

Research Article

Comprehensive Approach to Flue Gas Flow Optimization in Electrostatic Precipitators and Material Selection for Baffle Plates

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Abstract

This research presents a comprehensive evaluation of Unit #4, a 210 MWe BHEL-designed boiler in a thermal power station, focusing on Flue Gas Duct Airflow Assessment (FGDAA) and Computational Fluid Dynamics (CFD) analysis of the associated flue gas duct system. The unit operates with six Electrostatic Precipitators (ESPs), three Induced Draft (ID) fans, and two Forced Draft (FD) fans, and the primary objective is to optimize flue gas distribution among ESPs to enhance plant efficiency and reliability. Cold air velocity measurements using calibrated S-type Pitot tubes provided accurate estimation of mass flow distribution in various ducts, while FGDAA under different ID fan operating conditions highlighted important operational efficiency considerations. The study identified non-uniform mass flow distribution across ESPs, which motivated detailed CFD simulations and the development of improved engineering designs for baffle and guide plates to regulate flow. In addition, material selection for these components was investigated through cost analysis and mechanical characterization. Results showed that tungsten carbide-clad plates are significantly more expensive than ceramic guide plates, while microhardness testing indicated silicon carbide as a superior material due to its higher hardness and wear resistance. Wear testing on AISI 1018 steel further demonstrated the influence of mass concentration on erosive damage, underscoring the importance of optimized flow management in flue gas environments. Overall, the study provides valuable insights into airflow control, material selection, and design optimization to improve the performance and service life of flue gas duct systems in thermal power plants.

Keywords

Flue Gas Duct Airflow Assessment (FGDAA), Computational Fluid Dynamics (CFD) Analysis, ElectroStatic Precipitators (ESPs), Engineering Modifications of Baffle Plates, Silicon Carbide (SiC), Tungsten Carbide

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1. Background

This research article aims to conduct a comprehensive assessment of Unit #4, a BHEL-designed boiler boasting a capacity of 210MWe. The scope of this engagement encompasses the Flue Gas Duct Airflow Assessment (FGDAA) and Computational Fluid Dynamics (CFD) analysis of the flue gas duct associated with Unit #4.

Unit #4 at a Power Plant, operates with a configuration that includes 6 ElectroStatic Precipitators (ESP). Notably, four ESPs were installed during the initial construction phase, while an additional two have been recently incorporated. The operational dynamics of Unit #4 involve the utilization of 3 Induced Draft (ID) fans and 2 Forced Draft (FD) fans.

The primary objectives of this study are twofold: firstly, to assess the flue gas flow within various ducts through on-site FGDAA analysis, and secondly, to conduct CFD analysis with the aim of optimizing the distribution of flue gas load across all ESPs. By doing so, the ultimate goal is to enhance plant efficiency by achieving an optimal balance in flue gas distribution [1].

Furthermore, this comprehensive undertaking extends beyond analysis and proposes practical solutions. The study includes specifications, material design, and cost estimation for the incorporation of baffle plates or diverters into the existing flue gas duct [2]. This innovative approach seeks to optimize flue gas flow, ensuring that each ESP operates at peak efficiency [13]. As we delve into the intricacies of this endeavor, the emphasis remains on advancing the operational efficiency and sustainability of the Thermal Power Station [3].

2. Flue Gas Flow Within Various Ducts, at Thermal Power Station (TPS)

2.1. Survey of ESP Flue Gas Duct

The duct survey was conducted during the plant shutdown period, capturing the geometrical details of ducts extending from the Air Pre-heater (APH) outlet to the old ESPs A to D and the new ESPs A & B. This comprehensive examination involved measuring the dimensions of the ducts, dampers, splitter plates, and related components. Additionally, dimensions for the ESP outlets to Induced Draft (ID) fans and the ID fan outlet to the chimney were recorded [2-5].

During the survey, it was observed that baffles and diverters were in a severely eroded and damaged condition. The damper plate materials were largely absent, primarily due to ash-induced erosion [12]. The direction of flue gas flow into the ESP inlet ducts was regulated by steel damper plates strategically placed at the main entry to the ESP, aligning with the two APH outlets.

It is worth noting that the dampers and diverters were originally installed by Thermal Power Station (TPS) officials. The purpose behind their installation was to achieve a uniform mass flow of flue gas to different inlet ducts of ESP, thereby optimizing the flue gas distribution across all six ESPs. The current state of erosion [5] and damage suggests the need for a comprehensive solution to restore and enhance the functionality of these critical components for sustained plant efficiency [7].

Flue Gas Duct Airflow Analysis (FGDAA) was conducted for Unit #4 of TPS during the unit shutdown period, examining various combinations of Induced Draft (ID) fan flows (AB, BC, AC, and ABC) while maintaining a constant Forced Draft (FD) fan flow. The measurements were taken under the existing conditions of the flue gas ducts, where additional baffle plates and diverter/guide plates were found incorporated into the duct, supplementing the original engineering drawing of the flue gas duct supplied by the Original Equipment Manufacturer (OEM).

2.2. Location of Measurement Ports for FGDAA

Measurement ports were strategically placed at various locations as outlined below:

- 1) At the outlets of each ID fan (A, B, and C), three measurement ports were established.
- 2) Each outlet of all 6 ElectroStatic Precipitators (ESPs) was equipped with three measurement ports.
- 3) Three measurement ports were installed at each inlet of all 6 ESPs.
- 4) At the inlets to the Air Pre-heater (APH) A & B, four measurement ports were positioned.

The Figure 1 indicates the location of the measurement ports:

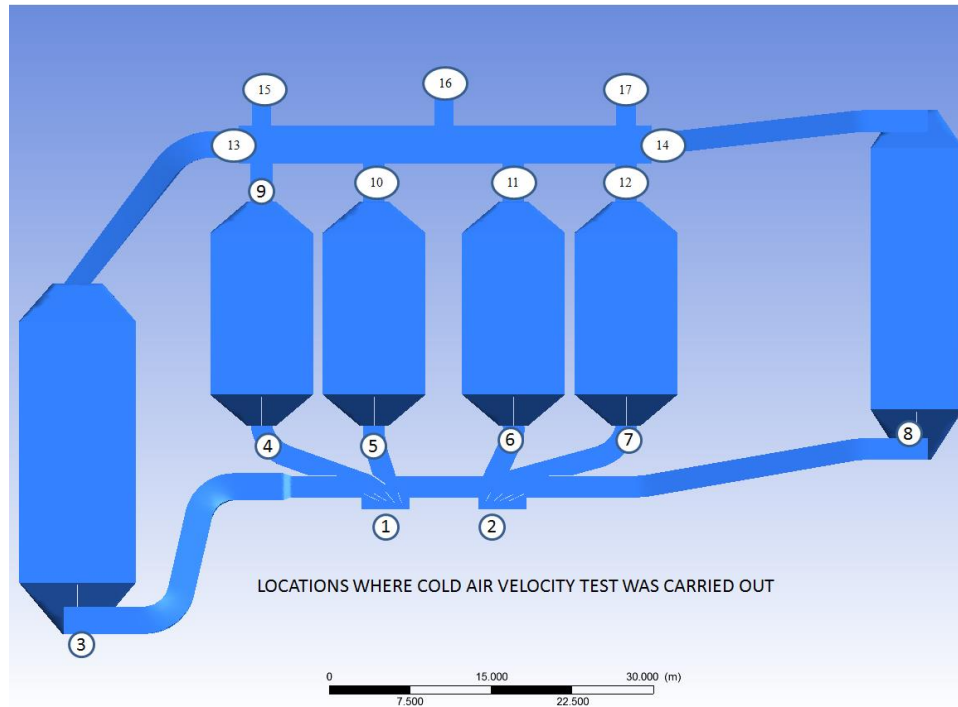


Figure 1. Locations at which FGDA was carried.

2.3. Principle of Measurement of Flue Gas Duct Airflow

The cold air velocity was ascertained through the utilization of a calibrated S-Type Pitot Tube, calibrated by the Fluid Control Research Institute in Palakkad. Figure 2 provides a schematic view of the S-Type Pitot Tube employed in the current study.

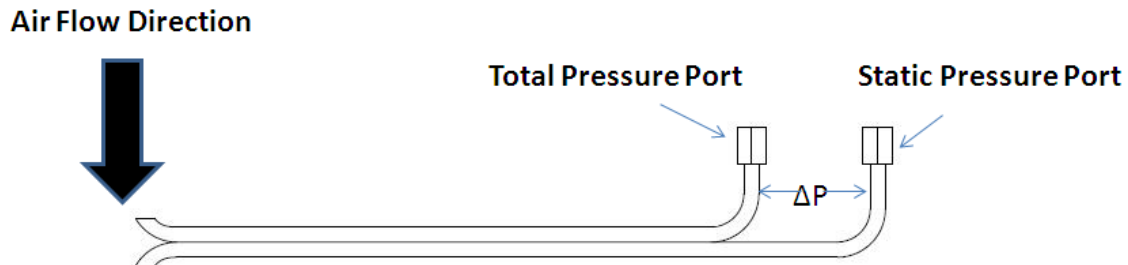


Figure 2. Schematics of an S-Type Pitot Tube.

Velocity (V) = $K \cdot \sqrt{\frac{2\Delta P}{\rho}}$ [8] Where, ΔP is the difference of pressure between the ports in pascals and ρ is the density of air ($\sim 1.2 \text{ kg/m}^3$) and K is the Pitot Tube flow coefficient. By determining the pressure difference ΔP , the velocity V is computed at the designated location of the probe front. Within a duct, local velocities ($V_1, V_2, \dots, V_n$) of the flow are measured at various points across the section, and subsequently, the average velocity is derived through calculation.

- 1) The average velocity $V_{\text{avg}} = (V_1 + V_2 + \dots + V_n)/n$
- 2) The mass flow through the duct $M = A \cdot V_{\text{ave}} \cdot \rho$,
- 3) Where A = Area of the duct ($b \times h$)

In this study, the determination of velocity at different locations was conducted using the KIMO electronic micro manometer. The Pitot Tube flow coefficient was acquired during the calibration process at the Fluid Control Research Institute in Palghat, and all measurements were conducted with consideration to the calibrated coefficient value. The mass flow distribution of cold air, calculated based on its velocity in various ducts, is illustrated in Figures 3 to 6.

2.4. Measurement of FGDA Under Different ID Fan Operations

A comprehensive examination known as Flue Gas Duct

Airflow Analysis (FGDAA) was carried out to investigate the airflow dynamics within the system. This analysis specifically targeted four distinct combinations of Induced Draft (ID) fans denoted as AB, BC, CA, and ABC. The investigation focused on the ducts situated between the outlets of the Air Pre-heater (APH) and the inlets of the Inlet Duct (ID) fans.

The primary objective was to assess and understand the distribution of mass flow within all six ElectroStatic Precipitators (ESPs) in the system. This involved employing a method meticulously outlined in section 2.3 of the study. The obtained data provided insights into the variations in mass flow across the ESPs under different ID fan combinations, offering valuable information for optimizing operational efficiency.

However, it was observed during the analysis that the precise mass balance between the APH outlet and the ID outlet was not achieved to the desired accuracy. The discrepancy was attributed to potential minor leakages detected at various points within the system. This observation was particularly notable as the plant was in a state of shutdown maintenance during the analysis, emphasizing the need for further investigation and rectification of potential leakages to ensure the integrity and efficiency of the system. The mass flow rates measured in all ESPs with the different ID Fan Combinations are listed in Table 1 to Table 5.

The designed flow conditions considered for various ESPs is as follows

Table 1. Flue gas flow rate as per the designed value.

ESP particulars	Design flue gas flow rate	
	(kg/s)	% of total air flow
New B	37.4	17.0
ESP A	33.0	15.0
ESP B	33.0	15.0
ESP C	33.0	15.0
ESP D	33.0	15.0
New A	50.6	23.0

The analysis reveals that the mass flow trend varies among the four ID fan combinations under study. The depicted percentage variations in gas flow are illustrated in Figures 3 to 6 below. Notably, in most of the ID fan combinations, the old ESP-C consistently exhibits higher mass flow compared to other configurations.

a) ID fan combinations A & B

Table 2. Differential Mass flow rate in ESPs AB ID Fan Combination.

ESP particulars	Measured flue gas flow rate		Difference in flue gas flow compared to design conditions (%)	Max. deviation of flue gas flow (%)
	Design flue gas flow rate (% of total air flow)	Measured flue gas flow (% of total air flow)		
New B	17.0	13.8	+3.2	9.4
ESP A	15.0	20.5	-5.5	
ESP B	15.0	16.4	-1.4	
ESP C	15.0	18.6	-3.6	
ESP D	15.0	17.1	-2.1	
New A	23.0	13.6	+9.4	

b) ID fan combinations B & C

Table 3. Differential Mass flow rate in ESPs BC ID Fan Combination.

ESP particulars	Measured flue gas flow rate		Difference in flue gas flow compared to design conditions (%)	Max. deviation of flue gas flow (%)
	Design flue gas flow rate (% of total air flow)	Measured flue gas flow (% of total air flow)		
New B	17.0	11.5	+5.5	10.1
ESP A	15.0	18.5	-3.5	
ESP B	15.0	13.4	+1.6	
ESP C	15.0	25.1	-10.1	
ESP D	15.0	14.8	+0.2	
New A	23.0	16.7	+6.3	

c) ID fan combinations A & C

Table 4. Differential Mass flow rate in ESPs AC ID Fan Combination.

ESP particulars	Measured flue gas flow rate		Difference in flue gas flow compared to design conditions (%)	Max. deviation of flue gas flow (%)
	Design flue gas flow rate (% of total air flow)	Measured flue gas flow (% of total air flow)		
New B	17.0	10.6	+6.4	9.7
ESP A	15.0	20.5	-5.5	
ESP B	15.0	12.6	+2.4	
ESP C	15.0	22.3	-7.3	
ESP D	15.0	20.7	-5.7	
New A	23.0	13.3	+9.7	

d) ID fan combinations A, B & C

Table 5. Differential Mass flow rate in ESPs ABC ID Fan Combination.

