance analysis of square cyclone separator, experimental and CFD approach to multi-objective optimization (Venkatesh et al., 2020), it is stated that the separation pattern and separation efficiency were determined in CFD simulations and the results indicated that the optimal square cyclone was the most successful. In a different study, the flow pattern of a cyclone which gathers large particles and adjoining cyclones which gather small particles was experimented and simulated using CFD. One of the most outstanding issues during the computation of the efficiency of cyclone is the influence of flow characters in cyclone. In large cyclones the flow is turbulent and the assumed friction factors yield satisfactory results.

Small cyclones are not true in this case. The flow within small cyclones may be laminar or even transitional. The operational conditions such as velocity, temperature, pressure, viscosity and cyclone diameter could be of great importance in such case and its influence varies with cyclone to cyclone. Operating parameters determine the efficiency of cyclone in laminar flow more than in turbulent case. This renders the efficiency and pressure drop very hard to predict particularly in small cyclone. The majority of the models are based on the empirical or semi-empirical equations. The models determine efficiency and estimate the cutoff size that is associated with 50 percent efficiency. Alves et al. (2015) state that the performance of a cyclone depends on geometry and operating conditions of a cyclone, and particle size distribution of the entrained particulate matter.

A number of models have been advanced to forecast the effectiveness of cyclone. The scientists are in a general agreement that operating parameters do certainly influence the performance of cyclones and thus they must be incorporated in the modeling. A lot of theories explain density, velocity of the gas, viscosity and the diameter of the particle. There is variation in approach of different scientists as far as effect of geometry is concerned. All the geometric parameters are considered by some and only few important parameters such as inlet and outlet diameter and height are considered in their models by some.

As stated, the majority of the theories assume cut size d50 that is the diameter of particle at which 50 percent of particles smaller and 50 percent of particles larger than that size will be collected.

There are two most common methods of calculating efficiency: Force Balance Theory (Lapple) that presupposes terminal velocity is reached when drag fore and centrifugal force are equal and Static Particle Approach that takes into consideration simple force balance when forces acting on particle are balanced. Many other complex theories have been put forward but basically they are all founded on either one of the two theories.

In the research of Evaluation of Centrifugal Force, Erosion, Strain Rate, and Wall Shear in a Stairmand Cyclone, Dizajyekan et al. (2022) stated that the centrifugal force exerted on wheat particles within the cyclone was enhanced through the increase in the inlet velocity. Also, the fluctuation of the Euler number was increasing with the increment of the inlet velocity. However, the Stokes number was increasing till the velocity of 16 ms 1 and then a small increase and decrease was indicated in this parameter. These are the significant outcomes that can be applied during the operation phases. Also the highest erosion rate was attained in the entrance and conical parts of the cyclone. It is interesting to note that the pattern of the distribution of the erosion on the cyclone wall is similar to the path of the wheat seeds. Also, the particles are more affected by the flow in V in= 16 m s -1. Conversely, in Vin = 10 m s -1 the effect of the flow on the particles is smaller than other velocities of the inlets. The domain of strain rate was enhanced by raising the inlet velocity. Then, it was elaborated in the neighboring sections in a gradual way. The primary effect of the increase in the inlet velocity was the bottom edge of the vortex finder. Also, an increase in the mass flow rate increased the strain rate within the cyclone. That it can be contended that it was increase because the cyclone was working at a higher mass flow rate and higher collision of the particles.

The highest wall shear is produced at the cyclone entrance and the high momentum of flow might be the main reason behind it. Also, the low wall shear was generated at the lower portion of the conical area. The shear of the wall was enhanced by increasing the mass flow rate. Finally, one can arrive at a conclusion that within the range of inlet velocity and mass flow rate, the V in= 16 m s -1 and mass flow rate. m= 0.01 is the most appropriate to be applied in the conveying process in wheat conveying cyclone. It may also be noted, that the entrance and conical parts of the cyclone are the most important parts in the perspective of erosion of a wheat conveying cyclone separator

In any of these experiments and studies, there has not been a hybrid set up where a combination of a vertical cyclone and a horizontal cyclone has been set up in the best way possible in a bid to establish the best orientation of the two so as to increase on the collection efficiency. Vortex diameter will also be examined so as to determine optimal diameter.

Summary of Research Gaps

Table 2-1: Summary of Research Gaps

RESEACAHER	TOPIC	FINDINGS
Sui,W(2023)	The secondary flows in a cyclone	Secondary flows such as recirculation, short-circuit and eccentric circumfluence, significantly impact the performance of cyclone separators
Zhao et al(2017)	Performance improvement of a cyclone separator using different shapes of vortex under high temperature operating condition	Altering the shape of the vortex finder in cyclone separators can significantly enhance performance under high temperature conditions. These modifications can lead to better separation efficiency and reduced pressure drop which are crucial for optimizing cyclone performance in demanding environments

Martignoni and Luciano (2017)	A comparison of numerical optimization methods for cyclone separators	That the numerical optimization methods, particularly those utilizing computational fluid dynamics (CFD), are effective in enhancing the performance of cyclone separators. These methods help identify optimal configurations and operational parameters, leading to improved efficiency and reduced operational costs
Balestrin et al. (2017)	An alternative for collection of small particles in cyclone; Experimental analysis and CFD modeling	This study concluded that using a combination of experimental analysis and CFD modeling can provide valuable insights into the performance of cyclone separators. This approach helps designing more efficient separators capable of handling small particles effectively.
Siadaty et al. (2018)	Research on the effects of operating conditions and inlet channel configurationon energy loss, heat transfer and irreversibility of fluid flow in single and double inlet cyclones	This study concludes that the operating conditions an inlet channel configuration significantly affects energy loss, heat transfer and fluid flow irreversibility in cyclone separator performance and energy efficiency.

CHAPTER 3: MATERIALS AND METHODS

3.1 Materials

Fully subscribed Simulation software, ANYSIS for simulation

Modelling software- fully subscribed for modeling the hybrid cyclone

Laptop, 6 gb ram , 128gb rom

3.2 Methods

This section presents the methods of the experiment

3.2.1 Experimental Design

In this study, factorial design was employed where the hybrid cyclone was taken as independent variable and effects of diameter change were monitored.

The use of factorial design is required due to the fact that it allows assessing multiple independent variables simultaneously. It provides a complete overview of the interaction of various components and their influence on the result, which is required to address interactions. It can easily gather a huge and varied amount of data by observing several parameters simultaneously in a single experiment, which makes the findings more plausible and valid.

The advantage of factorial design is that it can show the interaction of factors that would otherwise not be known had each factor been studied independently. In order to understand complex phenomena better, one should understand how these interactions occur. This will enhance the general quality and depth required. The results are also more reliable in this design since any confounding variables are controlled thus making the results more applicable in real life situations.

Moreover, factorial design is more powerful in the sense that it provides more data points and allows locating small effects more easily. It was more convenient to consider main effects, interaction effects, and even higher-order interactions because it was not rigid in the way it analyzed data. This rendered the data more complicated and practical. This is the usefulness of factorial design..

3.2.2 Experimental procedure

3.2.2.1 Problem Definition and Objective Setting

The first stage in conducting this research was to precisely describe the problem and study goals. The main goal was to see how well a hybrid cyclone separator could pick up small particles. To find out how different design changes, flow conditions, and particle qualities affect the performance of the separator, specific goals were set. These goals gave the study a definite path to follow, making sure that the analysis would produce useful and relevant information.

3.2.2.2 Design and Geometry Specification

After establishing the study objectives, the following step was to specify the design and geometry of the hybrid cyclone separator. This method involves creating a new configuration that fits the needs of this investigation. There were very detailed descriptions of the cyclone, including the sizes of the body, intake, and output arrangements. Then, Computer-Aided Design (CAD) software was used to turn the final design into a digital model so that the Computational Fluid Dynamics (CFD) simulations could be run..

3.2.2.3 Mesh Generation

After the geometry of the cyclone separator was defined, a computational mesh was generated to discretize the model to perform CFD. The mesh was created using advanced meshing tools with the correct level of detail particularly in key regions such as the cyclone intake, vortex finder and dust outflow. These places required a finer mesh in order to represent the flow dynamics there adequately since they were characterized by high gradients of velocity, pressure, or turbulence. The quality and the structure of the mesh were quite crucial in ensuring that the CFD simulations that followed were accurate and reliable.

3.2.2.4 Boundary Conditions and Initial Setup

Once the mesh had been generated, the CFD model was provided with boundary conditions to define the flow domain. We specify the inlet velocity or mass flow rate, the outlet pressure and the boundary conditions on the wall, such as no-slip boundary conditions. The type and size distribution of the particles which had to be examined were also determined. We predetermined the initial conditions of the flow field and the distribution of the particles such that the simulation can have a starting point. Such processes were required to make a realistic and accurate simulation environment.

