



Numerical Study of Coal-Air Mixture Erosion with Vane Addition in Elbow Coal Pipe

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Abstract

Background: Erosion in elbow coal pipes is a recurring problem in coal-fired power plants because the interaction between coal particles and airflow can cause localized wall thinning, leakage, and reduced reliability of the coal transport system.

Objective: This study evaluates the effects of vane position and radius on coal-air flow characteristics, erosion distribution and rate, and estimated pipe remaining life, validates the CFD model against field thickness measurements, and identifies the most suitable vane configuration among six alternatives.

Methods: A comparative numerical study was conducted using Computational Fluid Dynamics (CFD) in ANSYS Fluent 2024 R2. The simulation employed the realizable $k-\epsilon$ turbulence model, Discrete Phase Model (DPM), DNV erosion model, and one-way coupling under steady-state conditions. Six vane configurations were evaluated using positions of 0.5D and 0.75D and radii of R1100, R1250, and R1400.

Results: Validation at Patch A produced a relative error of 4.53%. The six configurations produced different erosion and remaining-life characteristics due to changes in flow distribution and particle impact. The 0.75D-R1250 configuration produced an erosion rate of 0.07 kg/m²s at Patch A and an estimated remaining life of 71.12 years, while its vane erosion rate was 9.67 kg/m²s.

Conclusion: The results demonstrate that vane position and radius influence erosion mitigation and flow behavior in elbow coal pipes. The findings provide a numerical basis for selecting vane configurations and prioritizing inspection and maintenance of erosion-prone coal pipe sections at PLTU Banten 3 Lontar.

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INTRODUCTION

The reliability of coal-fired power plants depends not only on the performance of the boiler and turbine systems but also on the reliability of the coal transport system that continuously supplies pulverized coal to the furnace. Coal-fired power plants remain an important component of the electricity supply system in Indonesia, making the reliability of their supporting equipment essential for maintaining continuous operation. Within the coal preparation and transport process, the pulverized coal produced by the mill is conveyed to the boiler through coal pipes using an air stream. Therefore, the integrity of coal pipes is important because damage to these components can interrupt coal delivery to the furnace and affect plant operation.

At PLTU Banten 3 Lontar, coal is processed through the coal handling and pulverizing system before being transported to the boiler. After entering the bunker, coal is regulated by the

coal feeder and pulverized in the mill to a fine particle size before being carried by air through the coal pipes. The resulting coal-air mixture forms a gas-solid two-phase flow that passes through several bends or elbows before reaching the furnace. Unlike straight pipe sections, elbows change the flow direction and consequently alter particle trajectories and velocity distributions. These changes can cause coal particles to deviate from the airflow streamlines and impact the pipe wall, particularly at the outer region of the elbow. Repeated particle impacts can produce localized erosion, wall thinning, and eventually leakage. Such leakage can disrupt coal delivery and may also create operational and safety risks because fine coal particles can escape from the transport system. The recurring erosion problem in coal pipe elbows therefore requires a mitigation approach that considers both flow behavior and particle-wall interaction.

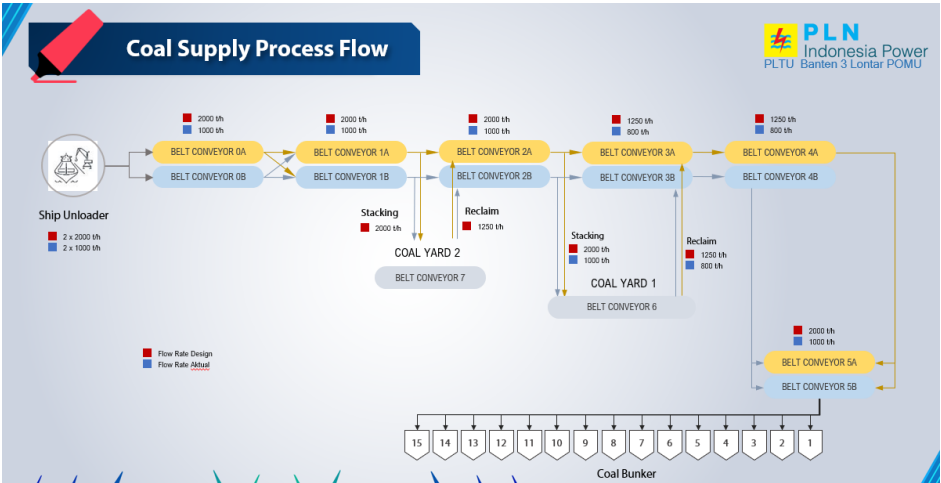


Figure 1. Coal Supply Process Flow from Coal Handling to Bunker

The coal handling process begins with the delivery and storage of coal before it is supplied to the bunker of each mill/pulverizer. This process ensures that the coal is available as feed for subsequent pulverization and transport to the boiler. After entering the bunker, coal is regulated by the coal feeder and pulverized in the mill to a fine particle size before being carried by air through the coal pipes. The pulverized coal is subsequently transported from the mill toward the boiler through the coal pipe system.