ESP particulars	Measured flue gas flow rate		Difference in flue gas flow compared to design conditions (%)	Max. deviation of flue gas flow (%)
	Design flue gas flow rate (% of total air flow)	Measured flue gas flow (% of total air flow)		
New B	17.0	15.2	+1.8	4.5
ESP A	15.0	10.5	+4.5	
ESP B	15.0	17.3	-2.3	
ESP C	15.0	18.8	-3.8	
ESP D	15.0	16.4	-1.4	
New A	23.0	21.8	+1.2	

Summary of Observations on Mass Flow Distribution in 6 ESPs:

The mass flow distribution is non-uniform across all Electro Static Precipitators (ESPs) for each studied combination.

The flow pattern within each ESP exhibits variations based on the specific combination of Induced Draft (ID) fans.

ESP-C consistently demonstrates elevated mass flow compared to the other ducts in all studied combinations.

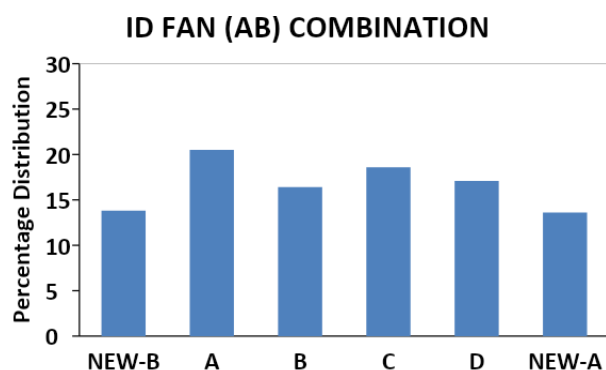


Figure 3. The distribution of mass flow in ESPs for ID fan AB combination.

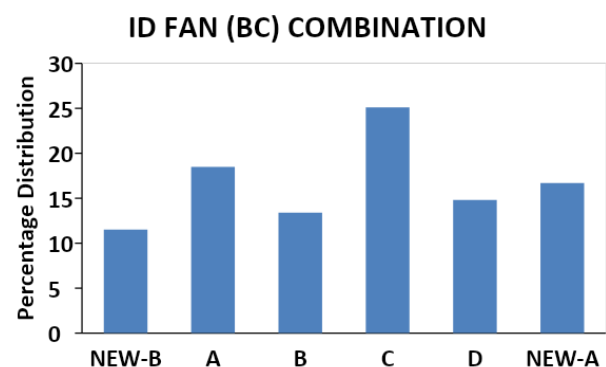


Figure 4. The distribution of mass flow in ESPs for ID fan BC combination.

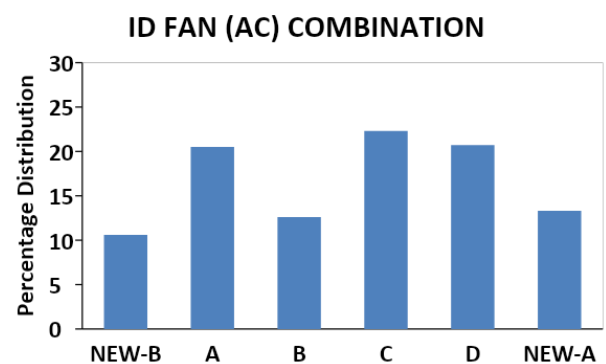


Figure 5. The distribution of mass flow in ESPs for ID fan AC combination.

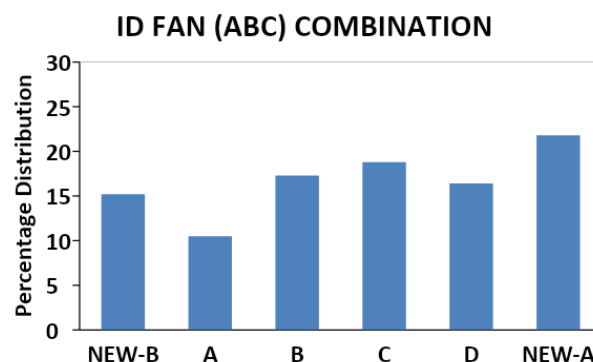


Figure 6. The distribution of mass flow in ESPs for ID fan ABC combination.

3. CFD Analysis

CFD analysis was conducted for two distinct scenarios. In the first case (Case-I), the simulation replicated conditions observed during the shutdown period. In the second case (Case-II), the simulation reflected the scenario where designed baffle/diverter plates were integrated into the flue gas duct. The CFD domain was confined between the outlets of Air Pre-heater (APH) A & B and the outlets of Induced Draft (ID) fans A, B, and C.

The CFD procedure encompassed tasks such as geometry creation based on the selected domain, fluid volume extraction, meshing, defining boundary conditions, and solving the numerical problem to achieve improved convergence of results. The assumption of isothermal flow, considering negligible heat transfer, was made, with the air assumed to have a temperature of approximately 140 degrees Celsius [12]. Mass flow conditions were specified at the inlets, and average static pressure conditions were chosen for the outlets to ensure robust convergence. The K-epsilon turbulence model was employed to capture turbulent fluctuations in the airflow. A total air flow of about 800 T/Hr was considered in all cases [13].

Several iterations were conducted for Case-II to identify the optimal baffle/diverter combination, aiming to achieve the most favorable mass flow distribution across all ID fan combinations. The details and results of both Case-I and Case-II are elaborated below [14, 15].

3.1. CFD Analysis of the Actual Geometry

Case -I: Without damper plates

The geometry utilized for Case-I is outlined below. This model approximates the observed condition of the flue gas duct during the Flue Gas Duct Airflow Analysis (FGDAA) [9].

Boundary Conditions:

Inlet Mass Flow Rate at APH Outlet: 110Kg/s. on each totaling to 220 kg/s mass flow

Outlet: 0 Pa static Pressure.

Porous Domain: 0.8 Porosity [6].

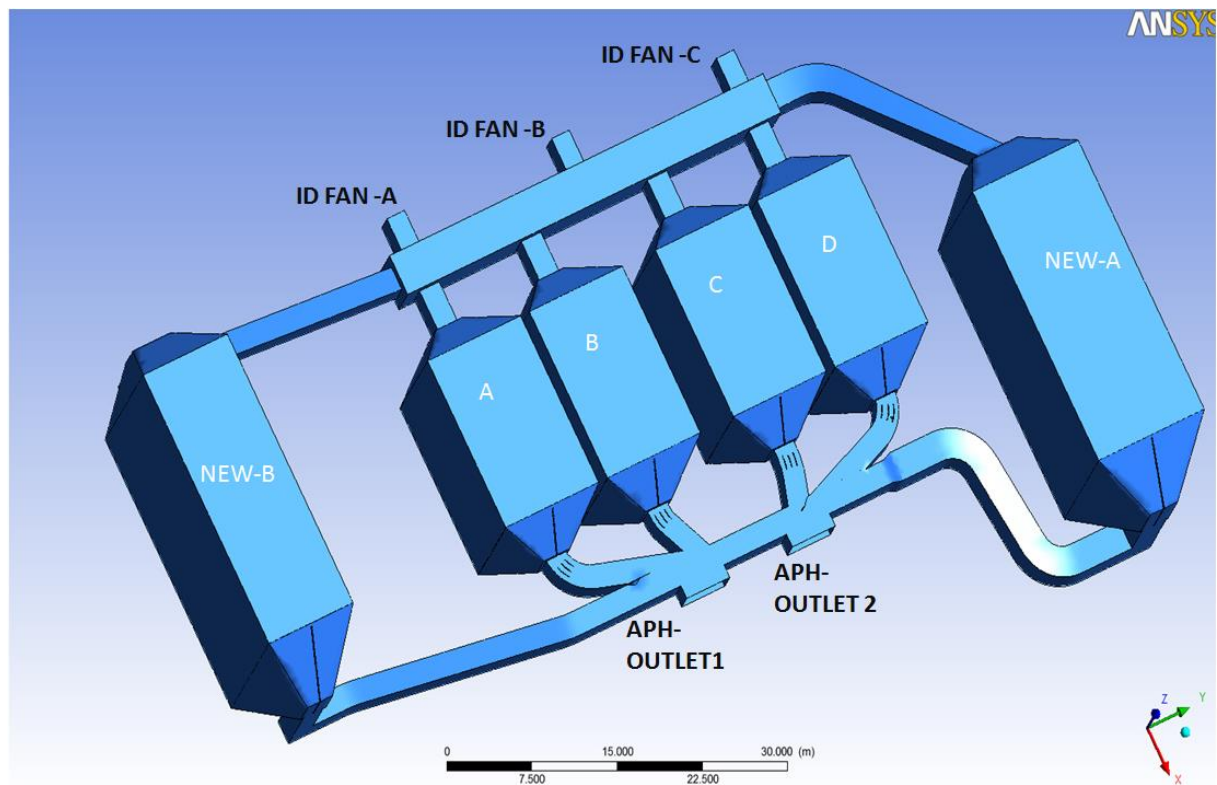


Figure 7. Unit #4, ESP without baffle plates at inlets of main duct.

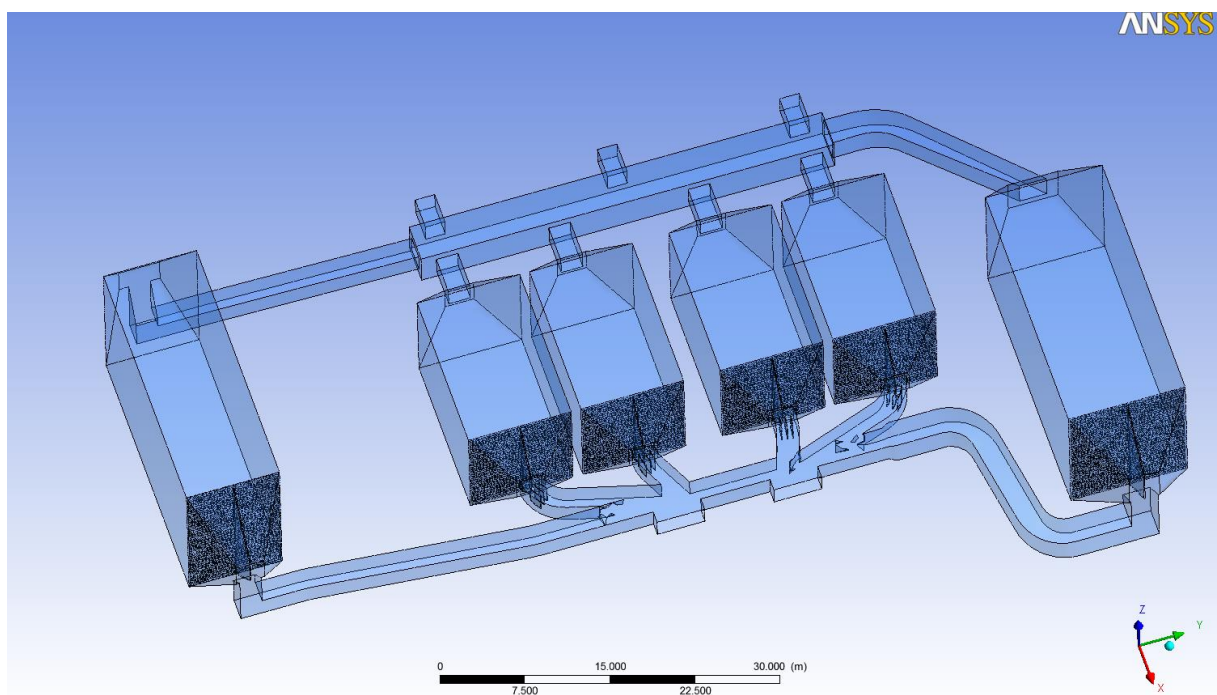


Figure 8. View of Unit #4, ESP geometry incorporated with perforated screen at inlets.

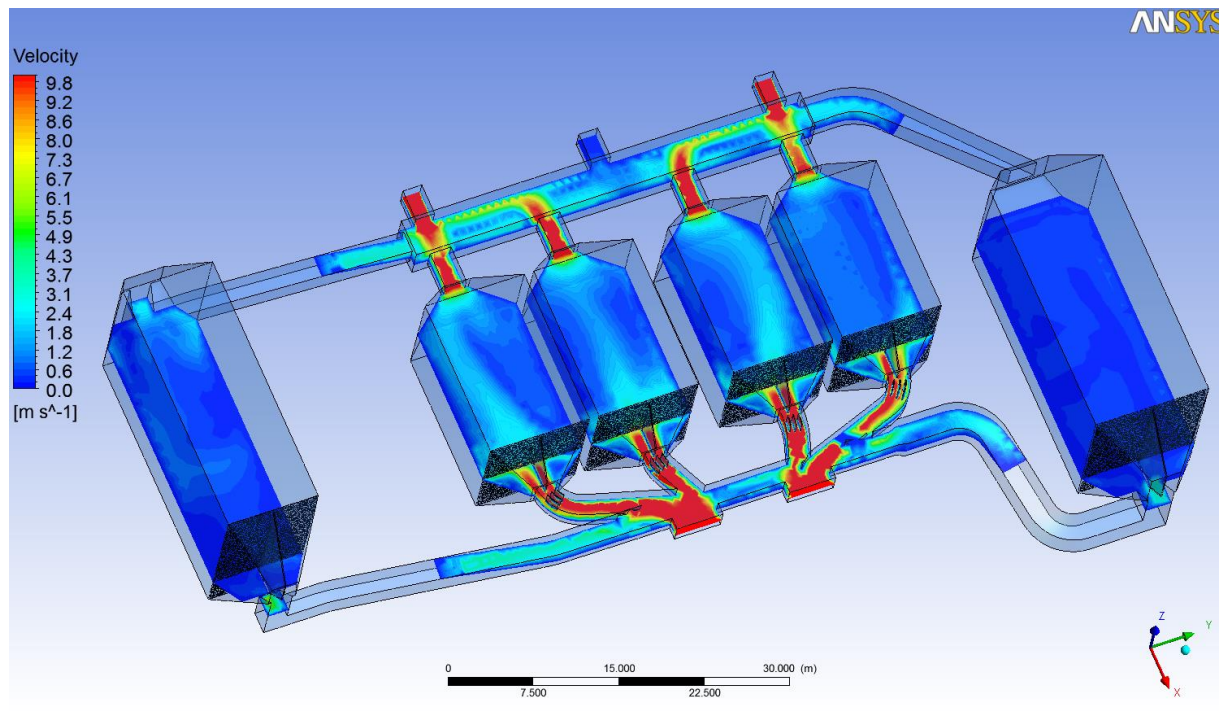


Figure 9. Velocity contours for Combination ID Fans A and C.