3.2.2.5 Selection of Turbulence and Dispersed Phase Models

Selection of the appropriate models of the turbulence and dispersion phases was also a significant aspect of the simulation setup. Depending on the complexity of the flow of the cyclone, different turbulence models such as k-e, k-w and Reynolds Stress Model (RSM) were tested. Particulate phase was treated by the Eulerian technique due to the size and concentration of the particles. We chose Lagrangian model to track each particle and the Eulerian model to represent the particulate phase as a fluid that flows continuously. This selection process was quite crucial in ensuring that the CFD model would be able to adequately predict the way the cyclone would behave in various scenarios.

3.2.2.6 Simulation Setup and Execution

Once the mesh and models were prepared, the CFD simulation was prepared in the software environment. The solver parameters, including the time step, convergence criteria and numerical methods were configured to ensure that the calculations were accurate and efficient. In most cases, the simulation approach began with a steady-state analysis. Where needed, transient analysis was performed next to record events that varied with time. The solver repeated the calculations numerous times to obtain the flow field, pressure distribution and the particle paths in the cyclone separator. This provided us with accurate data on its effectiveness.

3.2.2.7 Data Collection and Analysis

After the convergence was reached, the simulation results were retrieved and analyzed to find out the performance of the hybrid cyclone separator. Attention was given to such key performance indicators as collection efficiency, pressure drop, and velocity profiles. We examined the effectiveness of the cyclone and any additional systems to collect particles by examining the percentage of particles that were captured. We also considered pressure drop across the separator to determine how much energy the cyclone requires to operate..

3.2.2.8 Validation of CFD Results

The results of CFD were checked against the available experimental data or previous study results to ensure their accuracy and reliability. As part of this validation process we compared the CFD-generated metrics, including pressure drop and collecting efficiency, to real-world data. In case of any differences, the simulation was refined by altering the mesh, boundary conditions or turbulence models, etc. This validation was quite crucial in ensuring that the CFD model represented the working of the hybrid cyclone separator correctly.

3.2.2.9 Optimization and Iterative Refinement

According to the initial findings of the CFD simulation, the various design parameters were varied to ensure that the hybrid cyclone separator functions optimally. It was necessary to alter the shape of the cyclone, the inflow velocity and the particle size distribution. These new settings were then used to run the CFD simulations once more. We closely observed the results of these repeated simulations to get an idea on how the changes influenced things. This repetition went on and on until the required performance specifications were achieved and ensured that the end design is as efficient and effective as it could be.

3.2.2.10 Documentation and Reporting

The last section of the study involved the detailed description of the CFD analysis process and its findings. This documentation contained complete descriptions of the geometry, mesh generation, boundary conditions, turbulence models, and the simulation output. The documentation also addressed the optimization process, the validation efforts, and any significant new information that emerged as a result of the study. This careful reporting was significant to the thesis since it provided a clear and comprehensive image of the research process and its findings. It also ensured that the study could be replicated or extended in future.

Geometry, mesh and boundary Conditions

Geometry, mesh and boundary were set as below

Global Mesh Settings

Automatic initial mesh: On

Result resolution level: 3

Advanced narrow channel refinement: Off

Geometry Resolution

Evaluation of minimum gap size: Automatic

Evaluation of minimum wall thickness: Automatic

Table 3-1 Computational Domain Size

X min	-0.734 m
X max	0.959 m
Y min	-0.107 m
Y max	2.429 m
Z min	0.097 m
Z max	1.680 m
X size	1.693 m
Y size	2.536 m

Z size	1.584 m

Table 3-2 Boundary Conditions

2D plane flow	None
At X min	Default
At X max	Default
At Y min	Default
At Y max	Default
At Z min	Default
At Z max	Default

Physical Features

Heat conduction in solids: Off

Time dependent: Off

Gravitational effects: Off

Rotation: Off

Flow type: Laminar and turbulent

High Mach number flow: Off

Humidity: Off

Free surface: Off

Default roughness: 0 micrometer

Default wall conditions: Adiabatic wall

Table 3-3 Initial Conditions set

Thermodynamic parameters	Static Pressure: 101325.00 Pa Temperature: 293.20 K
Velocity parameters	Velocity vector Velocity in X direction: 30.000 m/s Velocity in Y direction: 0 m/s Velocity in Z direction: 0 m/s
Turbulence parameters	Turbulence intensity and length Intensity: 2.00 % Length: 0.016 m

Material Settings

Fluids

Air

Table 3-4 Fluid Subdomains

Fluid Subdomain 1

Default fluid type	Gas/Steam/Real Gas
Fluids	Air
Faces	Face<1>@LID33-1
Coordinate system	Face Coordinate System
Reference axis	X
Thermodynamic Parameters	Static Pressure: 101325.00 Pa

	Temperature: 293.20 K
Velocity Parameters	Velocity in X direction: 30.000 m/s Velocity in Y direction: 0 m/s Velocity in Z direction: 0 m/s
Turbulence parameters type:	Turbulence intensity and length
Intensity	2.00 %
Length	0.016 m
Flow type	Laminar and Turbulent
Humidity	Off

Boundary Conditions set

Environment Pressure 2

Type	Environment Pressure
Faces	LID33-1/Imported1//Face
Coordinate system	Face Coordinate System
Reference axis	X
Thermodynamic parameters	Environment pressure: 101325.00 Pa Temperature type: Temperature of initial components Temperature: 293.20 K
Turbulence parameters	Turbulence intensity and length Intensity: 2.00 % Length: 0.016 m

Boundary layer parameters	Boundary layer type: Turbulent

Inlet Velocity 2

Type	Inlet Velocity
Faces	LID34-1/Imported1//Face
Coordinate system	Face Coordinate System
Reference axis	X
Flow parameters	Flow vectors direction: Normal to face Velocity normal to face: 30.000 m/s Fully developed flow: No
Thermodynamic parameters	Approximate pressure: 101325.00 Pa Temperature type: Temperature of initial components Temperature: 293.20 K
Turbulence parameters	Turbulence intensity and length Intensity: 2.00 % Length: 0.016 m
Boundary layer parameters	Boundary layer type: Turbulent

Environment Pressure 3

Type	Environment Pressure
Faces	LID31-1/Imported1//Face
Coordinate system	Face Coordinate System
Reference axis	X

Thermodynamic parameters	Environment pressure: 101325.00 Pa Temperature type: Temperature of initial components Temperature: 293.20 K
Turbulence parameters	Turbulence intensity and length Intensity: 2.00 % Length: 0.016 m
Boundary layer parameters	Boundary layer type: Turbulent

Total Pressure 4

Type	Total pressure
Faces	LID32-1/Imported1//Face
Coordinate system	Face Coordinate System
Reference axis	X
Thermodynamic parameters	Total Pressure: 101325.00 Pa Temperature type: Temperature of initial components Temperature: 293.20 K
Turbulence parameters	Turbulence intensity and length Intensity: 2.00 % Length: 0.016 m
Boundary layer parameters	Boundary layer type: Turbulent

3.2.3 Experimental set up

The hybrid set up was arranged as below

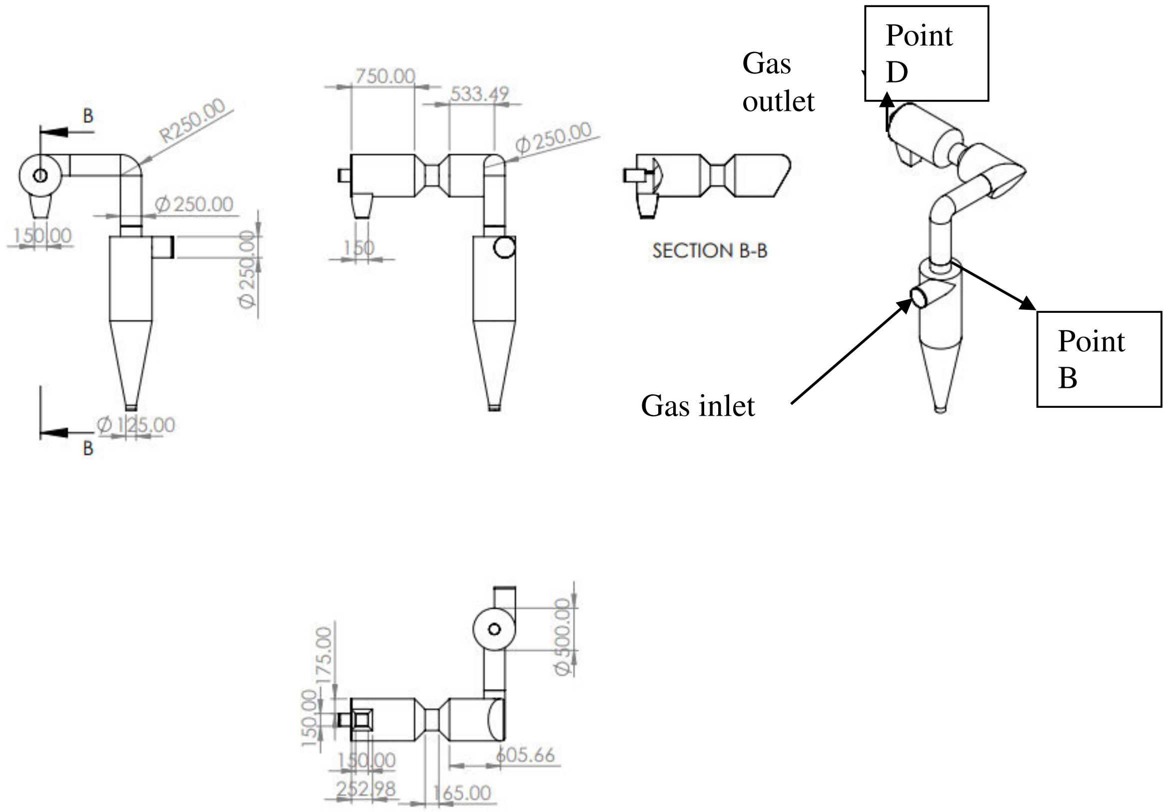


Figure 3-1-Experimental design set up

The design was arranged as seen in figure 3 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.