The resulting coal-air mixture forms a gas-solid two-phase flow that passes through several bends or elbows before reaching the furnace. Unlike straight pipe sections, elbows change the flow direction and consequently alter particle trajectories and velocity distributions. These changes can cause coal particles to deviate from the airflow streamlines and impact the pipe wall, particularly at the outer region of the elbow. Repeated particle impacts can produce localized erosion, wall thinning, and eventually leakage. Such leakage can disrupt coal delivery and may also create operational and safety risks because fine coal particles can escape from the transport system.

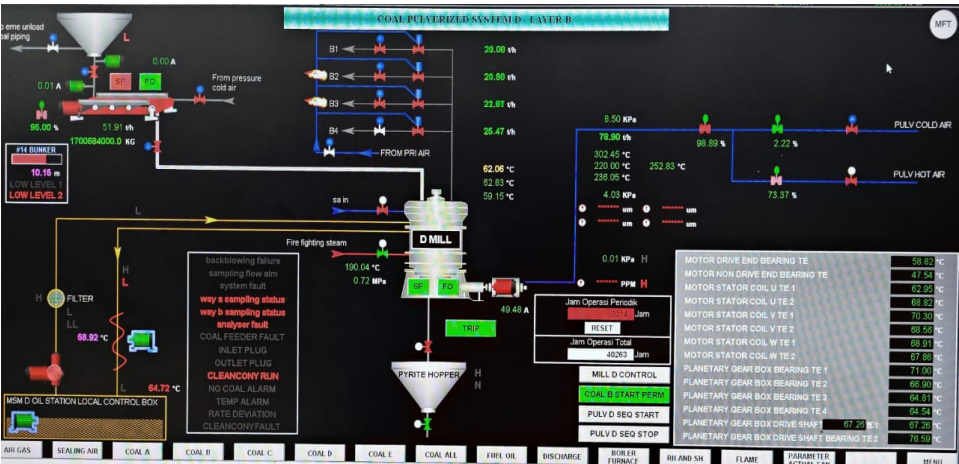


Figure 2. Coal Supply Process Flow from Bunker to Furnace

Erosion in pipe elbows has been widely investigated in gas-solid and liquid-solid flow systems. f et al. (2019) used CFD simulation to analyze erosion caused by sand particles in gas flow and showed that particle impact angle strongly affects the erosion distribution on elbow walls (Ahmad et al., 2026). Hong et al. (2021) numerically investigated gas-solid two-phase flow in shale gas systems and found that solid particles tend to concentrate toward the outer elbow wall as a consequence of particle inertia and centrifugal effects (Hong et al., 2023). Xu et al. (2016), using a CFD-DEM approach, demonstrated that the use of deflectors or inserts can reduce erosion on the main elbow wall, although erosion may subsequently become concentrated on the inserted component (Xu et al., 2025). Duarte et al. (2016) investigated a vortex chamber as an erosion-mitigation approach, while Atmaja et al. (2020) examined erosion prediction in oil-well pipe bends using several erosion models (Li et al., 2022; Prasetyo, 2024). These studies demonstrate that particle trajectory, impact velocity, impact angle, and elbow geometry are important factors governing erosion intensity.

Although previous studies have established the effectiveness of CFD-based approaches for predicting erosion and have examined various forms of elbow modification, an important question remains regarding how the position and radius of a flow director should be selected to control erosion in pulverized coal transport systems. Most of the existing studies cited above were conducted in oil and gas applications or in generalized gas-solid and liquid-solid flow systems. Consequently, their findings cannot be directly assumed to represent the flow and erosion behavior of pulverized coal transported through coal pipes in a coal-fired power plant. In particular, the interaction between vane position, vane radius, flow constriction, particle trajectory, erosion on the main elbow wall, and erosion on the vane itself has not been systematically evaluated for an actual coal pipe system in an Indonesian coal-fired power plant.

This gap is particularly relevant to coal pipes at PLTU Banten 3 Lontar, where recurring elbow leakage makes erosion mitigation an operational concern. The unresolved issue is therefore not simply whether a vane can reduce erosion, but which combination of vane position and radius can provide an appropriate balance between protection of the main elbow wall and erosion transferred to the vane. A systematic comparison is needed because a configuration that minimizes erosion on the main pipe wall may simultaneously produce excessive erosion on the vane or create local flow acceleration. The selection of a vane configuration consequently requires consideration of the resulting flow characteristics, erosion distribution, erosion rate, and estimated remaining life of both the main pipe wall and the vane.