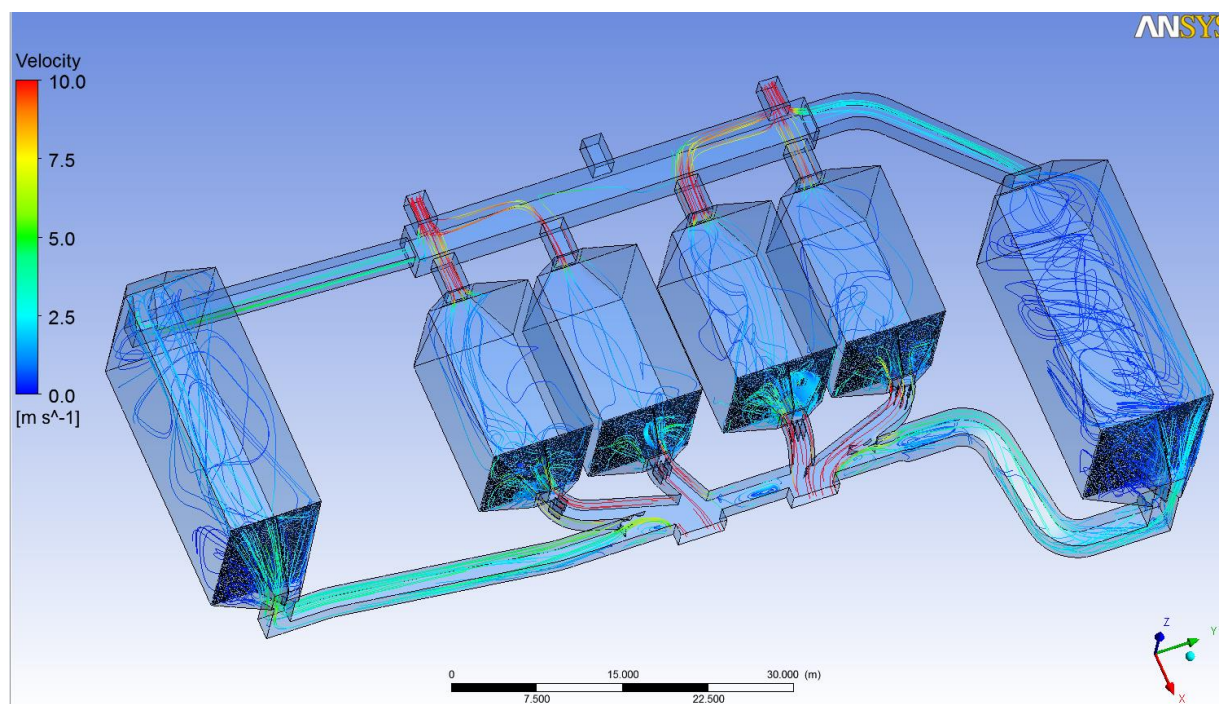


Figure 10. Velocity Streamlines for Combination ID Fans A and C.

The CFD analysis was conducted for the aforementioned geometry, specifically for the ID fan combination AC. The resulting mass flow distributions are presented in Figure 11.

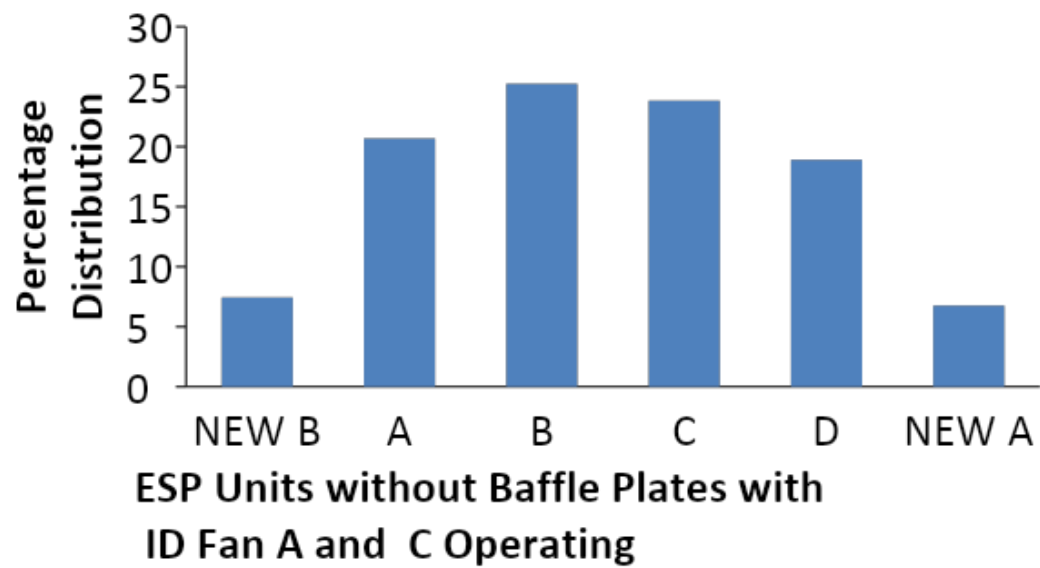


Figure 11. The distribution of mass flow in ESPs for ID fan A & C combination.

3.2. CFD Analysis Case -II: With Damper Plates

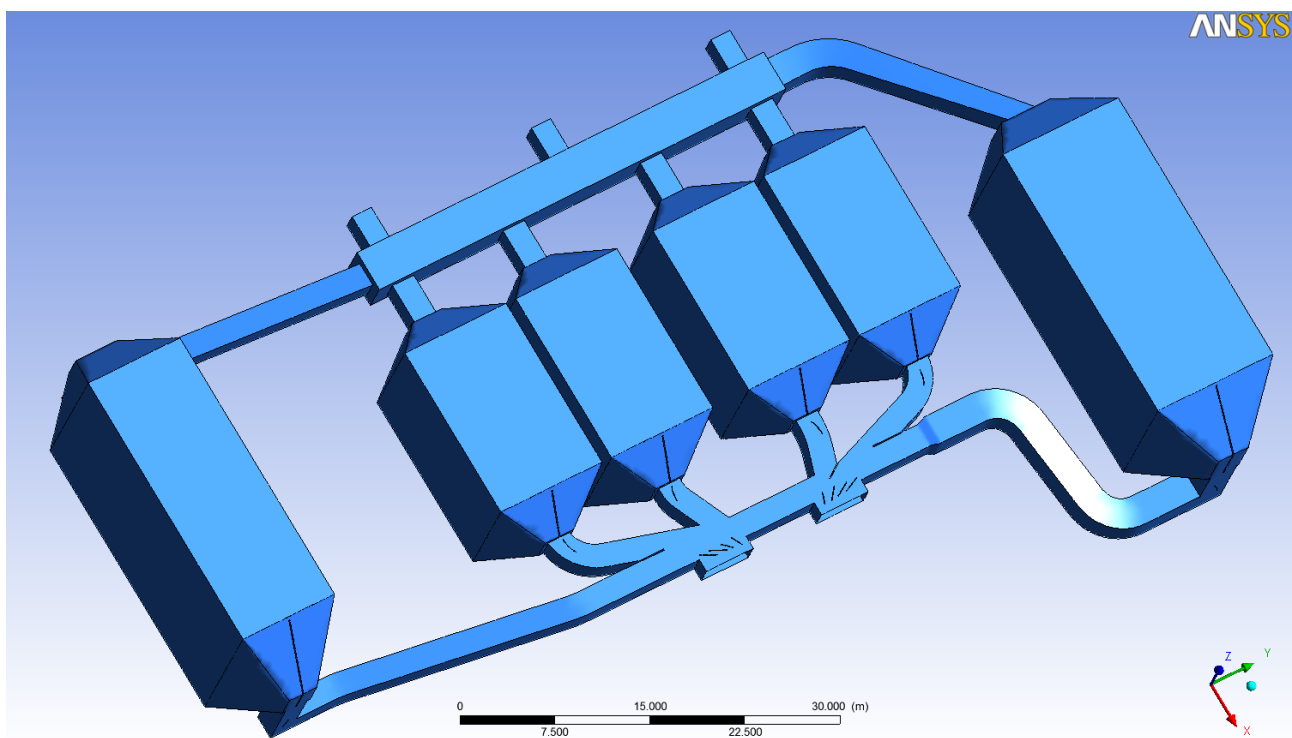


Figure 12. Unit #4, ESP with the baffle plates at the Air Pre-Heater Outlets (ESP main inlet duct).

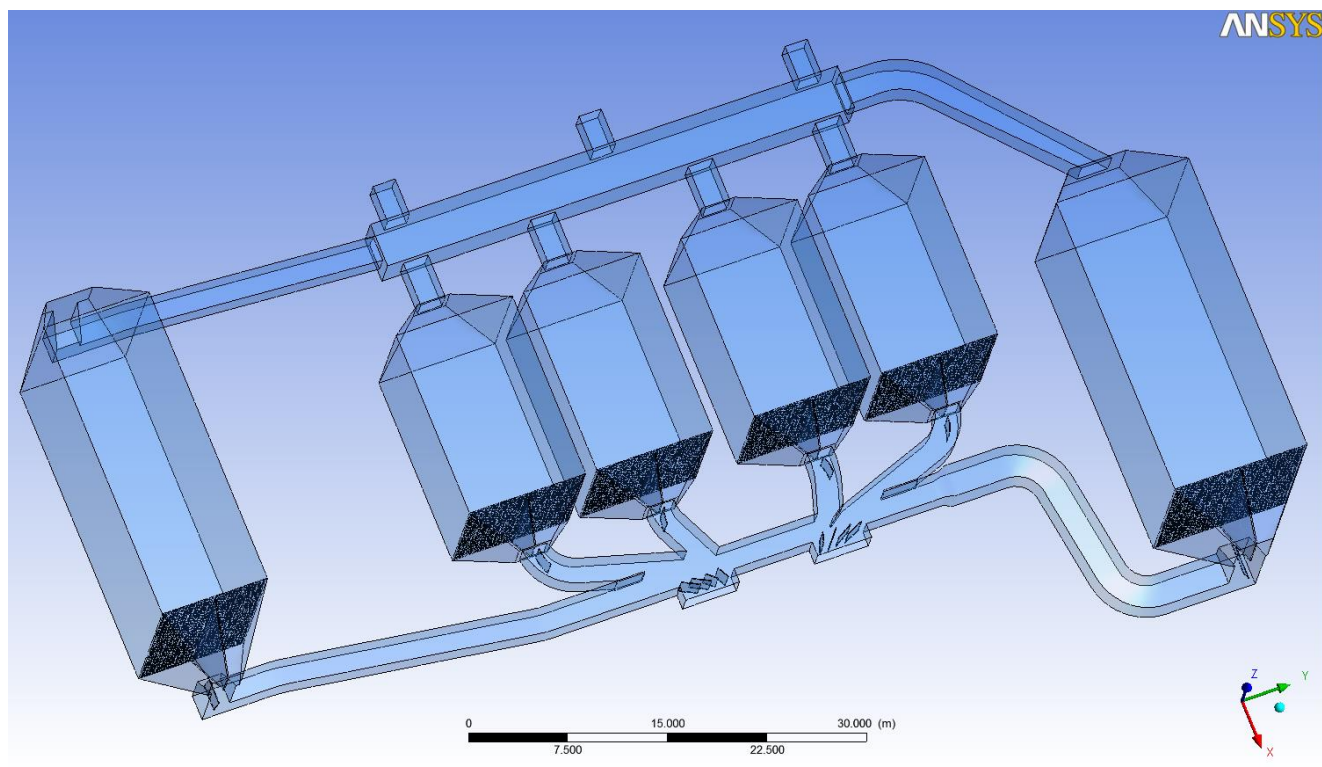


Figure 13. View of Unit #4 ESP showing 3D profiles baffle plates geometry with their locations.

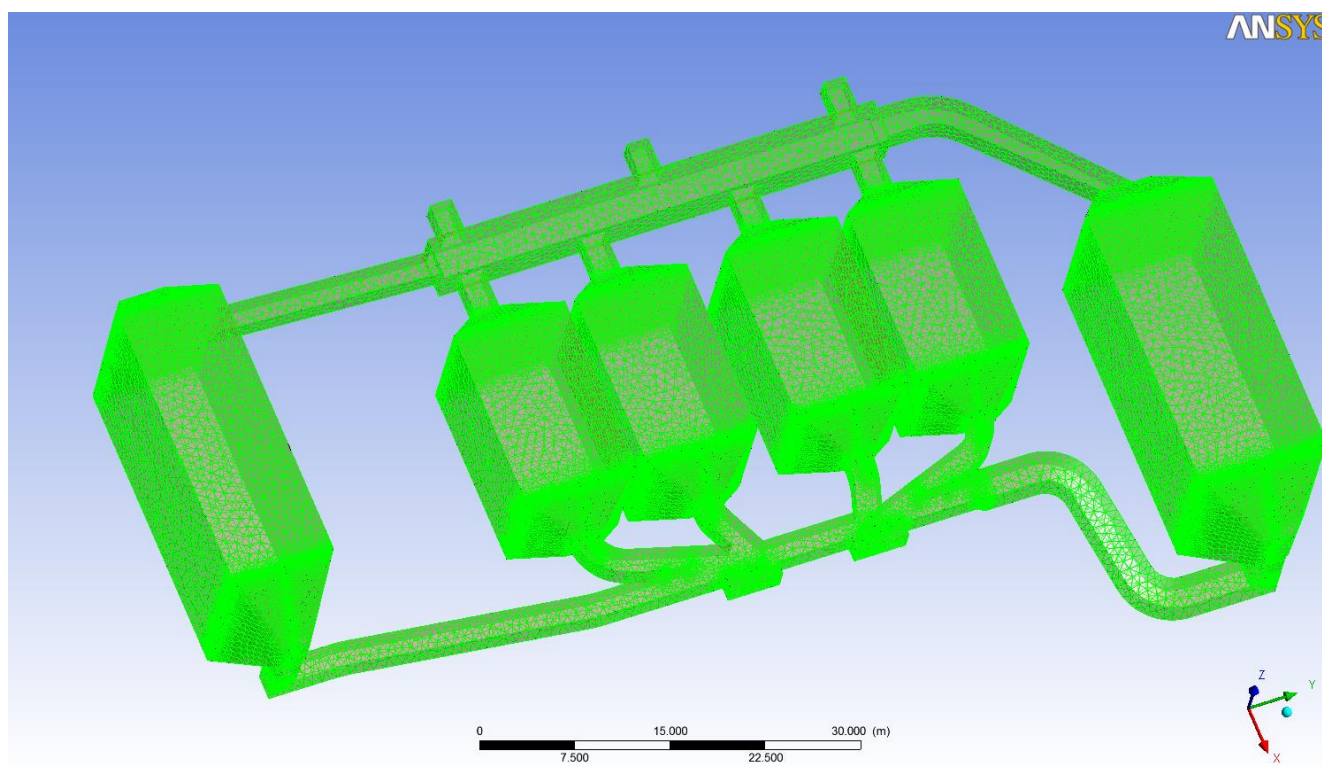


Figure 14. Discretized geometry of the complete ESP considered for CFD analysis (19 million tetra elements).