3.2.4 Design Analysis

3.2.4.1 Overview of Experimental Design

The experiment was meticulously designed to evaluate the performance of a hybrid cyclone separator using Computational Fluid Dynamics (CFD) as the primary analytical tool. The goal was to simulate and optimize the separator's efficiency in capturing particulate matter under various operating conditions. The experiment was structured to systematically explore the influence of key design parameters, including the cyclone's geometry, flow dynamics, and particulate properties. This comprehensive approach ensured a thorough understanding of how each factor affects the separator's overall performance.

3.2.4.2 Selection of Key Variables

The experiment was keen on selecting critical variables to be analyzed in detail. These were:

• Cyclone Geometry: This was the investigation of the effect of the geometry of the cyclone i.e. the diameter, the height of the cyclone, inlet and outlet shapes. It was assumed that the modifications in these dimensions would alter the patterns of internal flow and, therefore, the separator efficiency dramatically.

• Flow Conditions: The experiment was devoted to the study of the influence of the inlet velocity and pressure change on the performance of the cyclone. The importance of such flow conditions is that they determine the energy available to separate the particles and affect the pressure drop across the separator.

• Particulate Properties: Size, density and concentration of the particulates were determined as important variables. These characteristics were to play a major role in the interaction between the particles and the internal flow of the cyclone and hence the effectiveness of the separation.

CFD Simulation Design

This experiment was devoted to the CFD simulation design. It employed the factorial design that offered the opportunity of a systematic variation in the selected parameters. This method provided a close analysis of the primary effects of each variable and the interaction of the variables. The simulations were made in a manner that they are able to capture the complex behavior of the geometry of the cyclone, the flow conditions and the particulate properties. Models played a very important role in the selection of the CFD software:

- Turbulence Modeling: The flow in the cyclone is very turbulent and hence the turbulence models, which have been chosen, are the k-epsilon model and the Reynolds Stress Model (RSM) capable of modeling complex flow phenomena like swirl and recirculation.
- Particle Tracking: Lagrangian technique was used to track particles and this enabled tracking of individual particle trajectories. The method was quite helpful in ascertaining the effectiveness of the separator in terms of the variation in the size and density of the particles.

The orthogonal matrix for the design of experiment was a mixed 2-3 factor matrix L_{54} runs as shown

Table 3-5 orthogonal matrix for the design of experiment

Type of Cyclone	Diamete, D (mm)	Pressure, Pa	Density, Kg/m3	Temperature change(K)	Velocity change(m/s)	Relative Pressure, Pa	Efficiency %
Conventional	150						
Conventional	200						
Conventional	250						
Hybrid	150						
Hybrid	200						
Hybrid	250						

3.2.4.3 Validation and Calibration Process

Accuracy and reliability of the model included the validation and calibration of the CFD model. This was achieved through the comparison of the CFD results and experimental data that is available in the literature or in the preliminary laboratory tests. The parameters of the model were adjusted where need be to ensure that the simulation results were in line with the observed data to improve the precision of the model. This validation and calibration step played a vital role in enhancing validity of simulation results

3.2.4.4 Sensitivity Analysis

A sensitivity analysis was conducted to identify the most important parameters which affect the performance of the cyclone separator. It was analyzed by changing one parameter and keeping the rest unchanged to identify the factors of the design that affected efficiency and the pressure drop the most. The analysis gave these results which were applied in the optimization stage by determining the design areas that would most probably influence the performance in a positive manner.

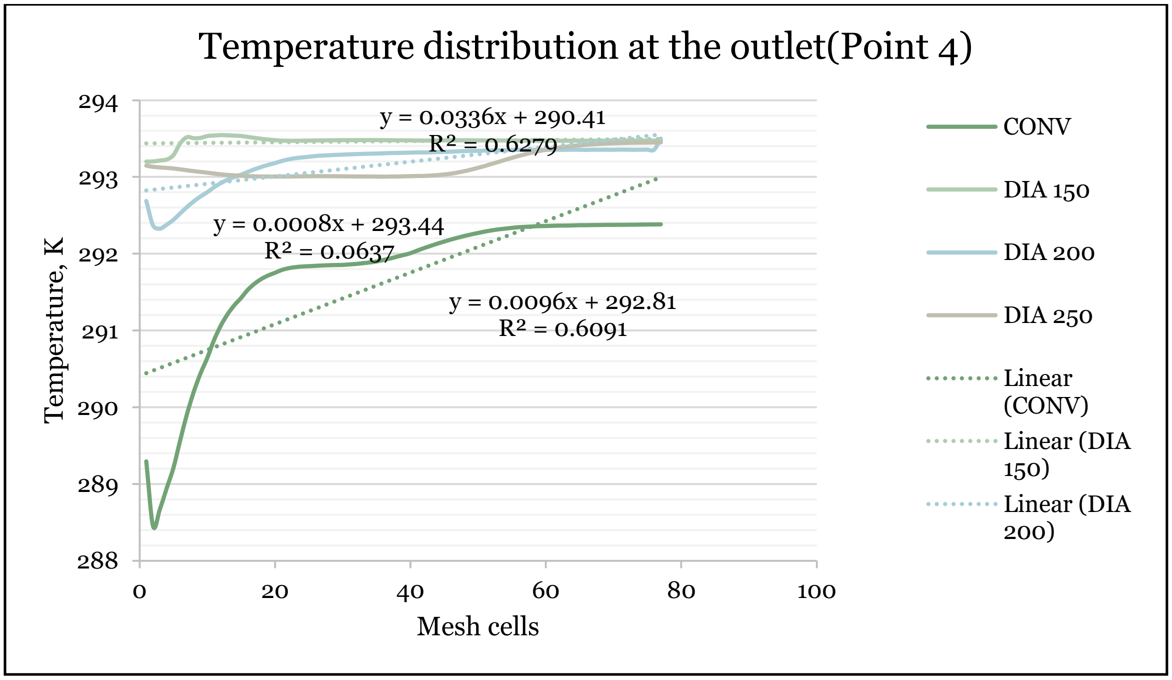
3.2.4.5 Optimization Strategy

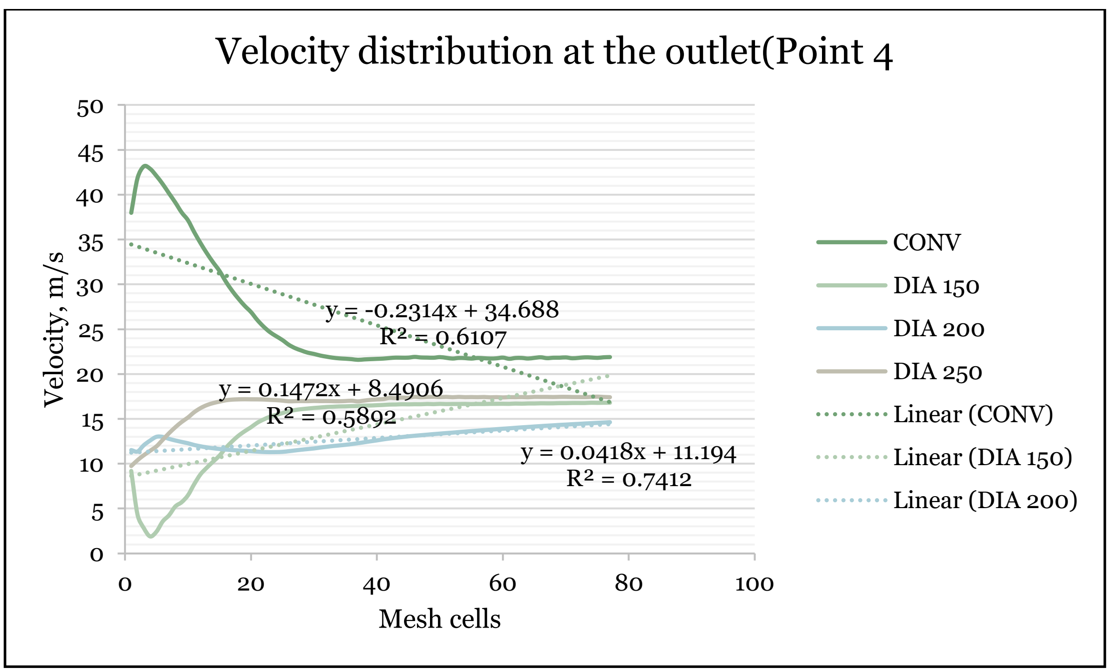
The final step in the design analysis was formulation of an optimization strategy. The cyclone was optimized iteratively using the information gained in the initial set of simulations and sensitivity analysis so as to attain optimal performance. This was in terms of geometry optimisation, flow condition optimisation and particulate property optimisation in order to achieve a balance between high collection efficiency and low pressure drop. The method was employed to ensure that the final design of the hybrid cyclone separator would meet the objectives of the study to offer effectiveness and efficiency to industrial application. The detailed design analysis provided a good foundation upon which the CFD simulations were performed and their results analyzed to provide a greater understanding on how hybrid cyclone separators can be optimized to perform better. ANOVA was used to determine the significance of effects of the inlet diameter on velocity, temperature, pressure and efficiency