To address this gap, the present study evaluates six vane configurations in the third elbow of the coal pipe at PLTU Banten 3 Lontar. The configurations combine two vane positions, namely 0.5D and 0.75D, with three vane radii, namely R1100, R1250, and R1400. The six configurations are compared using Computational Fluid Dynamics (CFD) to identify differences in velocity distribution, particle-flow behavior, erosion distribution, erosion rate, and estimated remaining life. The CFD results are also validated against field pipe-thickness measurement data at selected locations. This combination of systematic geometric variation and field-based validation provides a basis for evaluating vane configurations under conditions representative of an actual coal-fired power plant coal pipe system.

The urgency of this research arises from the need to reduce the likelihood of coal pipe leakage and to improve the reliability of the coal transport system through an engineering-based erosion mitigation strategy. The practical benefit of the study is to provide information for identifying erosion-prone locations, prioritizing inspection and thickness monitoring, and evaluating the use of replaceable vane components as a means of protecting the main elbow wall. Scientifically, the study contributes to the application of gas-solid erosion analysis to pulverized coal duct systems by clarifying the relationship between vane geometry, flow redistribution, and particle impact. The results can also provide a reference for future erosion-mitigation studies in solid-particle transport systems with similar flow characteristics.

Accordingly, the objectives of this study are to: (1) evaluate the effect of vane position and radius on the flow characteristics of the coal-air mixture in the elbow coal pipe; (2) compare the erosion distribution, erosion rate, thinning rate, and estimated remaining life of the main pipe wall and vane for six configurations; (3) validate the CFD erosion prediction using field pipe-thickness measurement data; and (4) determine the most suitable vane configuration based on the combined consideration of main elbow protection, vane erosion, flow behavior, and estimated

remaining life. These objectives are intended to provide a quantitative basis for erosion mitigation and maintenance planning for the coal pipe system at PLTU Banten 3 Lontar.

METHOD

This research used a numerical approach based on Computational Fluid Dynamics (CFD) simulation with ANSYS Fluent 2024-R2 to analyze erosion in the elbow coal pipe at PLTU Banten 3 Lontar, using sub-bituminous coal with a diameter of 0.075 mm (200 mesh) flowing with air in Q235-type carbon steel pipes. The simulation was conducted using the realizable k-ε turbulence model, the Discrete Phase Model (DPM) with the DNV erosion model, and a one-way coupling approach under steady-state conditions, with geometry variations in the form of vane additions to the third elbow in 6 variations based on vane radius (1100, 1250, and 1400 mm) at positions of 0.5 and 0.75 pipe diameters as shown in Figure 3. Validation was performed by comparing simulation results against actual pipe thickness data in the field, where results were considered valid if the maximum error percentage was 10%, and analysis was focused on turbulent kinetic energy and erosion distribution patterns as a basis for design recommendations to minimize elbow coal pipe damage.