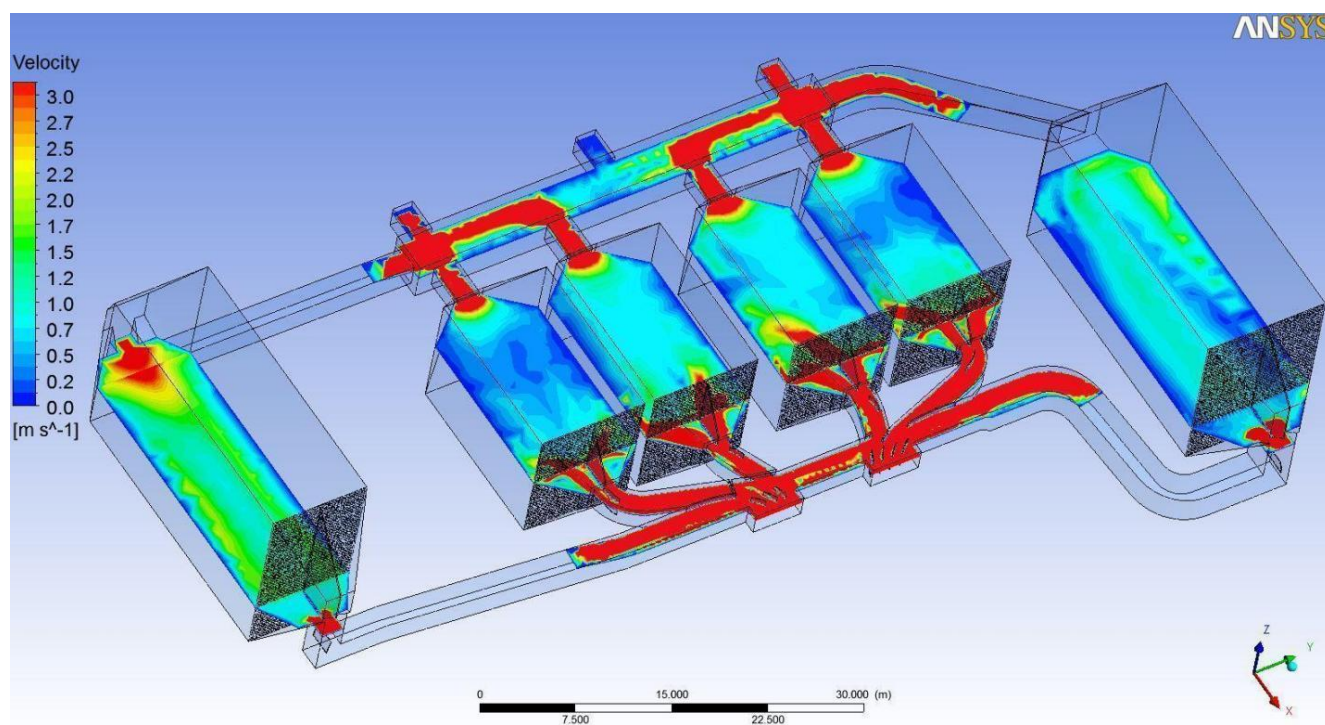


Figure 15. Velocity Contours for the combination of ID Fans A and C.

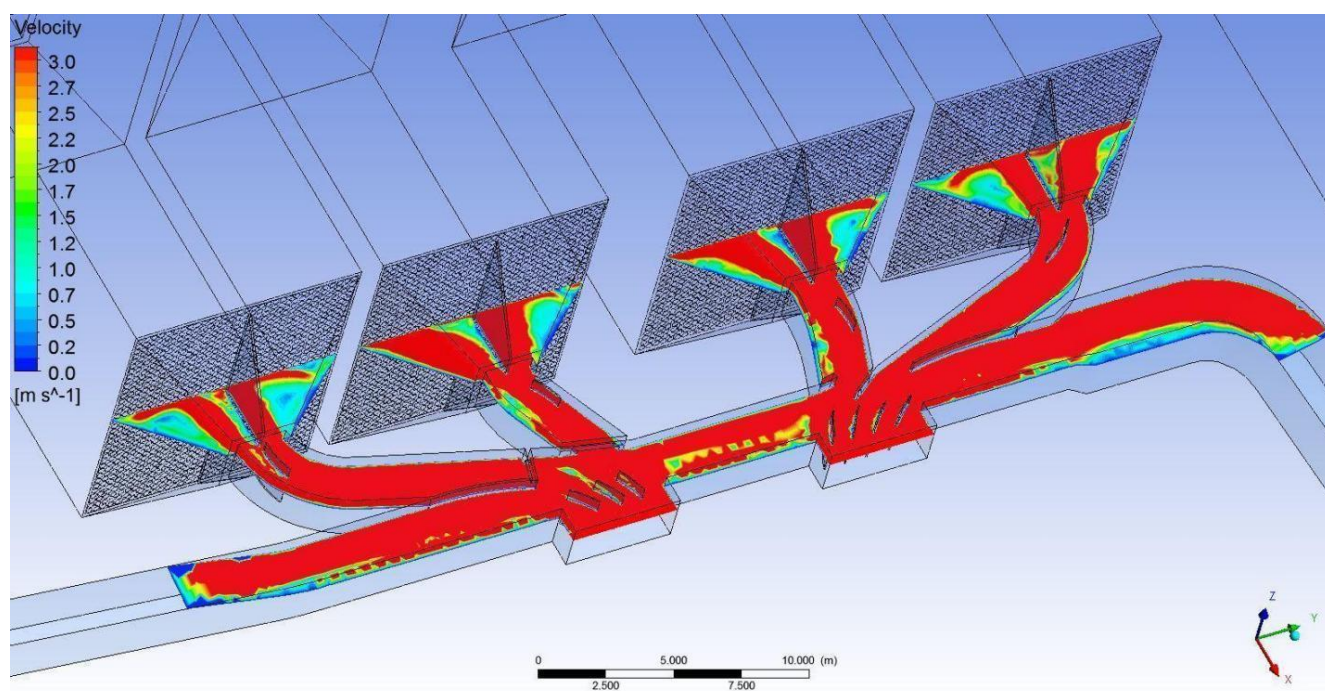


Figure 16. Velocity Contours near Duct Entry for the combination of ID Fans A & C.

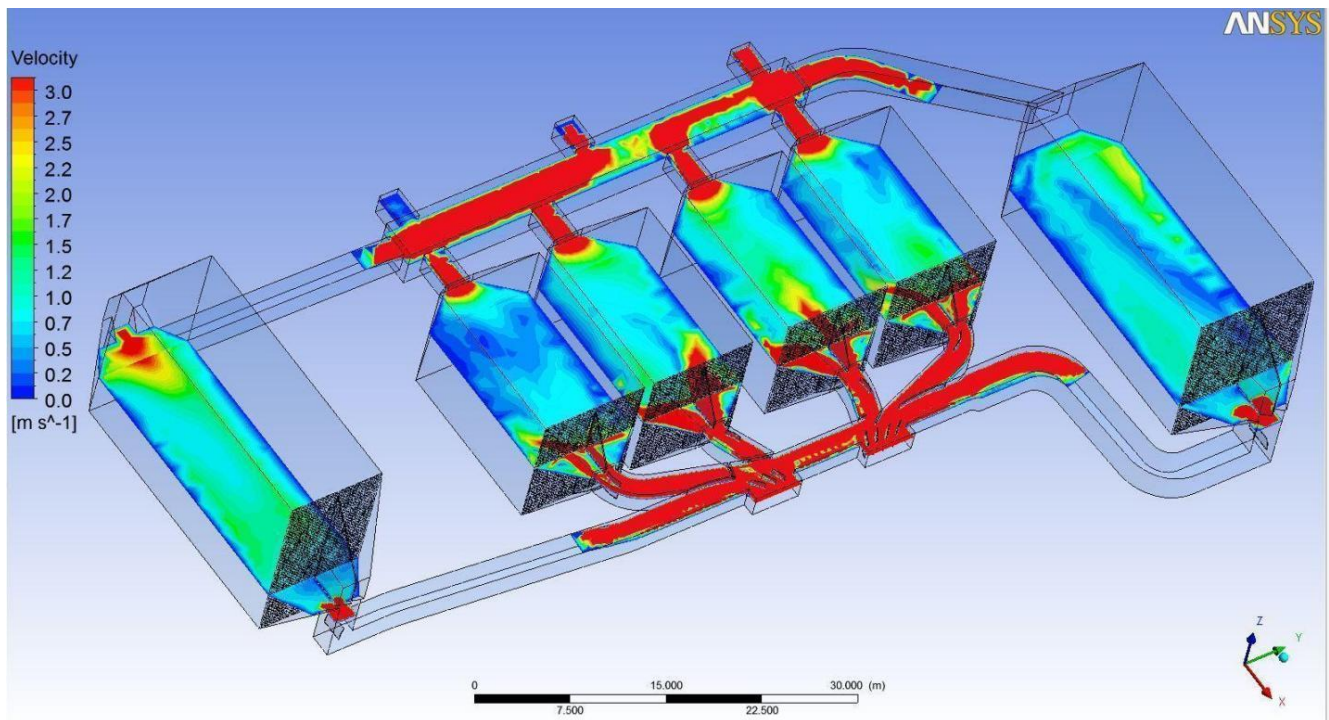


Figure 17. Velocity Contours for the combination of ID Fans B and C.

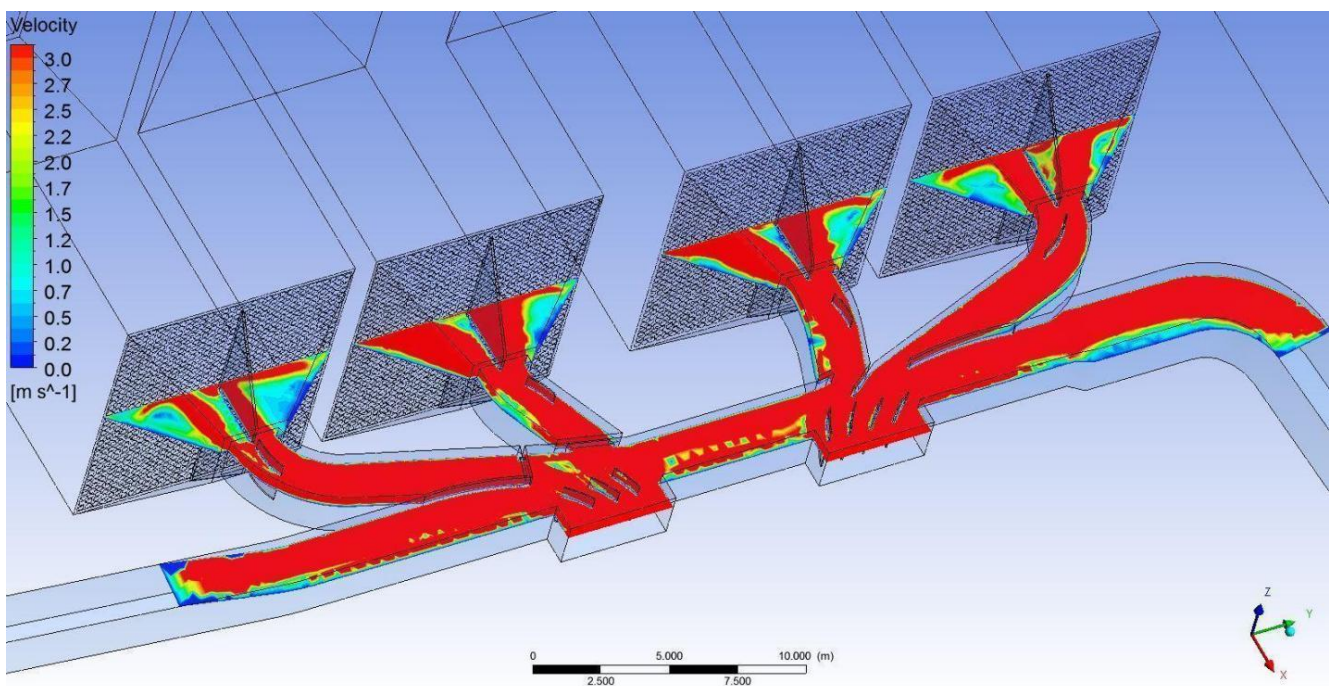


Figure 18. Velocity Contours near Duct Entry for the combination of ID Fans B & C.