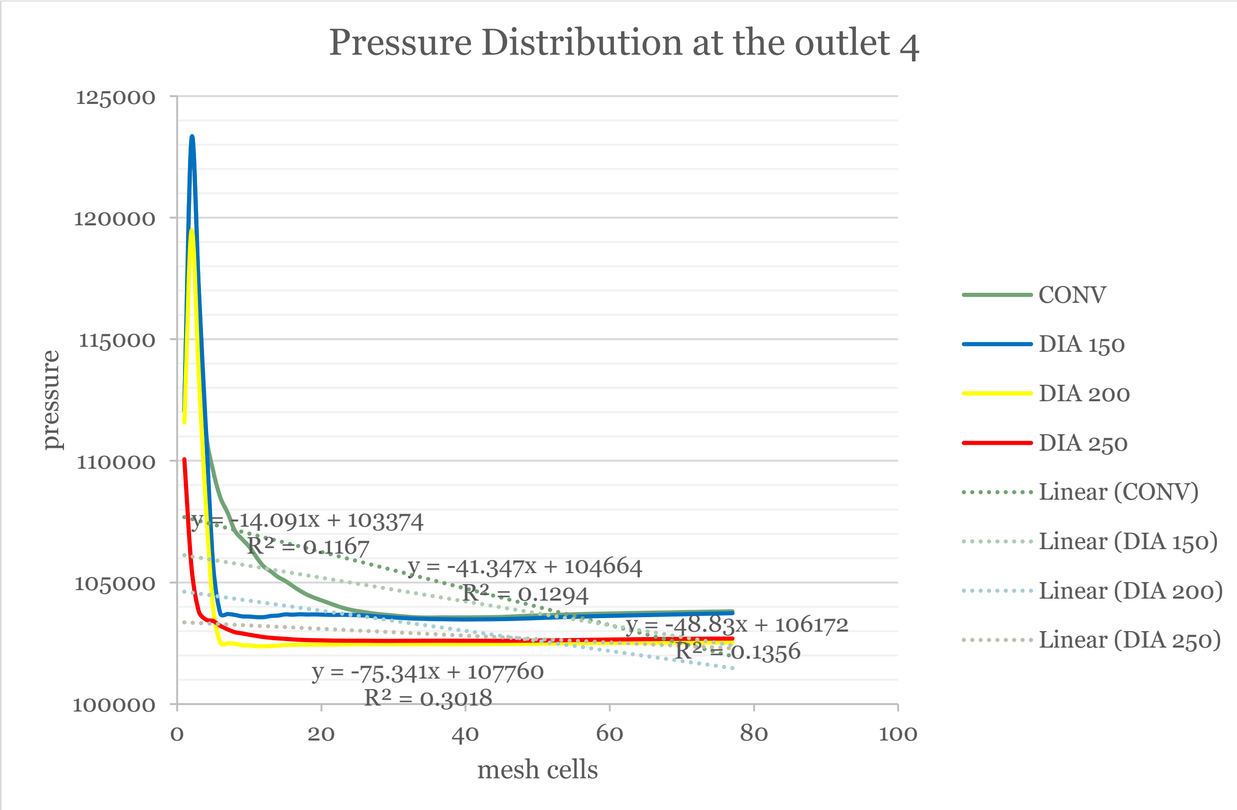
CHAPTER 4: RESULTS AND DISCUSSION

4.1 Determination of the effect of design parameters of the hybrid cyclone

4.1.1 Effect of inlet diameter on Temperature, velocity and pressure







DISCUSSION

It is seen from the experiment that once the gas enters the cyclone, temperature takes a small dip then rises steadily and is maintained at 293.47 K for 250mm diameter, 293.45 K for 200mm diameter and 293.47 K for 150mm diameter. It is evident therefore to note that the hybrid cyclone maintains a relatively high temperature throughout.

From the graphical representations, it is observed that velocity increases steadily for the diameters and then stabilizes at 16.79 m/s for 150mm diameter, at 16.69m/s for 200mm diameter and at 16.15 for 250mm. This shows that velocity of gas inside the hybrid cyclone decrease with increase in diameter. It therefore important to note that the hybrid cyclone is able to sustain stable velocity throughout

It is observed that there are differences in pressure achieved for the diameters varied.

For diameter 150mm pressure was 103,816 pa, for diameter 200mm pressure achieved was 102,660mm and for diameter 250 mm pressure achieved was 102, 766. This is therefore small visible changes with diameter variations of the hybrid.

Table 4-1- summary of the observations of Hybrid and conventional cyclone

Type of Cyclone	Diameter, D (mm)	Pressure, Pa	Density, Kg/m3	Temperature change(K)	Velocity change(m/s)	Relative Pressure, Pa	Efficiency %
Conventional	150	101,881.36	1.21	293.47	16.65	567.97	63.35
Conventional	200	101,945.69	1.21	293.45	16.51	624.26	63.42
Conventional	250	102,117.86	1.21	293.46	15.72	794.86	63.69
Hybrid	150	101,295.93	1.20	293.47	16.79	-28.93	81.26
Hybrid	200	101,025.64	1.20	293.32	16.69	-299.13	81.90
Hybrid	250	101,353.10	1.20	293.44	16.15	28.10	81.95

Therefore Convention Cyclone is represented by the table below

Table 4-2- summary of the observations of conventional cyclone

Diameter, D (mm)	Pressure, Pa	Density, Kg/m3	Relative Pressure, Pa	Efficiency %
150	101,881.36	1.21	567.97	63.35
200	101,945.69	1.21	624.26	63.42
250	102,117.86	1.21	794.86	63.69

ANOVA analysis

Table 4-3 Coded Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	1.20220	0.00062	1953.11	0.000	
A	0.001052	0.000487	2.16	0.067	1.00
B	0.000198	0.000487	0.41	0.696	1.00
A*A	0.000213	0.000522	0.41	0.696	1.02
B*B	-0.000287	0.000522	-0.55	0.599	1.02
A*B	0.000250	0.000688	0.36	0.727	1.00

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0013764	44.03%	4.05%	0.00%

Table 4-4 Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	5	0.000010	0.000002	1.10	0.437
Linear	2	0.000009	0.000005	2.42	0.159
A	1	0.000009	0.000009	4.67	0.067
B	1	0.000000	0.000000	0.17	0.696
Square	2	0.000001	0.000001	0.27	0.772

A*A	1	0.000000	0.000000	0.17	0.696
B*B	1	0.000001	0.000001	0.30	0.599
2-Way Interaction	1	0.000000	0.000000	0.13	0.727
A*B	1	0.000000	0.000000	0.13	0.727
Error	7	0.000013	0.000002		
Lack-of-Fit	3	0.000006	0.000002	1.27	0.398
Pure Error	4	0.000007	0.000002		
Total	12	0.000024			

A one-way ANOVA was conducted to examine the differences in efficiency between conventional and hybrid cyclone separators across various diameters. The analysis produced an F-statistic of 5522.60 and a p-value of 1.96×10^{-7}.

Interpretation:

The high F-statistic indicates substantial variance between the two types of cyclone separators, far exceeding the variance within each group. Additionally, the extremely low p-value, well below the 0.05 significance level, suggests that the observed differences in efficiency are statistically significant.

Conclusion:

Based on these results, the null hypothesis (H_0), which proposed no significant difference in efficiency between the cyclone types, is rejected. Instead, the alternative hypothesis (H_1) is accepted, confirming that there is a statistically significant difference in the efficiency of conventional and hybrid cyclone separators. Specifically, the hybrid separators demonstrate markedly higher efficiency compared to the conventional separators across all tested diameters. This finding underscores the superior performance of the hybrid design in particulate capture efficiency.