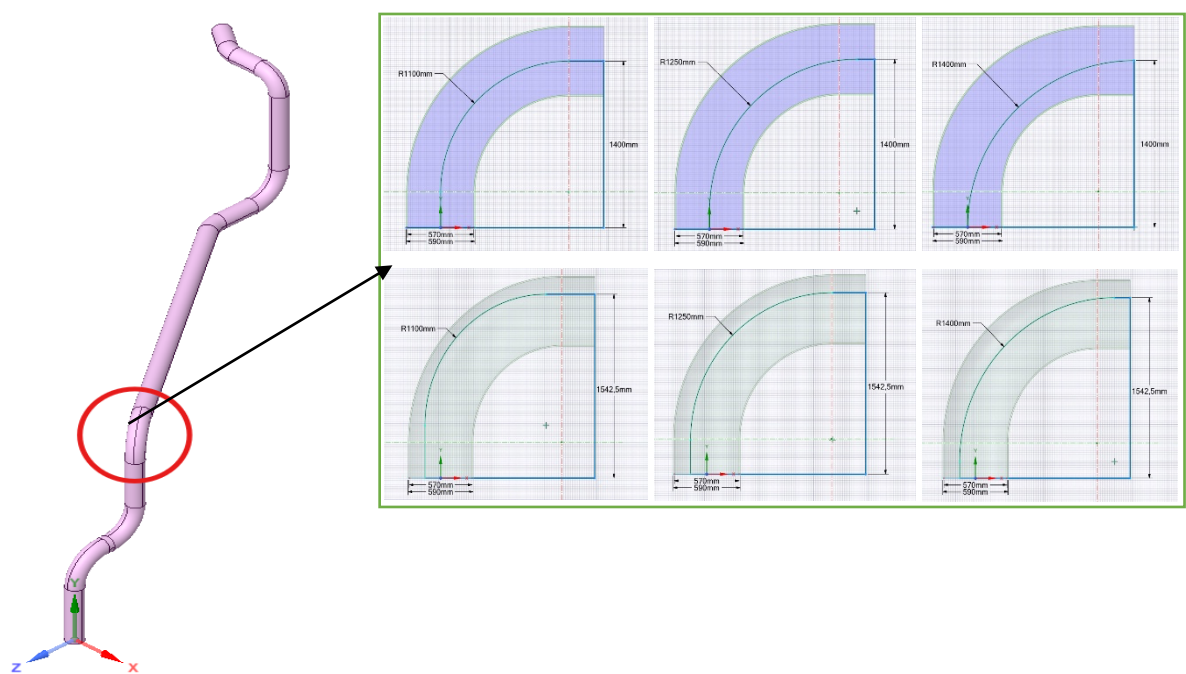


Figure 3. Vane Addition Position and Elbow Variations

RESULTS AND DISCUSSION

Results

Geometry and Fluid Domain Creation

In the initial stage, the geometry model of the coal pipe A1 outlet mill E (Figure 4) at PLTU Lontar was created using Space Claim software in ANSYS 2024 R2. This model was developed based on the design provided by Dongfang Electric Corporation so that it is representative of the actual pipe conditions and was checked in the field.

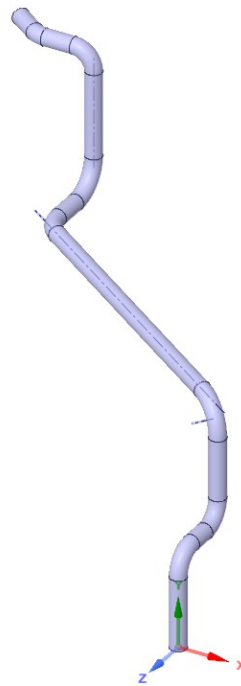


Figure 4. Coal Pipe A1 Outlet Mill E Geometry

In the simulation, one important aspect is the creation of the fluid domain for the simulation. The fluid domain of the numerical simulation will affect the results produced by the simulation. The fluid domain creation is shown in Figure 5, consisting of:

Inlet: the location where the coal & air mixture enters the pipe

Outlet: the location where the coal & air mixture fluid exits

Wall: the locations of the pipe walls are defined as wall boundaries

Figure 5. The fluid domain is important to ensure accurate flow simulation inside the coal pipe A1 Outlet Mill E.

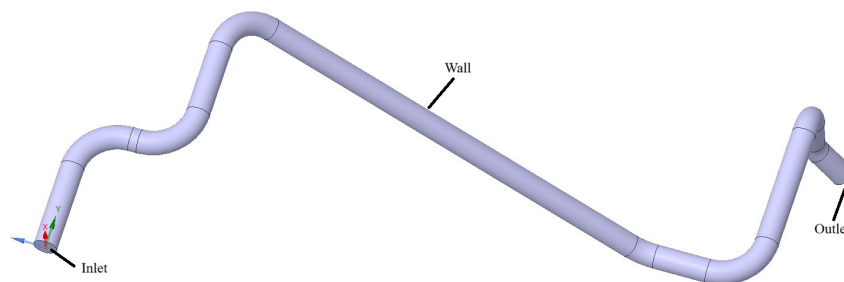


Figure 5. Fluid Domain

Meshing and Grid Independence Test

Mesh quality is important as shown in Figure 6 because mesh quality directly affects the accuracy and stability of numerical simulations, such as in finite element analysis or fluid dynamics. A poor mesh (e.g., overly skewed or non-orthogonal) can cause significant numerical errors or even simulation failure, as indicated by the Skewness and Orthogonal Quality spectrum mapping quality from "Unacceptable" to "Excellent."

By using color scales and numerical values, Figure 6 helps researchers quickly identify mesh areas that need improvement before running the simulation. Therefore, understanding and maintaining good mesh quality is a crucial step in ensuring valid and reliable simulation results.