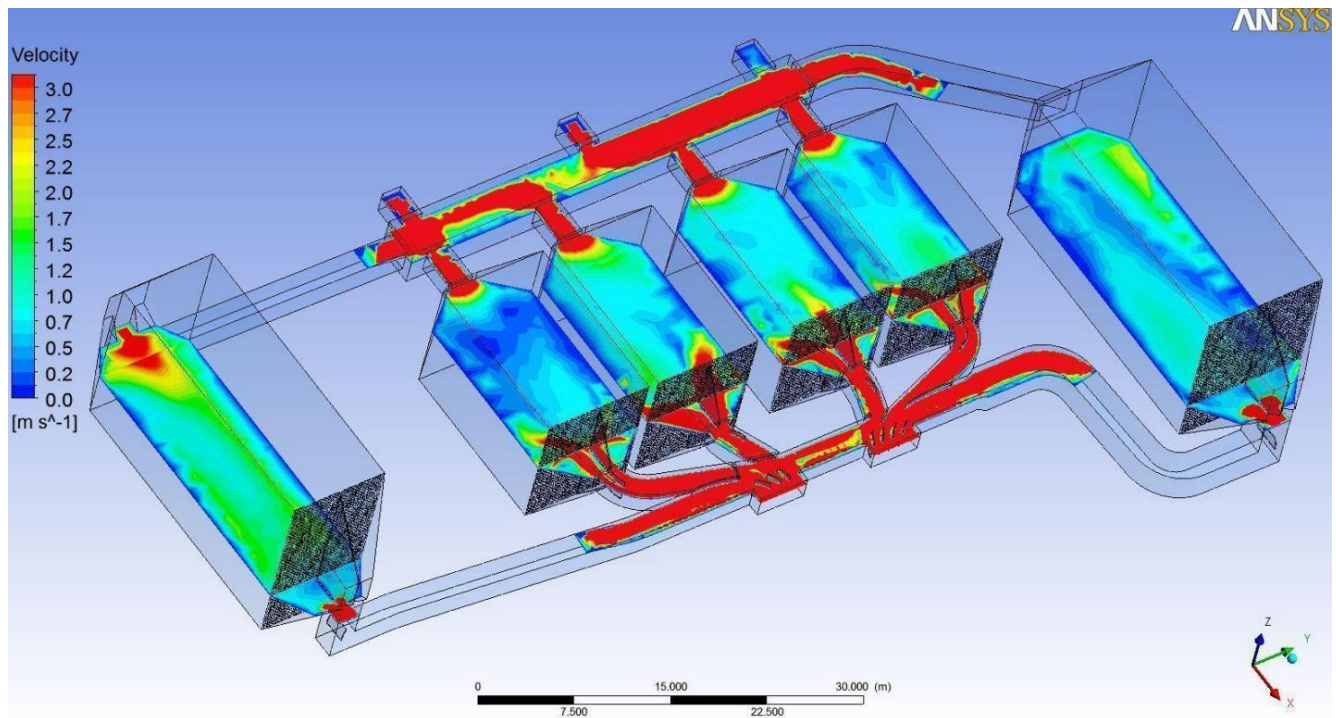


Figure 19. Velocity Contours for the combination of ID Fans A & B.

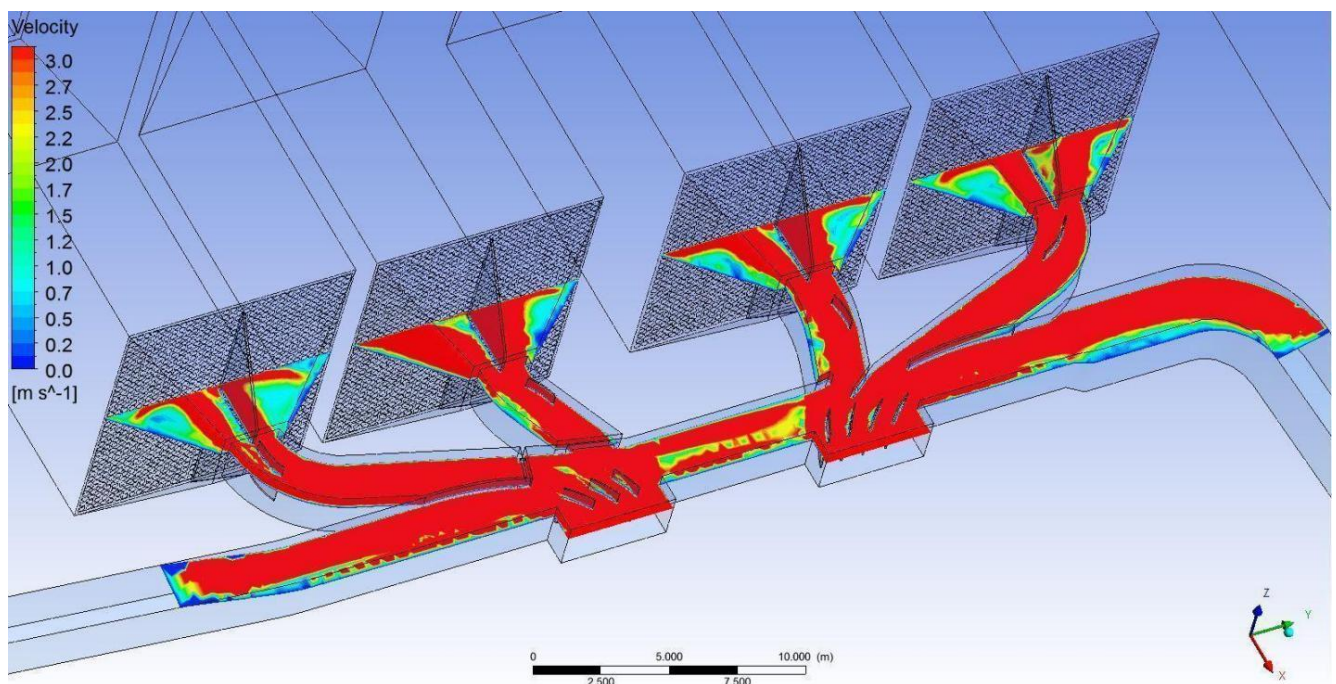


Figure 20. Velocity Contours near Duct Entry for the combination of ID Fans A & B.

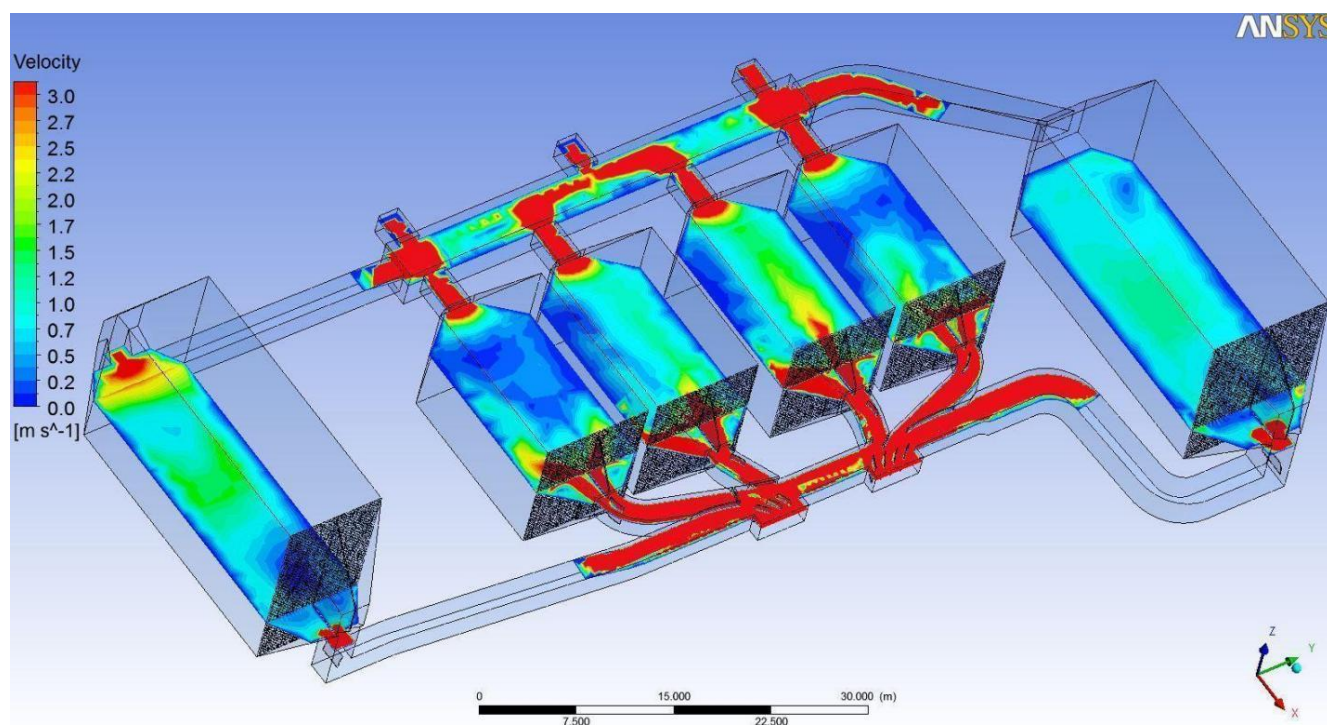


Figure 21. Velocity Contours for the combination of ID Fans A, B and C.

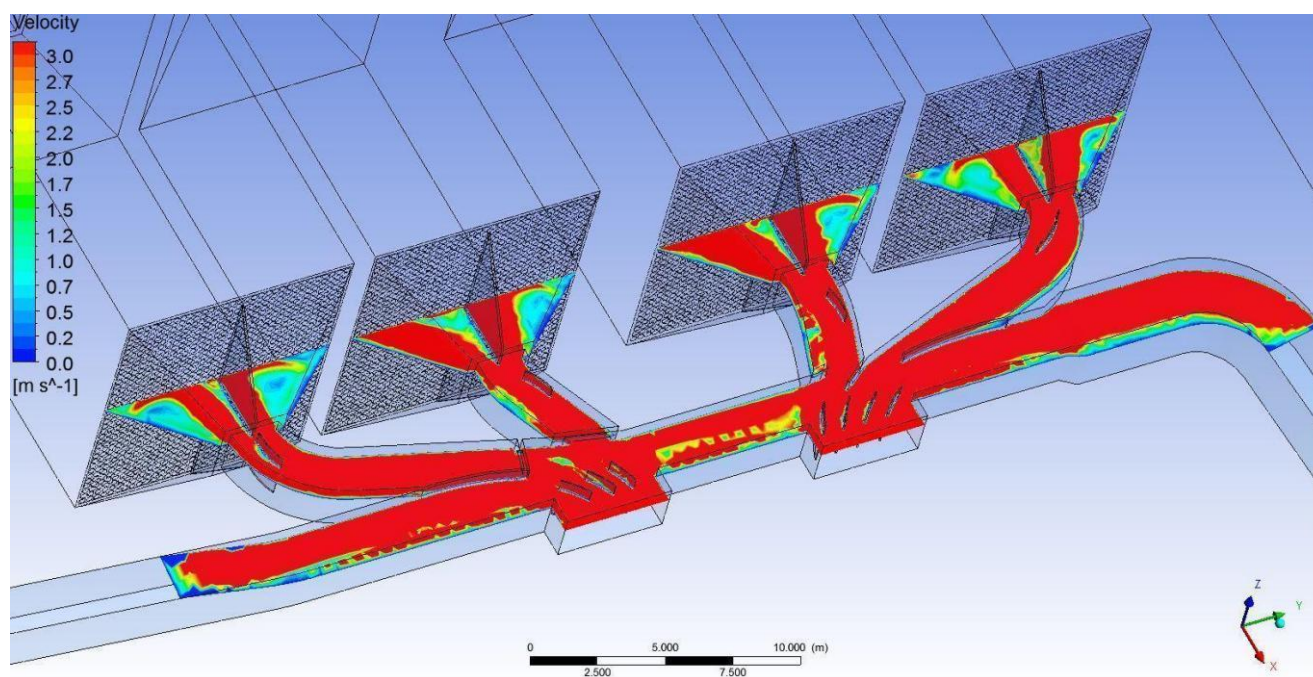


Figure 22. Velocity Contours near Duct Entry for the combination of ID Fans A, B & C.

The outcomes of the CFD analysis, detailing the mass flow distributions in various ESPs for different combinations of ID fans, are provided below.

a) ID fan combinations A & B

Table 6. Comparison of Measured and CFD Determined values in each ESPs in AB ID Fan Combination.

ESP particulars	Measured flue gas flow rate		Difference in flue gas flow compared to design conditions (%)	Max. deviation of flue gas flow (%)
	Design flue gas flow rate (% of total air flow)	Measured flue gas flow (% of total air flow)		
New B	17.0	16.6	+0.4	1.9
ESP A	15.0	15.3	-0.3	
ESP B	15.0	16.2	-1.2	
ESP C	15.0	15.5	-0.5	
ESP D	15.0	15.3	-0.3	
New A	23.0	21.1	+1.9	

b) ID fan combinations B & C

Table 7. Comparison of Measured and CFD Determined values in each ESPs in BC ID Fan Combination.

ESP particulars	Measured flue gas flow rate		Difference in flue gas flow compared to design conditions (%)	Max. deviation of flue gas flow (%)
	Design flue gas flow rate (% of total air flow)	Measured flue gas flow (% of total air flow)		
New B	17.0	15.4	+1.6	3
ESP A	15.0	13.6	+1.4	
ESP B	15.0	16.3	-1.3	
ESP C	15.0	17.1	-2.1	
ESP D	15.0	17.3	-2.3	
New A	23.0	20	-3	

c) ID fan combinations A & C

Table 8. Comparison of Measured and CFD Determined values in each ESPs in AC ID Fan Combination.

ESP particulars	Measured flue gas flow rate		Difference in flue gas flow compared to design conditions (%)	Max. deviation of flue gas flow (%)
	Design flue gas flow rate (% of total air flow)	Measured flue gas flow (% of total air flow)		
New B	17.0	16.3	+0.7	3
ESP A	15.0	14.3	+0.7	
ESP B	15.0	16	-1	
ESP C	15.0	16.5	-1.5	
ESP D	15.0	16.9	-1.9	
New A	23.0	20	+3	

d) ID fan combinations A, B & C

Table 9. Comparison of Measured and CFD Determined values in each ESPs in ABC ID Fan Combination.