Regression Equation in Uncoded Units

$$\text{Density} = 1.20220 + 0.001052\ A + 0.000198\ B + 0.000213\ A*A - 0.000287\ B*B + 0.000250\ A*B$$

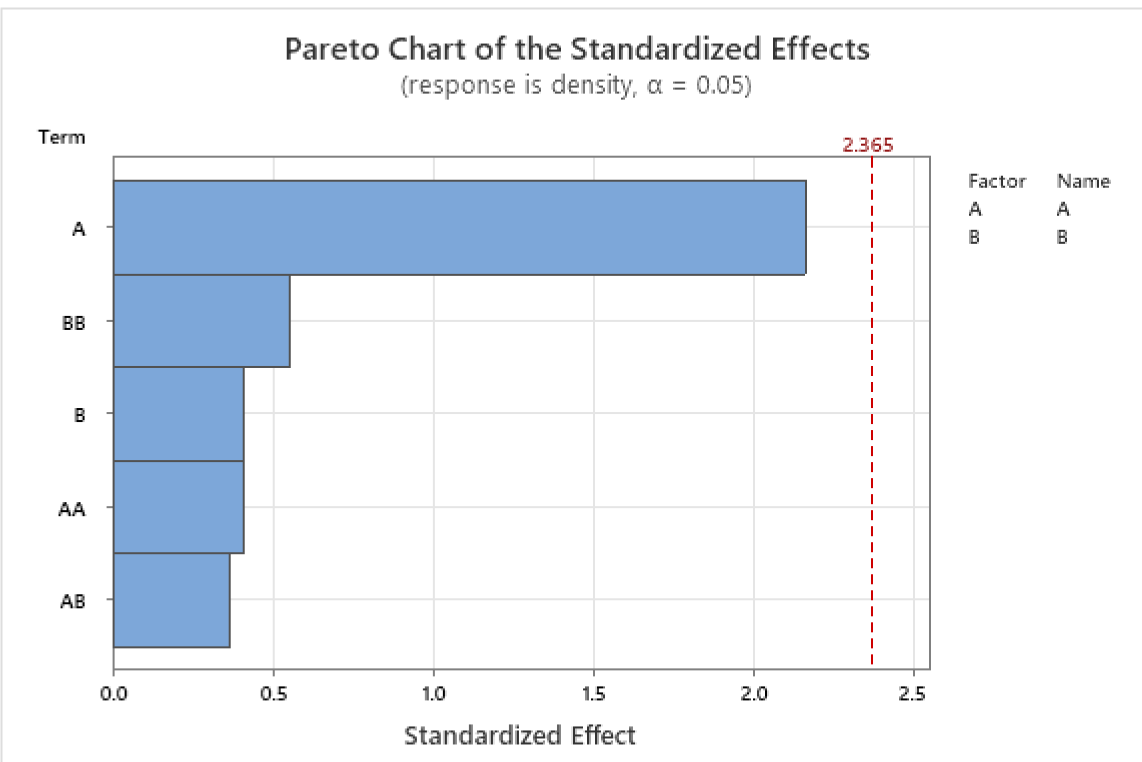


Figure 4-1 Pareto chart for standardized effects

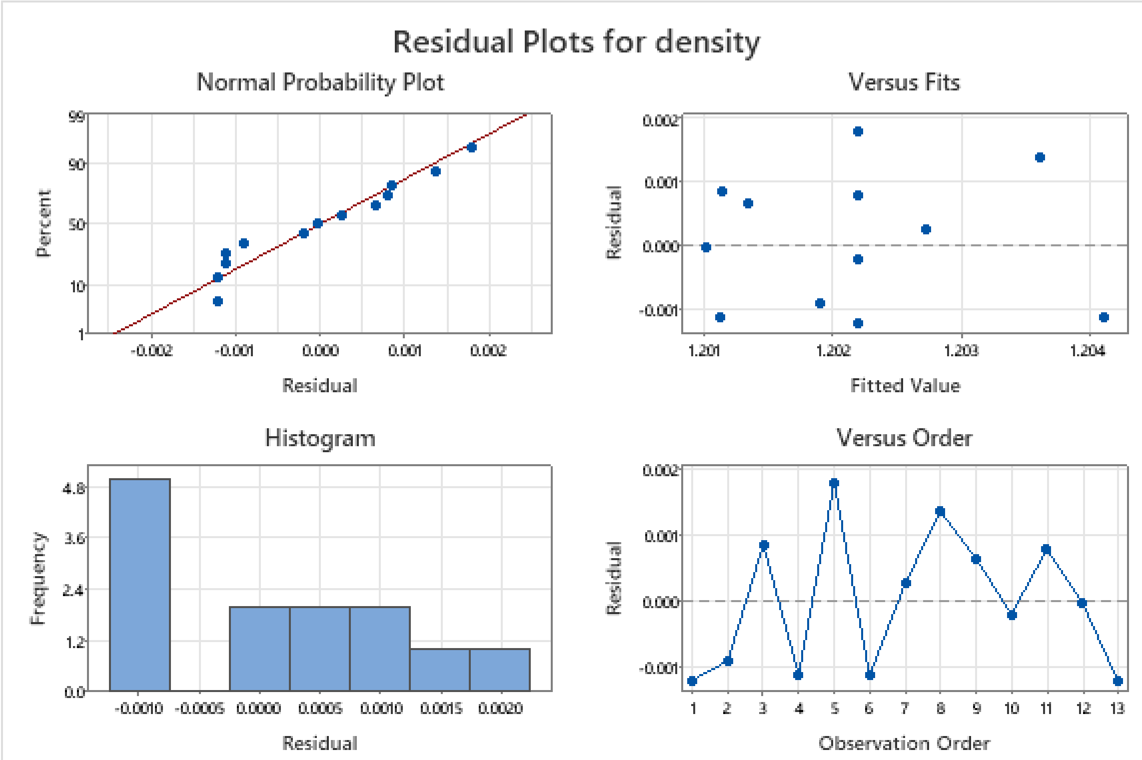


Figure 4-2 Residual plots for density

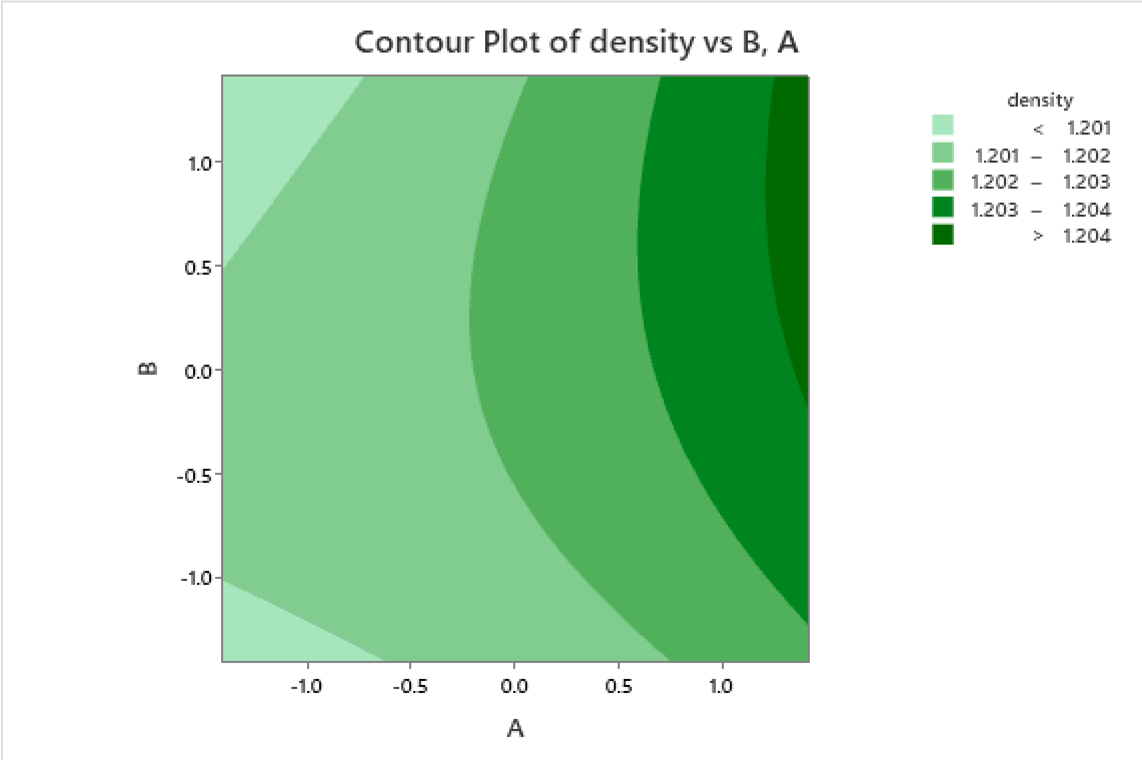


Figure 4-3 contour plot of density vs B, A

KEY

A-Diameter

B-intercept

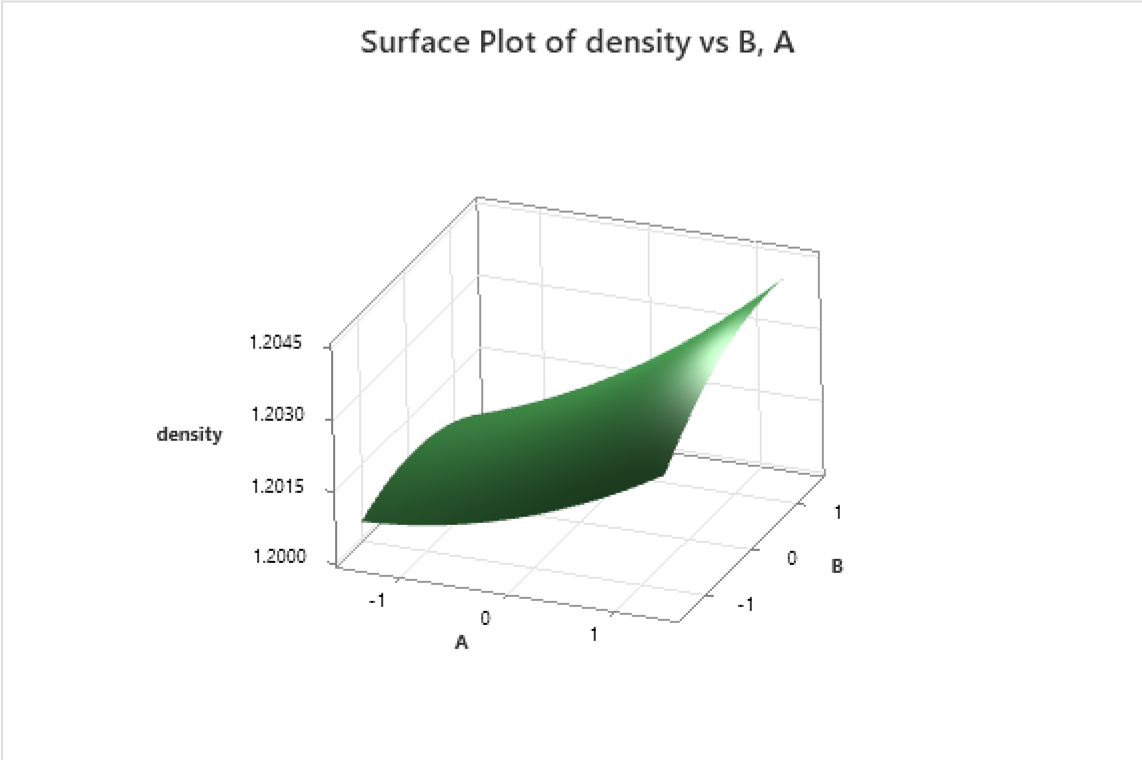


Figure 4-4 Surface plot of density vs B, A

It is seen from the analysis that there is marked improvement in terms of efficiency

There is significant amount of particulate matter collected by the hybrid cyclone

From the density column, conventional density is 1.21 kg/m3 while on the hybrid side it is 1.20 for all the diameters. This is also another indication that with the use of the hybrid cyclone there is a positive effect in term of reduction of particulate matter leaving the system.

4.2 Impact of cyclone orientation of hybrid cyclone on the collection efficiency of particulate fly ash

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

a) Temperature

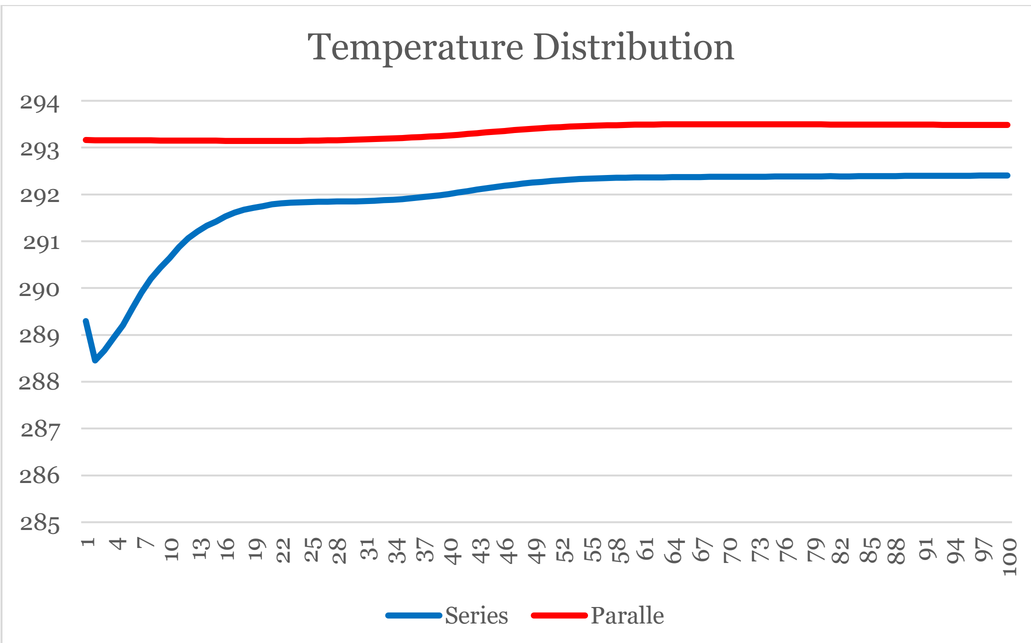