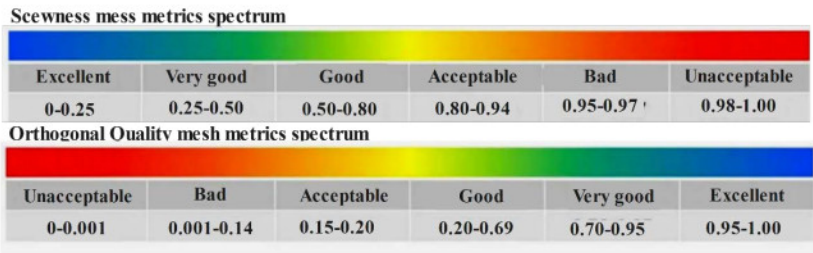
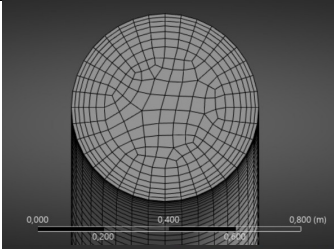
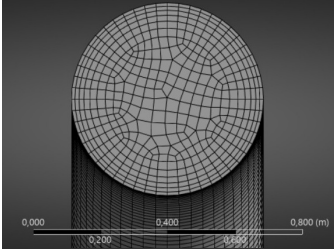
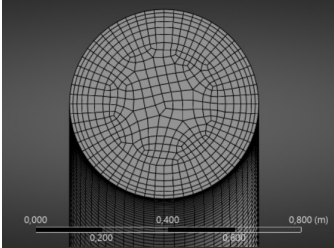
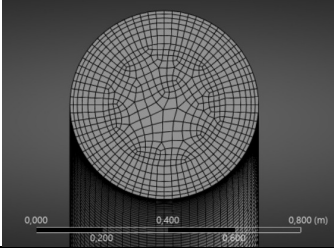


Figure 6. Mesh Quality

The fluid domain flows according to the pipe shape with many elbows, so the multizone mesh type with hexahedral shape was chosen due to its advantages for meshing complex models, faster computation, and more efficient element usage. The meshing process continued with a key step, namely using face meshing to control how mesh elements are shaped and distributed on the model surfaces. After that, the mesh was refined near the coal pipe walls and elbow areas, then inflation was added to improve the accuracy of particle trajectory and erosion predictions and to reduce the number of elements to be simulated. Performing this process helps avoid distorted or overly large mesh elements that could reduce the accuracy of simulation results. In addition to the number of elements, the number of nodes (individual points that form the framework of a mesh) was also considered because nodes ensure continuity in the mesh model so that displacements can be transferred smoothly between elements. The meshing results are presented in Table 1 and the mesh quality results in Table 2.

Table 1
Meshing Results

Mesh	Element	Nodes	Detail of Face Mesh
M1	204910	217798	
M2	439438	465392	
M3	636840	671489	
M4	980990	1030428	

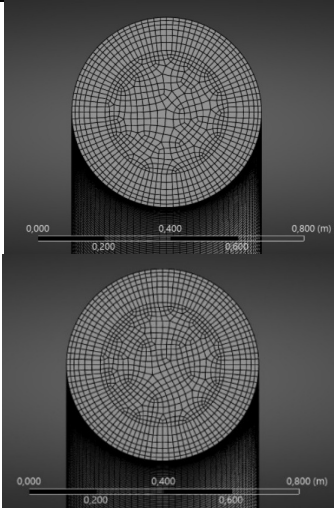
Mesh	Element	Nodes	Detail of Face Mesh
M5	1653996	1731946	
M6	2096631	2190100	

Table 2
Mesh Quality Results

Mesh		M1	M2	M3	M4	M5	M6
Element		204910	439438	636840	980990	1653996	2096631
Skewness	min	0.0365	0.0088	0.0113	0.0091	0.0084	0.0071
	max	0.4130	0.4232	0.4295	0.4362	0.4465	0.4454
	avg	0.1233	0.1132	0.1085	0.1063	0.1040	0.1026
Orthogonal	min	0.8780	0.8522	0.8649	0.8556	0.8508	0.8414
	max	0.9989	0.9997	0.9999	0.9999	1.0000	0.9999
	avg	0.9841	0.9868	0.9872	0.9876	0.9880	0.9877
Aspect Ratio	min	1.0307	1.0134	1.0228	1.0181	1.0164	1.0171
	max	5.9011	4.0699	3.5277	3.0858	3.1241	3.1443
	avg	2.7824	2.0873	1.8429	1.6863	1.5640	1.5302

From the mesh quality results in Table 2, it shows that the skewness category of the six meshing models simulated falls into the very good quality category. In the orthogonal category, the five meshing models simulated also fall into the very good quality category. In the aspect ratio category, according to ANSYS application standards (<10), the five meshing models simulated fall into that category. This indicates that the mesh quality of the 3D fluid domain model from the six meshing models for simulation is already good and can proceed to the next process.

To ensure that the number of mesh elements does not affect the simulation results, a grid independence test was conducted. The grid independence test was performed by comparing simulation results at several mesh density levels. The mesh is considered independent if the change in results is below the specified tolerance limit. The grid independence test results for maximum erosion can be seen in Table 3 and Figure 7.