ESP particulars	Measured flue gas flow rate		Difference in flue gas flow compared to design conditions (%)	Max. deviation of flue gas flow (%)
	Design flue gas flow rate (% of total air flow)	Measured flue gas flow (% of total air flow)		
New B	17.0	16.4	0.6	2.8
ESP A	15.0	14.1	0.9	
ESP B	15.0	15.9	-0.9	
ESP C	15.0	16.6	-1.6	
ESP D	15.0	16.8	-1.8	
New A	23.0	20.2	2.8	

The CFD analysis results, illustrating mass flow distributions in various ESPs for different combinations of ID fans, are presented in Figures 23 to 26.

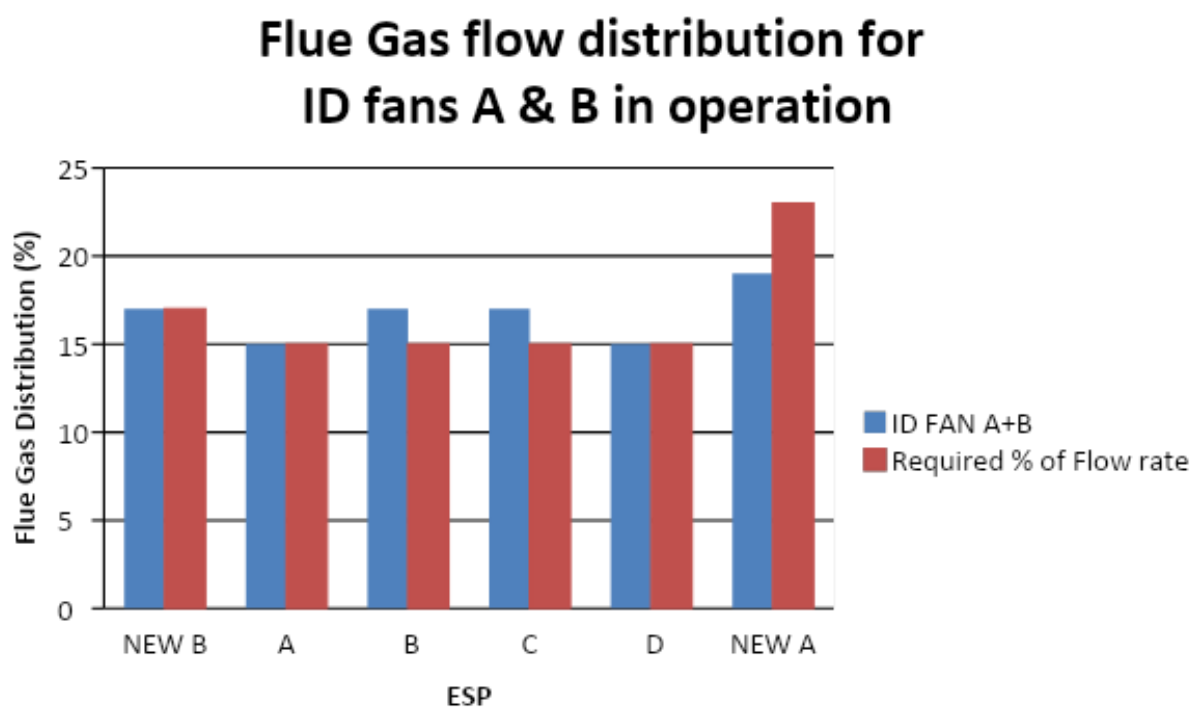


Figure 23. The distribution of mass flow in ESPs for ID fan AB combination.

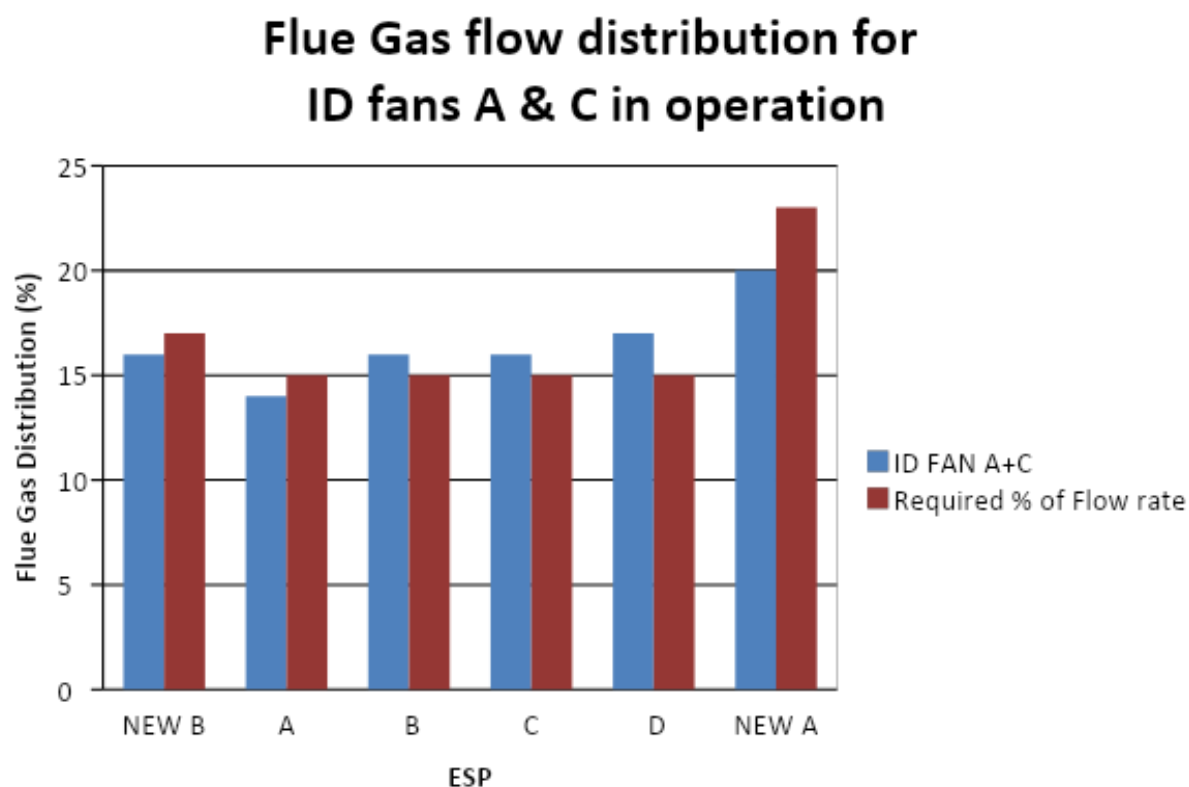


Figure 24. The distribution of mass flow in ESPs for ID fan AC combination.

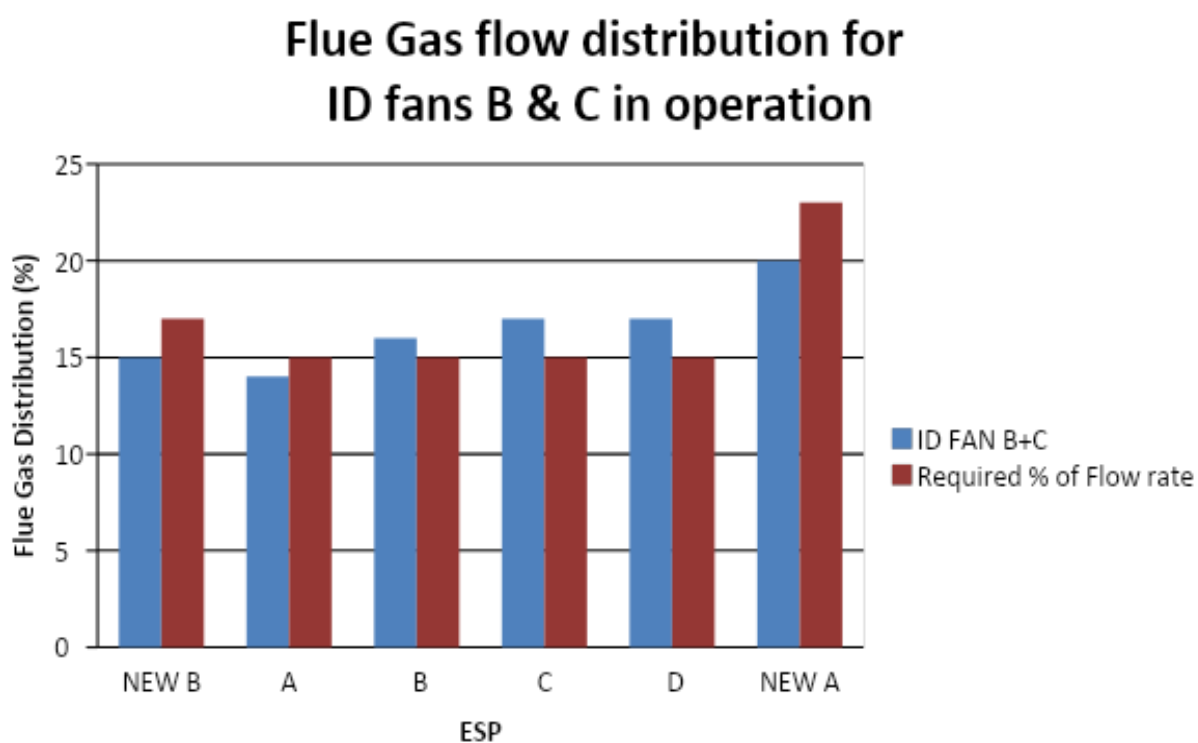


Figure 25. The distribution of mass flow in ESPs for ID fan BC combination.

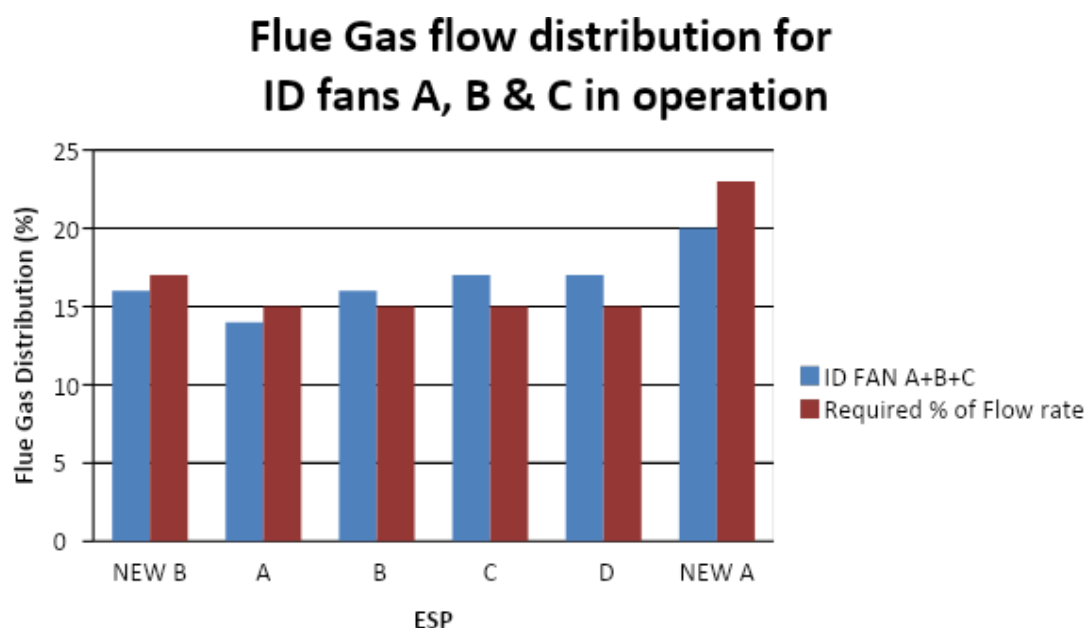


Figure 26. The distribution of mass flow in ESPs for ID fan ABC combination.

4. Engineering Design and Cost Estimation for Baffle/Guide Plates Ensuring Near-Uniform Flow in ESPs

4.1. Design and Geometry of Guide Plates

The geometry and positioning of guide plates within ESP units significantly impact operational performance. In new ESPs, characterized by longer gas path lengths and distant ID fan locations, lower suction velocities at their inlets are observed. Numerous geometrical configurations were assessed in CFD analysis to achieve near-uniform distribution, considering factors such as size, radius of curvature, and orientation [6, 8, 9]. To achieve uniform flow matching the capacity of each ESP unit, modifications were explored, including changes in duct inlet area at various inlets and the incorporation of inclined plates at junctions of old and new ESPs. While 8mm mild steel performed adequately initially, its susceptibility to erosion from abrasive ash resulted in continuous ESP performance degradation. To address this, the proposal suggests utilizing erosion-resistant lining materials like cladded steel or sintered ceramic tile blocks in critical flue gas inlet regions [16].

Figures 27 to 30 depict the geometries of various guide plates considered for ESP application. The proposal advocates the use of curved guide plates, especially at ESP inlets, to achieve near-uniform flow on either side of the central splitter plate. In other locations, such as APH outlets to ESP duct inlets, curved guide plates are also recommended.

4.2. Materials for Guide Plates

The selection of guide plate material is predicated on its resistance to erosive wear. Considering service requirements such as ash loading, temperature, and particle velocity, the following materials are identified as suitable for guide plates:

Silicon carbide-based cast ceramic materials with a 5 mm mild steel backing [10].

Tungsten Carbide (WC) cladding on a 12 mm thick mild steel backup plate with 0.75 mm cladding [11].

The erosion resistance of these materials has been assessed under accelerated conditions in a laboratory setup. Based on their performance in laboratory erosion resistance tests, these materials are slated for field evaluation. It is anticipated that the service life of these materials will be a minimum of 2 years.

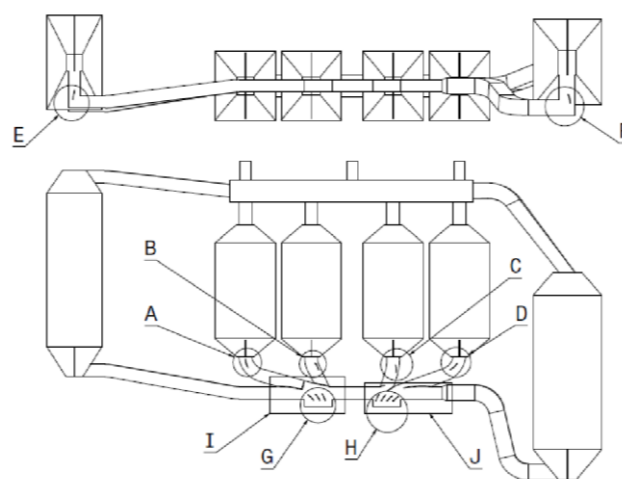


Figure 27. Layout of ESPs in Unit #4 boiler.