Figure 4-5-Graph for temperature distribution in the hybrid cyclone Diameter 250mm

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.

b) Pressure

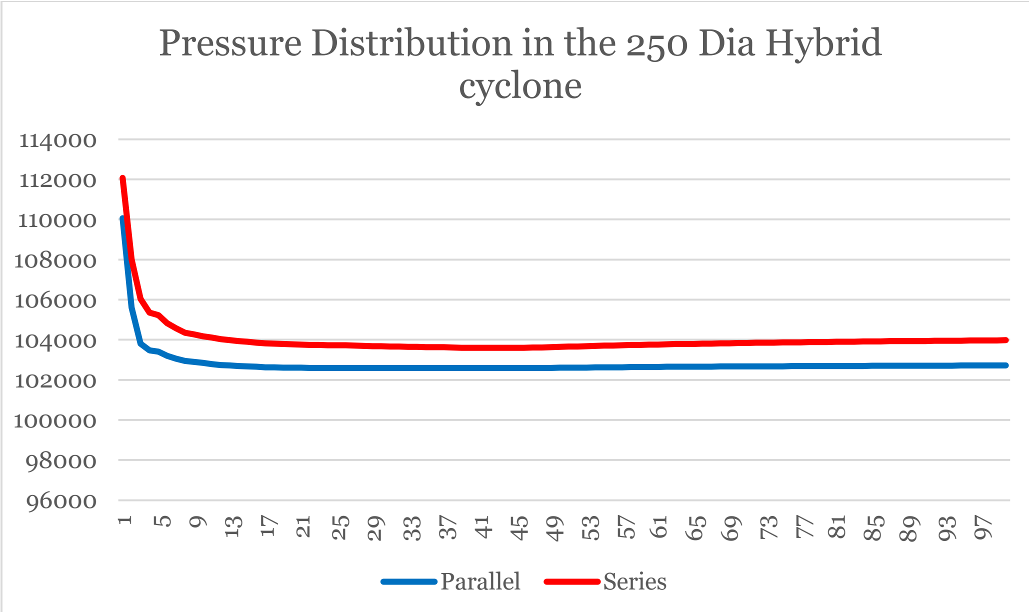


Figure 4-6-Graph for pressure distribution in the hybrid cyclone Diameter 250mm

Table 4-5-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%

DISCUSSION

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.

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.

4.3 To develop a Mathematical model for the hybrid cyclone

Table 4-6-summary of the observations of Hybrid and conventional cyclone-Series orientation

Type of Cyclone	Diameter, D (mm)	Pressure, Pa	Density, Kg/m3	Relative Pressure, Pa	Efficiency %
Conventional	150	101,881.36	1.22	567.97	63.35
Conventional	200	101,945.69	1.23	624.26	63.42
Conventional	250	102,117.86	1.22	794.86	63.69
Hybrid	150	101,295.93	1.21	-28.93	81.26
Hybrid	200	101,025.64	1.21	-29.13	81.90
Hybrid	250	101,353.10	1.21	28.10	81.95

A linear regression analysis for the Series hybrid cyclone was conducted to explore the relationship between the diameter of the cyclone separator and its efficiency as shown.