Table 3
Grid Independence Test Results for Maximum Erosion

Element	Erosion Max (kg/m ² s)	Thinning (mm/year)	Δ% vs previous mesh
204910	1.88E+00	7.54	0.22
439438	2.30E+00	9.22	0.17
636840	2.68E+00	10.76	0.37
980990	3.68E+00	14.78	0.01
1653996	3.73E+00	14.98	0.00
2096631	3.72E+00	14.95	-

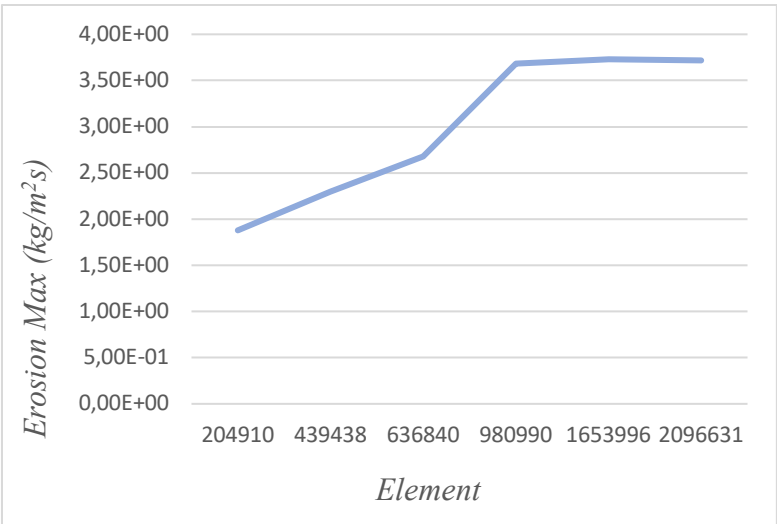


Figure 7. Grid Independence Test Graph for Maximum Erosion

Solution Convergence Results
Simulation Residual Model

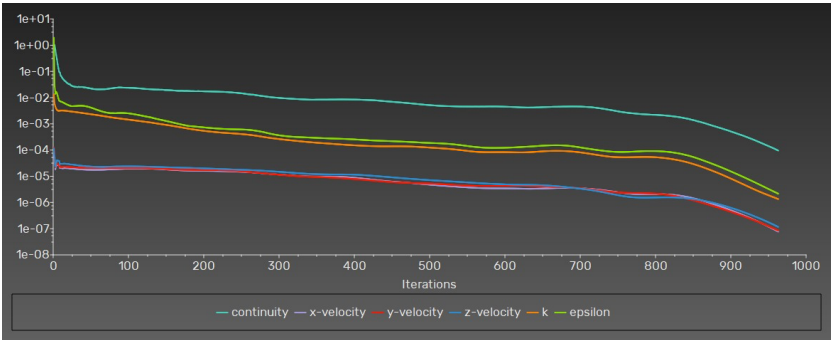


Figure 8. Residuals per Time Step of Simulation

The convergence graph in Figure 8 displays the residual behavior of six CFD simulation variables over 1000 iterations, including continuity, three velocity components (x, y, z), and turbulence parameters k and epsilon, where all variables show a consistent decreasing residual trend, indicating that the simulation is running well and stably. The velocity components achieved the highest convergence with residuals dropping to 1×10^{-7} to 1×10^{-8} , turbulence parameters k and epsilon reached 1×10^{-5} to 1×10^{-6} , while continuity reached around 1×10^{-4} , which is still within acceptable limits, so overall the simulation is declared to have reached a stable, physically valid solution and can be used as a basis for further analysis with a high level of confidence.

Mass Balance

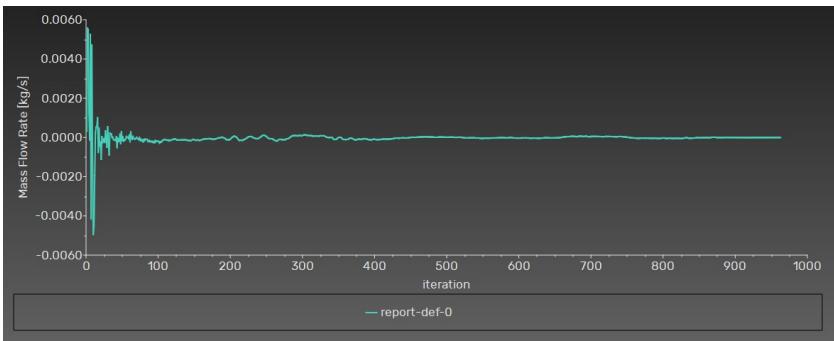


Figure 9. Mass Flow Rate of Simulation

The Mass Flow Rate graph in Figure 9 shows the convergence development of the CFD simulation over 1000 iterations, where in the initial phase (0--50 iterations) large fluctuations of up to ± 0.006 kg/s occurred due to the initial transient conditions that were not yet stable, then gradually decreased in the middle phase (50--200 iterations) as the system moved toward equilibrium, until in the final phase (200--1000 iterations) the curve became almost flat and oscillated very slightly around zero, indicating that the principle of mass conservation has been accurately fulfilled and the simulation has reached a physically valid solution that can be used as a basis for further analysis.