5. Mounting of Guide Plates

a) WC Clad plate as Guide plates:

The installation of guide plates can be executed on-site by adhering to standard welding procedures, particularly for WC clad plates. The clad plate manufacturer will provide specialized WC-based welding electrodes designed for seamlessly joining the plates, aligning with the ESP duct's height. Vertical support will be established by welding a channel section along the entire height of the plate, employing stitch welding for structural integrity.

b) Cast Silicon carbide with MS plate backing:

The cast plates are engineered with embedded mounting bolts at two distinct locations across the width of the guide plate. In the pre-cast state, these bolts are affixed to the backing mild steel (MS) plate. Once fabricated, the vertical support for the guide plates will be provided by a mild steel (MS) channel support, strategically positioned on the rear side of the base MS plate to align with the bolt axis.

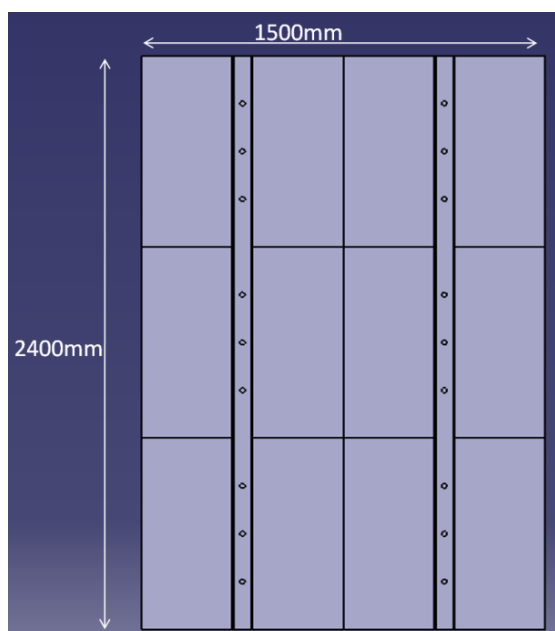


Figure 28. Fixing arrangement using MS angle support.

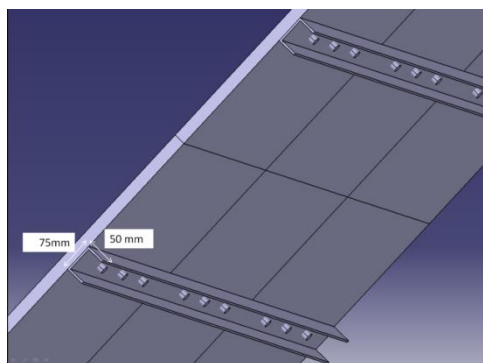


Figure 29. Another view of angle beam support.

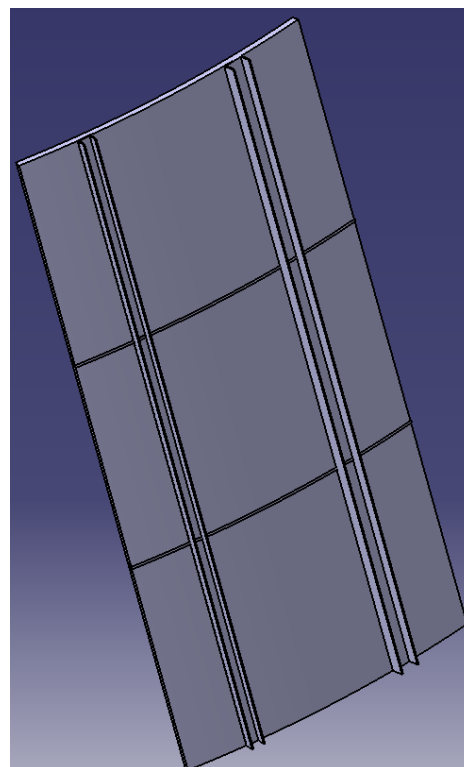


Figure 30. Curved plate fixing arrangements.

6. Material Study and Evaluating Guide Plate Costs: Budgetary Analysis

The expense for the alterations differs depending on the choice between ceramic or clad wear plates.

a) Providing ceramic guide plates:

The cost of the cast ceramic guide plates will be calculated based on the square meter area, with an approximate supplier cost of Rs. 35,000/- per square meter. Additional duties and taxes at 12.36% will be applied, resulting in a total cost of Rs. 40,000/- per square meter.

For the overall modification, the total ceramic plate area required in the duct is 35 m², amounting to an estimated cost of Rs. 14.0 lakhs. Additional expenses include approximately Rs. 50,000/- for transportation and Rs. 1.0 lakh for installation charges, bringing the total cost to Rs. 15.5 lakhs.

b) Providing clad wear plates:

The cost of the hard tungsten carbide clad plate is set at Rs. 1.00 lakh per square meter. Consequently, the cost is approximately three times that of the ceramic plate [16].

c) Implementing alterations in the current geometry by welding mild steel plates in non-critical areas.

The total weight of the mild steel (MS) plate needed is anticipated to be 2.7 tons. At a rate of Rs. 50/kg, the overall material cost is projected to be Rs. 1.50 lakhs.

Therefore, the comprehensive estimated cost for both ceramic and mild steel plates will be: Rs. 17.0 lakhs. Considering a 25% escalation in material costs over time, the total cost for implementing the modifications is projected to

be Rs. 21.5 lakhs.

Micro Hardness Test:

Performing a microhardness test using the Vickers hardness test rig involves creating an indentation on the material's surface using a Vickers indenter. The diagonal length of the resulting indentation is measured to calculate the Vickers hardness. Here's a general process for conducting the test and a discussion of how the results might indicate the suitability of silicon carbide (SiC) over tungsten carbide (WC) for coating flue gas flow baffle plates as shown in Figure 31:

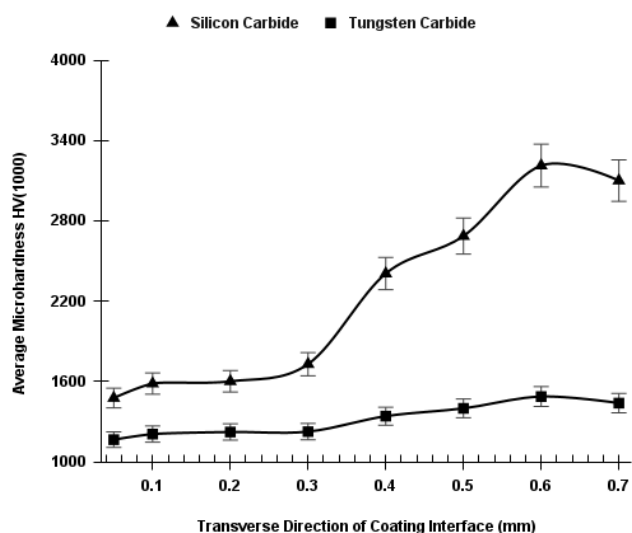


Figure 31. Microhardness comparison among the materials with coating interface.

Microhardness Test Process

a) Sample Preparation [17]: Cut or prepare representative

samples of both silicon carbide and tungsten carbide coatings on substrate material. Ensure that the sample surfaces are smooth and free from any defects.

- Mounting: Mount the samples securely on the microhardness test rig to prevent movement during the test.
- Indentation: Apply a minor load to the Vickers indenter. Gradually increase the load to the desired testing load. Hold the load for a specified dwell time to ensure adequate indentation.
- Measurement: Measure the diagonal lengths of the resulting indentation using a microscope. Calculate the Vickers hardness number using the formula:

$$HV = \frac{1.854 \times Q}{s^2}$$
 where 'Q' is the applied force and 's' is the average diagonal length.
- Analysis: Record and compare the Vickers hardness values for both silicon carbide and tungsten carbide.

Summary of results obtained

- Silicon Carbide Hardness:** The Vickers hardness test indicates that silicon carbide has a higher hardness compared to tungsten carbide, it suggests that SiC is more resistant to indentation and deformation. The higher hardness may translate to better wear resistance, making it more suitable for applications with abrasive environments like flue gas flow.
- Suitability for Flue Gas Flow Baffle Plates:** Baffle plates in flue gas applications can experience abrasive wear due to the flow of particles. A harder material like silicon carbide may offer superior resistance to wear, maintaining its integrity over a more extended period.
- Silicon carbide's excellent hardness and high-temperature stability** make it a potentially suitable choice for protecting baffle plates in harsh environments.

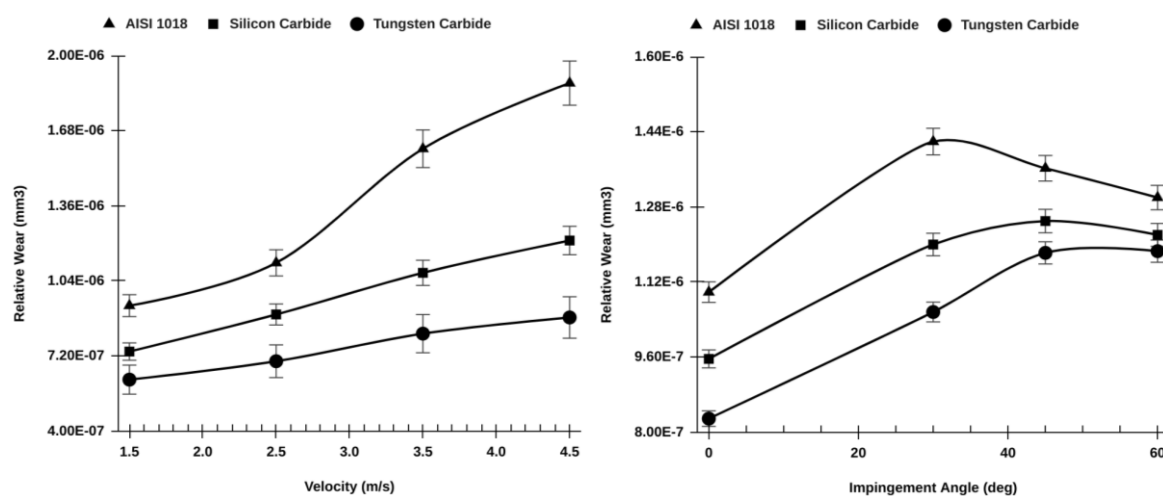


Figure 32. Variation of Relative Wear w.r.t Velocity for AISI 1018, SiC and WC.

While silicon carbide (SiC)[19], indeed exhibits high hardness as a hard material, wear resistance is an intricate

property influenced by factors beyond hardness alone. Several reasons account for tungsten carbide's (WC) superior wear

resistance compared to silicon carbide. Tungsten carbide typically features a microstructure that incorporates a binder phase, such as cobalt, enhancing toughness and resisting cracking and chipping, thereby contributing to improved wear resistance. Conversely, silicon carbide, with its inherent brittleness, becomes susceptible to fracture under specific conditions indicative in Figure 32.

Adhesive wear, characterized by material transfer between contacting surfaces leading to increased friction and wear, is more likely to occur in silicon carbide. In contrast, tungsten carbide, owing to its tough binder phase, demonstrates better resistance to adhesive wear. The chemical environment can influence wear resistance in specific applications. Tungsten carbide, being more chemically resistant to certain environments than silicon carbide, is a significant factor. The wear resistance is affected by the particle size and structure of the materials.

Tungsten carbide coatings, often possessing a well-controlled structure, provide a more uniform and predictable wear behavior. In contrast, the microstructure of silicon carbide coatings can vary, impacting wear resistance. The wear performance of materials relies heavily on specific conditions such as load, contact geometry, and sliding speed, with different materials excelling under different wear conditions.

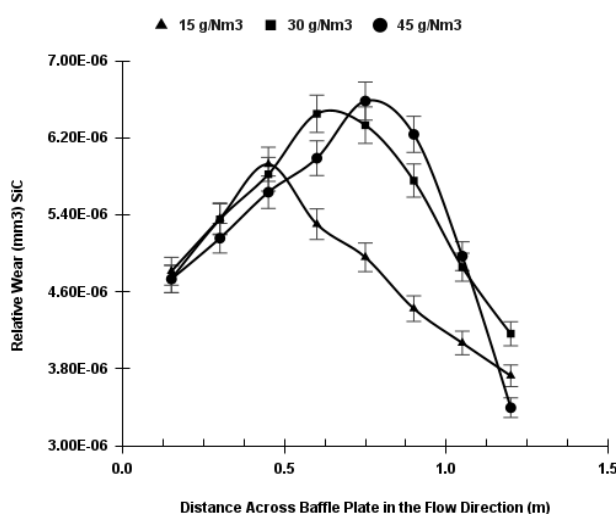
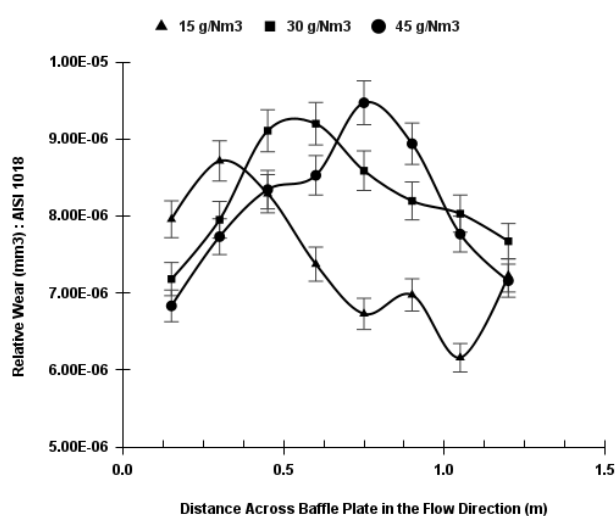
AISI 1018 is a low-carbon steel with a ferritic-pearlitic microstructure, composed of ferrite and pearlite phases. Silicon Carbide possesses a crystalline microstructure, typically with a hexagonal crystal lattice. Tungsten Carbide generally exhibits a fine-grained microstructure, featuring tungsten carbide particles embedded in a cobalt matrix. In terms of Strength and Toughness, AISI 1018 demonstrates moderate levels. It is susceptible to corrosion in certain environments. Silicon Carbide showcases very high hardness

and excellent wear resistance. Its chemical inertness makes it resistant to many chemical reactions. Tungsten Carbide, with extremely high hardness and exceptional wear resistance, is somewhat brittle. However, its toughness can be improved with specific alloying and coating techniques.