Regression Equation for the Series Hybrid cyclone

Diameter,D (mm)		
150	Efficiency = %	-3318 + 0.05075 Pressure, Pa - 1441 Density, Kg/m3 - 0.05564 Relative Pressure, Pa
200	Efficiency = %	-3303 + 0.05075 Pressure, Pa - 1441 Density, Kg/m3 - 0.05564 Relative Pressure, Pa
250	Efficiency = %	-3317 + 0.05075 Pressure, Pa - 1441 Density, Kg/m3 - 0.05564 Relative Pressure, Pa

DISCUSSION

General Formula Structure

Each efficiency equation is a function of:

- **Pressure (Pa)** — increases efficiency
- **Density (kg/m³)** — decreases efficiency
- **Relative Pressure (Pa)** — also decreases efficiency
- **Constant term** — baseline offset, unique to each diameter

All equations follow the structure:

Efficiency (%) = Constant + (0.05075 × Pressure) - (1441 × Density) - (0.05564 × Relative Pressure)

Comparative Breakdown

Diameter (mm)	Constant Term	Pressure Coefficient	Density Coefficient	Rel. Pressure Coefficient
150	-3318	+0.05075	-1441	-0.05564

Diameter (mm)	Constant Term	Pressure Coefficient	Density Coefficient	Rel. Pressure Coefficient
200	-3303	+0.05075	-1441	-0.05564
250	-3317	+0.05075	-1441	-0.05564

Observations:

- Coefficients are identical across all diameters, which means pressure and fluid properties affect all systems similarly.
- The constant term varies slightly, implying minor intrinsic differences in baseline efficiency due to diameter-specific geometry or flow dynamics.

Interpretation

- The 200 mm diameter has the highest constant (-3303), meaning all else equal, it starts from a slightly higher baseline efficiency.
- Larger or smaller diameters (150 mm and 250 mm) trail slightly with constants of -3318 and -3317, suggesting negligible but measurable impact from internal flow structure or thermal dynamics.

- Efficiency performance is dominantly governed by operating pressure and fluid properties, not diameter alone.
- The 200 mm configuration may offer the best design trade-off for this system, but only marginally — real-world selection should factor in pressure ratings, cost, space constraints, and installation complexity.
- Ultimately, fine-tuning pressure conditions and minimizing fluid density will yield the most pronounced efficiency gains across all diameters.

Therefore the optimum mathematical model for the estimation of hybrid cyclone efficiency can be considered as:

Efficiency % = -3303 + 0.05075 Pressure, Pa - 1441 Density, Kg/m3 - 0.05564 Relative Pressure, Pa

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The study concludes that varying the inlet diameter significantly influences the hybrid cyclone's collection efficiency for particulate fly ash. Across diameters of 150 mm, 200 mm, and 250 mm, the hybrid cyclone consistently outperformed the conventional designs, achieving efficiencies between 81.26% and 81.95% compared to conventional cyclones' 63.35% to 63.69%. This improvement is attributed to optimized fluid dynamics, including stabilized temperature and velocity distribution, which enhance particulate settling and pre-filtration effectiveness. The 200 mm diameter emerged as the most balanced design, offering favorable pressure conditions and high baseline efficiency, making it a strong candidate for industrial adaptation.

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.

A regression-based mathematical model was successfully developed to estimate hybrid cyclone efficiency using parameters such as pressure, density, and relative pressure. The model, expressed as:

$\text{Efficiency (\%)} = -3303 + 0.05075P - 1441 \times \rho - 0.05564 \times P_r$

demonstrates that pressure positively contributes to efficiency, while density and relative pressure act as detractors. The model is robust across different diameters, offering a useful predictive tool for process engineers to estimate cyclone performance under varying operating conditions. Its validation against experimental data suggests high reliability and scalability for field application.

5.2 Recommendation

1. Dynamic CFD Modeling with Multiphase Flow-Future research should incorporate transient and multiphase flow simulations to capture particulate behavior in real-time operational conditions, especially in humid environments typical of Western Kenya.
2. Hybrid Cyclone Integration with Secondary Collectors-Investigate the synergy between hybrid cyclones and secondary particulate collectors like electrostatic precipitators and bag filters to develop a fully optimized dust mitigation chain.
3. Life-Cycle Cost and Durability Analysis-Extend the study to include economic modeling and wear analysis to assess the long-term sustainability, maintenance needs, and replacement cycles of hybrid cyclones in industrial settings.
4. Hybrid Cyclone Performance in Diverse Biomass Fuels-Evaluate how different biomass combustion by-products (e.g., maize cobs, coffee husks) affect cyclone behavior and performance, expanding applicability beyond bagasse-fired boilers.
5. Community Health and Environmental Impact Assessment-Link technical outcomes to health metrics and environmental studies to quantify reductions in airborne pollutants and assess broader socio-economic benefits to populations near sugar mills.

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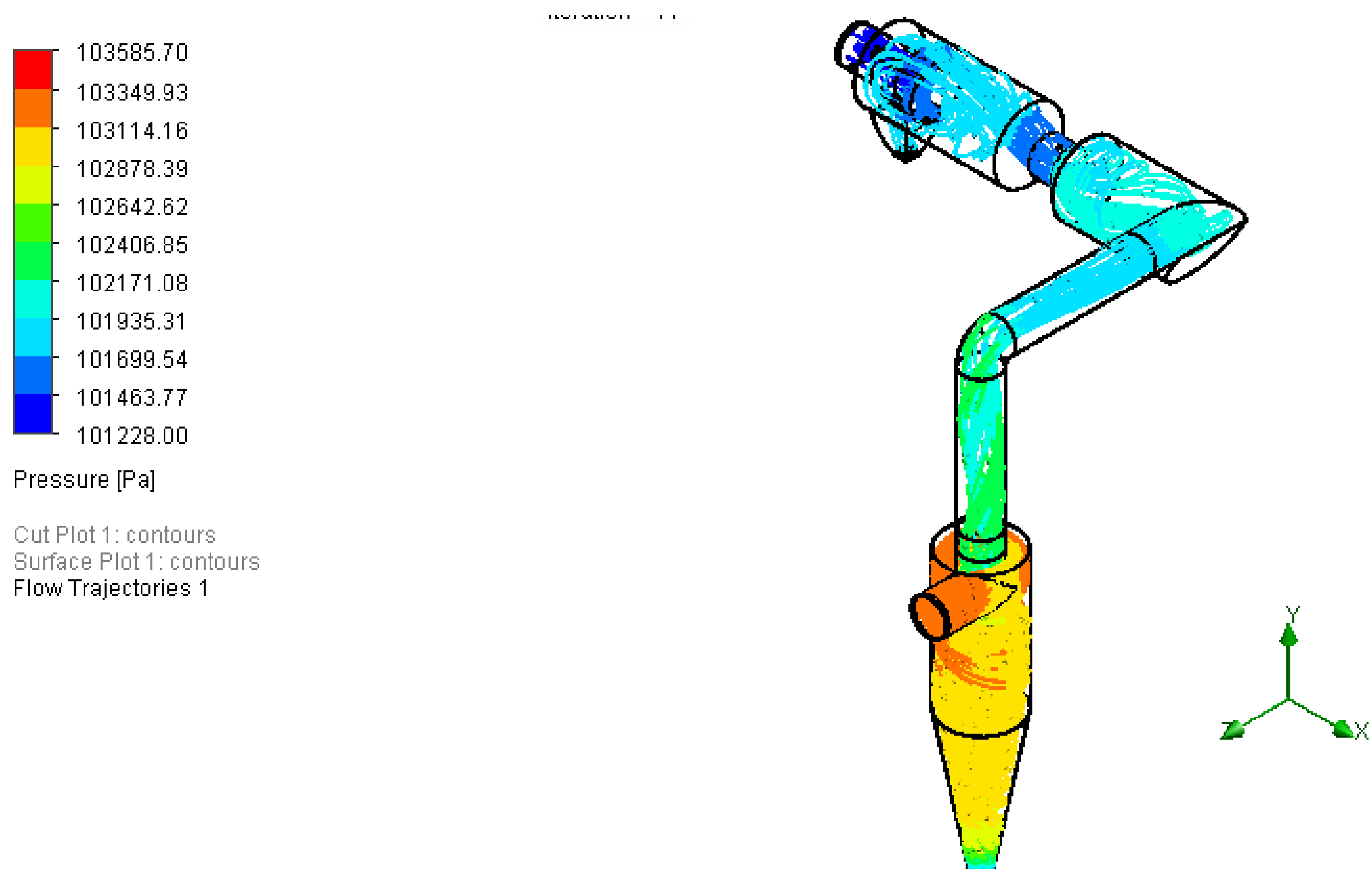
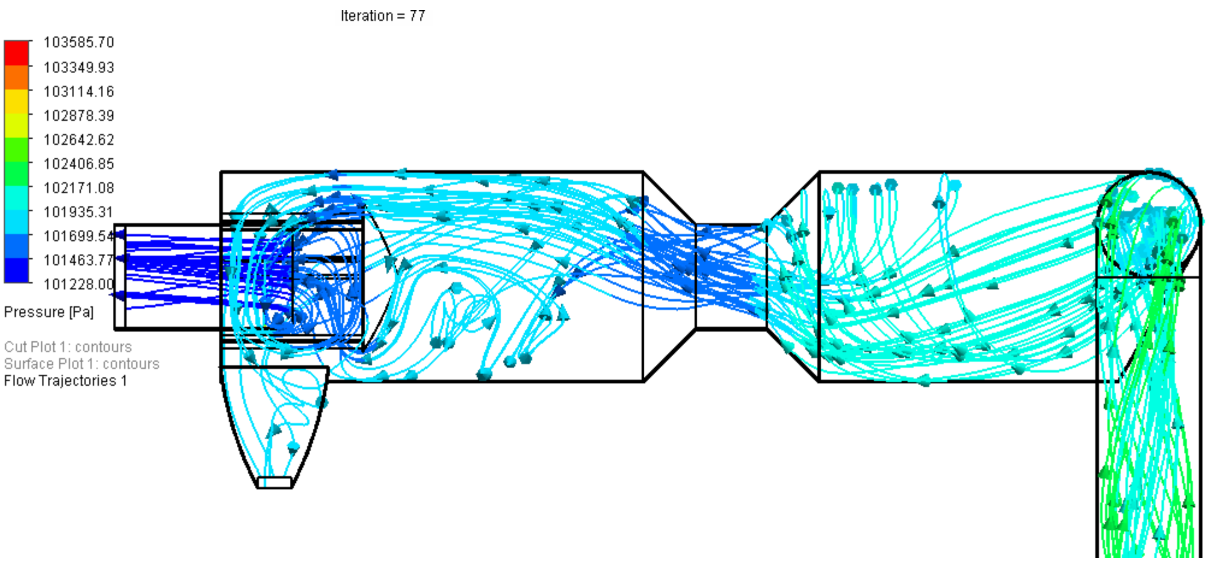
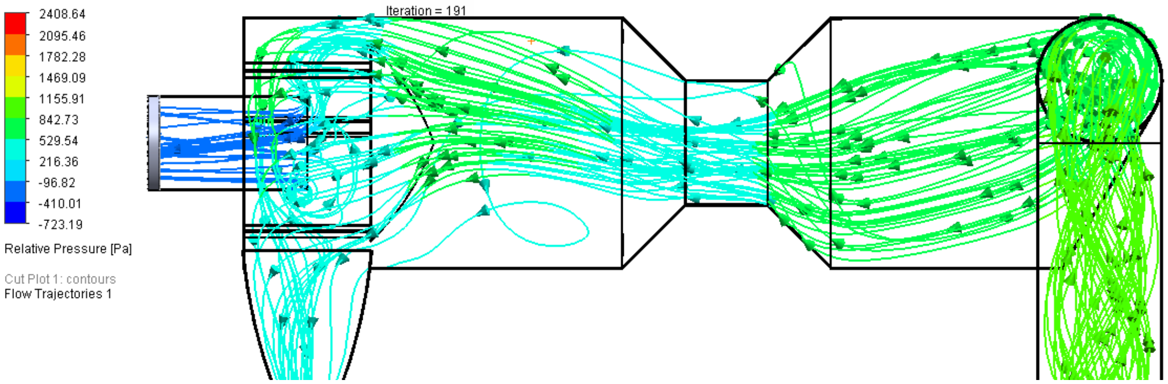
APPENDICES