Simulation Result Validation

The erosion rate data from the simulation were extracted at pipe wall locations equivalent to patches A and B during pipe thickness measurement in the field. The extraction area in Figure 10 was adjusted to the dimensions of the ultrasonic probe used in the inspection, allowing direct comparison between simulation results and field data.

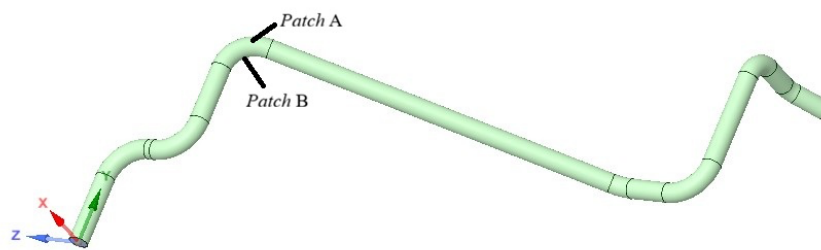


Figure 10. Erosion Data Patch Locations

The thinning rate values from the simulation results were compared with the thinning conditions in the field. To enable validation with the CFD simulation results, a unit conversion from $\text{kg/m}^2\text{s}$ to mm/year was performed using equation (1) below:

$$E = \dot{t}(\text{mm/yr}) \times \left(\frac{1 \times 10^{-3} \text{ m/mm}}{31560000 \text{ s/yr}} \right) \times \rho_t \quad (1)$$

Where: E = Erosion ($\text{kg/m}^2\text{s}$)

$\dot{t}$ = Thinning rate (mm/year)

ρ_t = Pipe material density (kg/m^3)

Thus, by comparing the relative errors, the results are shown in Table 4.

Table 4

Comparison of Field Erosion and Simulation Erosion

Patch	Erosion Field	Erosion CFD	Ratio field/CFD	Error Relative
A	6.21	6.51	0.95	4.53%
B	0.00	0.00	1	0.00%

In Table 4, the comparison results show that the erosion rate values from the simulation are in the same order of magnitude as the field estimates. The observed quantitative deviation is still within the acceptable range ($<10\%$) for numerical simulations based on empirical models.

Flow Phenomena Occurring in the Coal Pipe

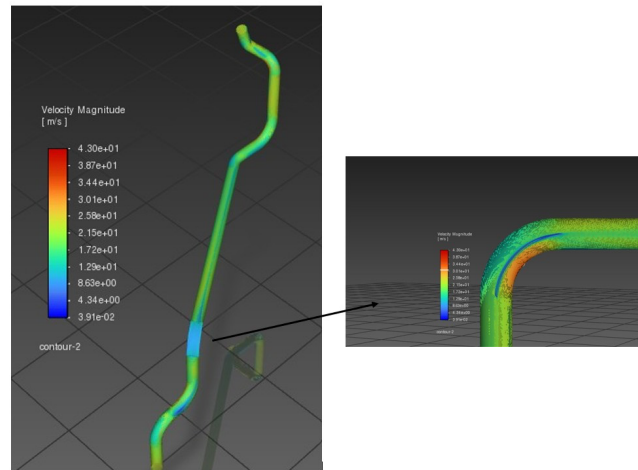


Figure 11. Velocity Contour of Coal Pipe with Vane Addition at 0.5D Radius 1250

Figure 11 displays the velocity contour of the flow in the coal pipe with vane 0.5D radius 1250, using a color scale from dark blue (lowest velocity ~ 0.039 m/s) to dark red (highest velocity ~ 43.0 m/s), where overall the flow velocity tends to be higher on the outer side of the elbow curvature, but the addition of the vane in this configuration produces a different velocity distribution pattern compared to the elbow without a vane, indicating that the vane plays a role in modifying the flow characteristics of the coal-air mixture in the elbow.