Considering these properties, AISI 1018 may not be the optimal choice for coating in ESP ducts due to its relatively lower wear resistance and susceptibility to corrosion compared to the other materials. Silicon Carbide, with its high hardness and wear resistance, is suitable for coating baffle plates in ESP ducts, particularly in applications with abrasive flue gases. Its chemical inertness adds extra protection against corrosive environments. Tungsten Carbide, owing to its outstanding hardness and wear resistance, is well-suited for abrasive environments. However, its inherent brittleness may necessitate careful consideration and potential modifications to enhance toughness for specific applications.

Summary from the Wear Test are highlighted in the following points:

- 1) Silicon Carbide (SiC) stands out as an excellent choice due to its combination of high hardness, exceptional wear resistance, and chemical inertness. The crystalline microstructure adds to its durability in abrasive environments, making it well-suited for coating baffle plates in ESP ducts.
- 2) Tungsten Carbide (WC) is also a strong candidate, but the inherent brittleness may require additional measures to address toughness, depending on the specific requirements of the application.
- 3) AISI 1018 Steel is less optimal for coating in environments with abrasive and corrosive flue gases due to its lower hardness and wear resistance compared to SiC and WC.



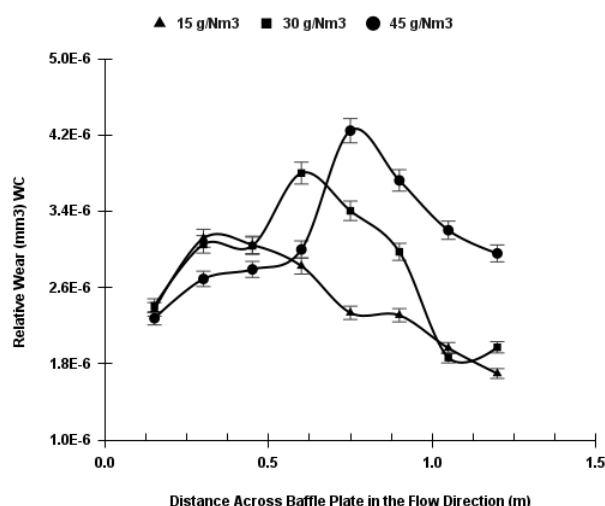


Figure 33. Relative Wear of AISI 1018, SiC and WC under Differential Mass Concentration across the Baffle Plate.

The graph depicting "Relative Wear vs Distance across the baffle plate along the flow direction" reveals significant insights into the impact of mass concentration on the wear behavior of AISI 1018. As observed, there is a clear correlation between the increase in mass concentration and the rise in Peak Relative Wear. This indicates that higher mass concentrations lead to intensified wear on the material.

Furthermore, a noteworthy observation is the shift in the position of maximum erosion. With an increase in mass concentration from 30 g/Nm³ to 45 g/Nm³, the peak erosion point shifted from 0.3 m to 0.6 m and eventually to 0.75 m. This shift is attributed to the effects of self-shielding caused by rebounding particles. The phenomenon of self-shielding

occurs when particles rebound off the baffle plate, creating a shield or protective layer that alters the distribution of erosive forces. As a result, the maximum erosion point is displaced along the flow direction.

The graph Figure 33 indicates a direct relationship between mass concentration and wear, with higher concentrations leading to increased wear. The observed shift in the maximum erosion point is a consequence of self-shielding effects caused by rebounding particles, showcasing the intricate dynamics of erosion mechanisms in this system. This scientific understanding is crucial for optimizing material performance and durability under varying environmental conditions.

7. Bill of Materials for Incorporation of Modifications in ESP

Table 10. BOM of modifications to optimize the Flue Gas Flow in all ESPs.

Sl No	Details	Qty	Dimensions (mm)	Location	Material
1	Guide Plates (Detail G & H)	7	Radius = 5000 Depth = 2000 Arc Length = 1200	APH 1 = 3 APH 2 = 4	Clad or Cast Ceramic
2	Diverter Plates in ESP A, B, C & D (Detail A, B, C & D)	4	Radius = 3000 Depth = 2000 Arc Length = 1500	OLD ESP A = 1 OLD ESP B = 1 OLD ESP C = 1 OLD ESP D = 1	Mild Steel of 8mm thickness
3	Diverter Plate at New ESP B (Detail E)	1	Radius = 6000 Depth = 2000 Arc Length = 1500	New ESP B = 1	Mild Steel of 8mm thickness
4	Diverter Plate at New ESP A (Detail F)	1	Radius = 6000 Depth = 2500 Arc Length = 2000	New ESP A = 1	Mild Steel of 8mm thickness
5	Diverter Plates in Main duct (Detail I)	1	Radius = 15000 Depth = 2000	Between New ESP B & Old ESP A = 1	Cast Ceramic

SI No	Details	Qty	Dimensions (mm)	Location	Material
			Arc Length = 4300		
6	Diverter Plates in Main duct (Detail J)	1	Radius = 15000 Depth = 2000 Arc Length = 4500	Between Old ESP D New WSP A& = 1	Cast Ceramic
7	Restriction of Inlet area (Detail I)	3	300mm * 2000mm = 1 No 300mm * 1700mm = 2 Nos	Top and Left and Right sides of ESP A	Mild Steel of 8mm thickness
8	Restriction of Inlet area (Detail I)	3	350mm * 2000mm = 1 No 350mm * 1650mm = 2 Nos	Top and Left and Right sides of ESP B	Mild Steel of 8mm thickness
9	Restriction of Inlet area (Detail J)	1	650mm * 2000mm = 1 No	Left of ESP C Inlet	Mild Steel of 8mm thickness
10	Restriction of Inlet area. (Detail J)	1	1300mm * 2000mm = 1 No	Right of ESP C Inlet	Mild Steel of 8mm thickness

8. Conclusions

1) Principle of Measurement of Flue Gas Duct Airflow:

The cold air velocity was determined using a calibrated S-Type Pitot Tube, providing accurate measurements for the velocity at various locations within the duct system. The mass flow distribution of cold air in various ducts was analyzed, revealing insights into airflow dynamics.

2) Measurement of FGDA under Different ID Fan Operations:

Flue Gas Duct Airflow Analysis (FGDA) was conducted for four different combinations of Induced Draft (ID) fans. The analysis focused on the ducts between the Air Pre-heater (APH) outlets and the Inlet Duct (ID) fan inlets, providing valuable data for optimizing operational efficiency. Minor leakages were observed during the analysis, emphasizing the need for further investigation and rectification during shutdown maintenance.

3) Mass Flow Distribution Observations in 6 ESPs:

Mass flow distribution across Electro Static Precipitators (ESPs) was found to be non-uniform for all studied combinations. Flow patterns within ESPs varied based on different combinations of ID fans. ESP-C consistently exhibited higher mass flow compared to other ducts in most ID fan combinations.

4) CFD Analysis:

Computational Fluid Dynamics (CFD) analysis was conducted for two cases, simulating shutdown conditions and incorporating designed baffle/diverter plates. The analysis provided insights into mass flow distributions in various ESPs for different ID fan combinations. Several iterations were performed to optimize baffle/diverter combinations for improved mass flow distribution.

5) Engineering Design and Cost Estimation for Baffle/Guide Plates:

The proposed engineering design involved modifying the geometry of guide plates to achieve near-uniform flow in ESPs. Materials such as silicon carbide-based cast ceramic and Tungsten Carbide (WC) cladding were identified for guide plates based on their erosive wear resistance potential. Mounting methods for WC clad plates and cast silicon carbide plates were detailed.

6) Guide Plate Cost Evaluation:

The cost for ceramic guide plates was estimated based on the square meter area, with additional expenses for duties, taxes, transportation, and installation. Tungsten Carbide (WC) clad plates were projected to cost three times that of ceramic plates (Ref Table 10).

7) Erosion Tests:

The microhardness test indicates silicon carbide (SiC) has superior hardness and wear resistance compared to tungsten carbide (WC), making it promising for flue gas baffle plates. However, WC's wear resistance stems from its microstructure, offering advantages in specific conditions. The wear test underscores SiC's excellence for baffle plates, while tungsten carbide may need toughness enhancements. AISI 1018 steel is less optimal. The wear graph shows increased mass concentration intensifying wear on AISI 1018, with the maximum erosion point shifting due to self-shielding, crucial for optimizing material performance in erosive environments.

The summary outlines the comprehensive assessment of flue gas duct airflow. Utilizing calibrated S-Type Pitot Tubes, airflow dynamics were analyzed, uncovering non-uniform mass flow distributions in ESPs. Computational Fluid Dynamics (CFD) simulations and engineering designs proposed modifications for uniform flow, emphasizing materials like silicon carbide and Tungsten Carbide. Cost evaluations indicated Tungsten Carbide clad plates as pricier.

Microhardness tests favored silicon carbide for baffle plates, emphasizing its wear resistance. The wear test highlighted increased wear on AISI 1018 with mass concentration, crucial for optimizing material performance in erosive environments.

Abbreviations

FGDAA	Flue Gas Duct Airflow Assessment
CFD	Computational Fluid Dynamics
ESP	Electrostatic Precipitator
ID	Induced Draft
FD	Forced Draft
TPS	Thermal Power Station
APH	Air Pre-Heater
OEM	Original Equipment Manufacturer
SiC	Silicon Carbide
WC	Tungsten Carbide
MS	Mild Steel
BOM	Bill of Materials
HV	Vickers Hardness Number
AISI	American Iron and Steel Institute
MWe	Megawatt Electrical

Conflicts of Interest

The authors declare no conflicts of interest.

References

- [1] L. Morawska, V. Agranovski, Z. Ristovski and M. Jamriska, 2002, Effect of face velocity and the nature of aerosol on the collection of submicrometer particles by electrostatic precipitator, *Indoor air*, 12 (2002) 129-137.
- [2] S. M. E. Haque, M. G. Rasul, A. V. Deev, M. M. K. Khan and N. Subaschandar, 2009 Flow simulation in an electrostatic precipitator of a thermal power plant, *Applied Thermal Engineering*, 29 (2009) 2037-2042.
- [3] I. Gallimberti, 1998, Recent advancements in the physical modelling of electrostatic precipitators, *Journal of Electrostatics*, 43 (1998) 219-247.
- [4] M. G. Rasul, B. S. Tanty, B. Mohanty, Modeling and analysis of blast furnace performance for efficient utilization of energy, *Applied Thermal Engineering* 27 (2007) 78-88.
- [5] L. Zhao, E. Dela Cruz, K. Adamiak,, A. A. Berezin, J. S. Chang, A numerical model of a wire-plate electrostatic precipitator under electrohydrodynamic flow conditions, in: Conference proceedings. The 10th International Conference on Electrostatic Precipitator, Australia, 2006.
- [6] G. Skodras, S. P. Kalidas, D. Sofialidis, O. Faltsi, P. Grammelis, G. P. Sakellariopoulos, Particulate removal via electrostatic precipitators - CFD simulation, *Fuel Processing Technology* 87 (2006) 623-631.
- [7] K. S. P. Nikas, A. A. Varnos, G. C. Bergeles, Numerical simulation of the flow and the collection mechanisms inside a laboratory scale electrostatic precipitator, *Journal of Electrostatics* 63 (2005) 423-443.
- [8] C. U. Bottner, M. Sommerfeld, Euler/Lagrange calculations of particle motion in turbulent flow coupled with an electric field, in: *Proceedings of ECCOMAS Computational Fluid Dynamics Conference*, 2001.
- [9] B. J. Dumont, R. G. Mudry, Computational fluid dynamic modeling of electrostatic precipitators, in: *Proceedings of Electric Power Conference*, 2003.
- [10] Dimitrijevic M, Posarac M, Volkov-Husovic T, Devacerski A, Matovic B. Behavior of silicon carbide/cordierite composite material after cyclic thermal shock. *Ceram Int* 2009; 35(3): 1077-81.
- [11] Arul Inigo Raja, Z. Edward Kennedy, G. Rajaram, G. Prabhakaran, Erosion behavior of Tungsten carbide-cobalt and alumina coatings on stainless steel 316, *Materials Today: Proceedings*, Volume 55, Part 2, 2022, Pages 375-379.
- [12] Tomlinson WJ, Matthews SJ. Cavitation erosion of structural ceramics. *Ceram Int* 1994; 20: 201-9.
- [13] Niebuhr D. Cavitation erosion behavior of ceramics in aqueous solutions. *Wear* 2007; 263: 295-300.
- [14] I. Gallimberti, I. Recent advancements in the physical modeling of electrostatic precipitators, *Journal of Electrostatics* 43 (1998) 219-247.
- [15] Isato Morita, Totu Ogasahara, Franklin Howard N. Recent experience with hitachi platetype SCR catalyst, vol. 02 *The Institute of Clean Air Companies Fourm* (2002), pp. 1-20, 2002.
- [16] Yang Xu, Wen-yan Li, Structure design of baffle plates in SCR denitrification reactor, *Power Syst Eng*, 37 (10) (2008), pp. 49-52, 2008.
- [17] Girish R. Desale, Bhupendra K. Gandhi, S. C. Jain, Effect of erodent properties on erosion wear of ductile type materials, *Wear*, Volume 261, Issues 7-8, 20 October 2006, Pages 914-921.
- [18] B. K. Gandhi, S. N. Singh, V. Seshadri, Study of the parametric dependence of erosion wear for the parallel flow of solid-liquid mixtures, *Tribology International* Volume 32, Issue 5, April 1999, Pages 275-282.
- [19] Anisha Ekka, Amruta Panda, Trupti Ranjan Mahapatra, Debadutta Mishra, Erosion and wear analysis of fly ash filled GFRP composite, *Materials Today: Proceedings*, 2023.