Flow Trajectory for Diameter 150 Hybrid

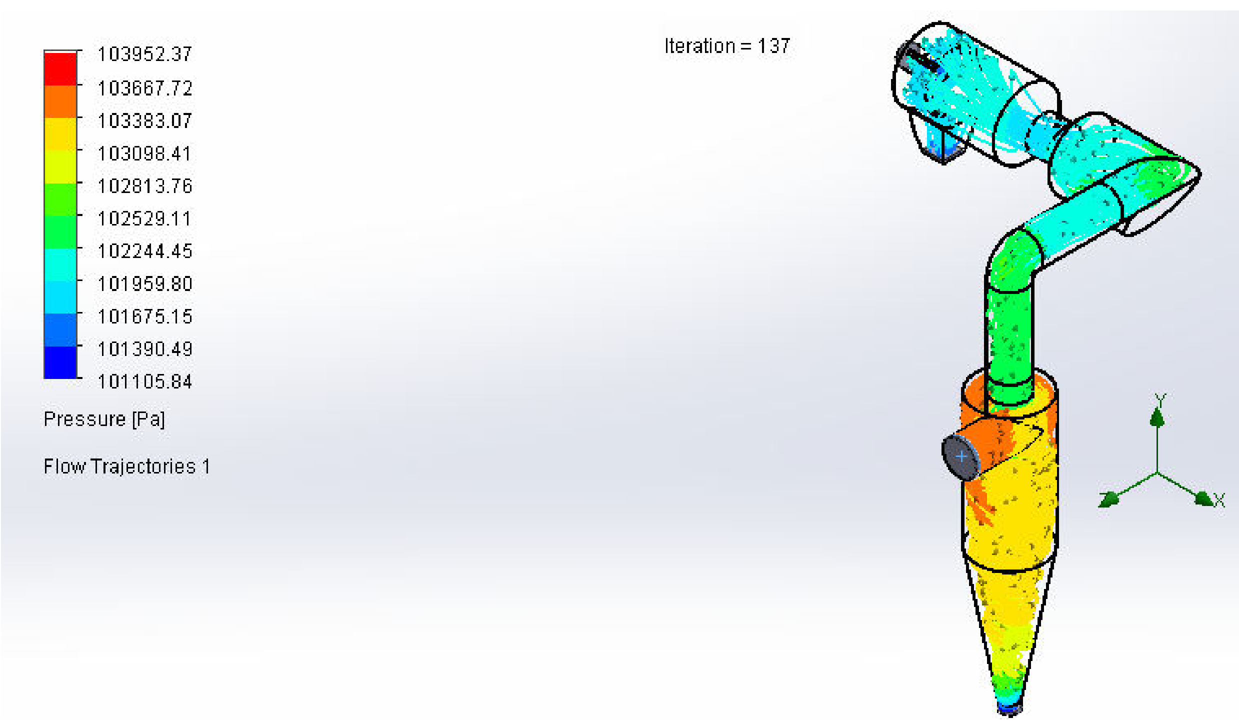


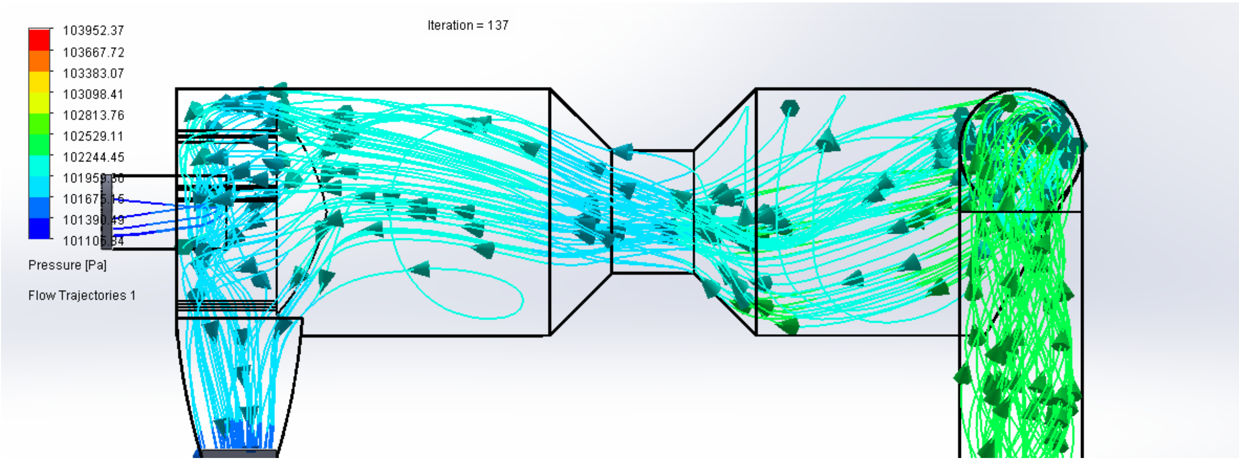


Flow Trajectory for Diameter 200 Hybrid



Flow Trajectory for Diameter 250 Hybrid





Data for different orientations

Parameter	Parallel Orientation	Series Orientation
Density (Fluid) [kg/m^3]	1.21	1.23
Pressure [Pa]	101105.84	103952.37
Temperature [K]	292.37	293.68
Temperature (Fluid) [K]	292.37	293.68
Velocity [m/s]	0	52.013
Velocity (X) [m/s]	-31.264	30.847
Velocity (Y) [m/s]	-50.883	34.037
Velocity (Z) [m/s]	-41.302	30.204
Mach Number [ ]	0	0.15
Velocity RRF [m/s]	0	52.013
Velocity RRF (X) [m/s]	-31.264	30.847
Velocity RRF (Y) [m/s]	-50.883	34.037
Velocity RRF (Z) [m/s]	-41.302	30.204
Vorticity [1/s]	0.34	1003.37
Relative Pressure [Pa]	-219.16	2627.37
Shear Stress [Pa]	0	13.73
Bottleneck Number [ ]	4.8460001e-08	1.0000000
Heat Transfer Coefficient [W/m^2/K]	0	0
ShortCut Number [ ]	3.5263193e-07	1.0000000
Surface Heat Flux [W/m^2]	0	0
Surface Heat Flux (Convective) [W/m^2]	-1.834e+07	1.101e+07
Acoustic Power [W/m^3]	0	6.106e-06
Acoustic Power Level [dB]	0	67.86