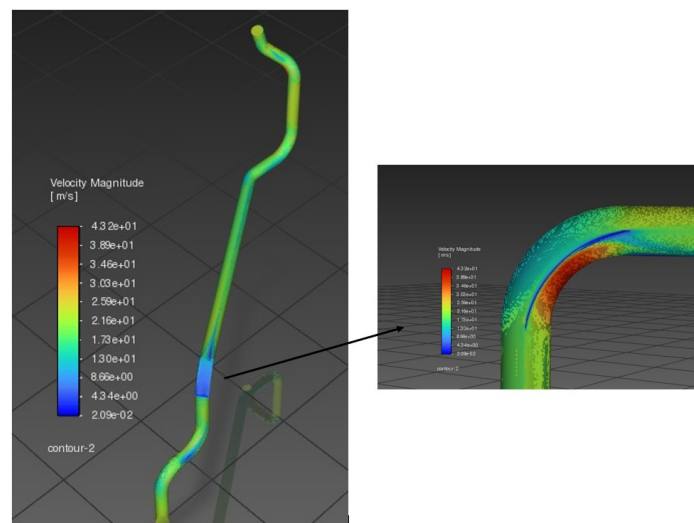
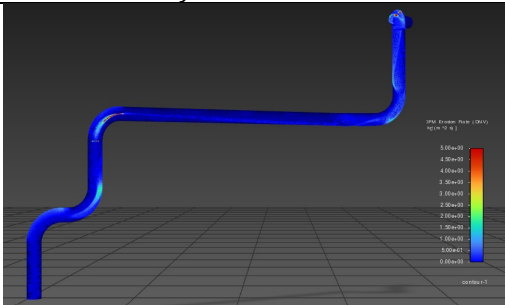


Figure 12. Velocity Contour of Coal Pipe with Vane Addition at 0.5D Radius 1400

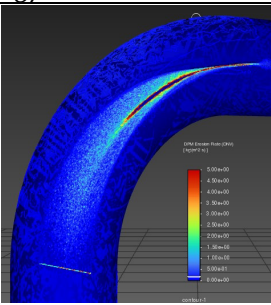
Figure 12 displays the velocity contour distribution of the flow in the coal pipe with vane 0.5D radius 1400, using a color scale from dark blue (lowest velocity ~ 0.021 m/s) to dark red (highest velocity ~ 43.2 m/s), where high velocity is concentrated on the inner side of the elbow diameter due to centrifugal effects and cross-sectional area narrowing, while low velocity is dominant on the outer side of the elbow pipe diameter. Comparing Figure 11 and Figure 12, the addition of a vane with a larger radius (0.5D radius 1400) causes a more significant increase in flow velocity on the inner side of the pipe due to flow constriction, but at the same time reduces the velocity on the outer side of the pipe more noticeably than the vane with a smaller radius (0.5D radius 1250), thus the selection of the vane radius is proven to significantly influence the velocity distribution characteristics of the coal-air mixture flow in the elbow coal pipe.

Erosion Rate Distribution in the Coal Pipe

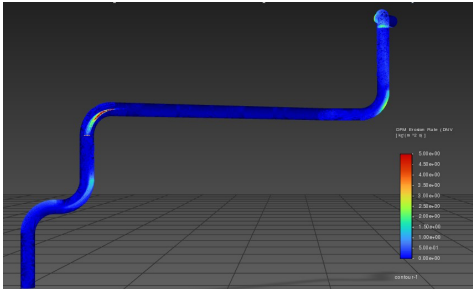
Table 5
Erosion Contour Results for Variations A-F with Max Erosion 5 kg/m²s



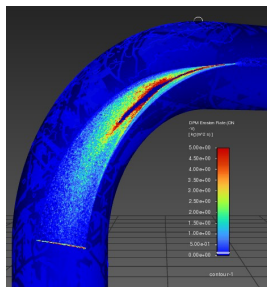
Erosion contour results along the pipe, Variation A, at 0.5D radius 1100



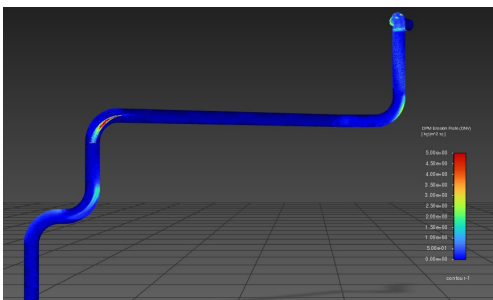
Elbow contour – Type A, 0.5D, radius 1110



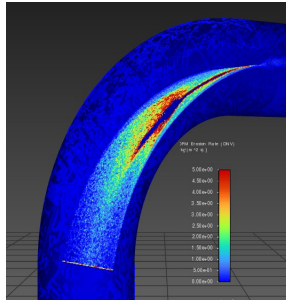
Erosion Contour Results Along the Pipe for Variation B at 0.5D, Radius 1250



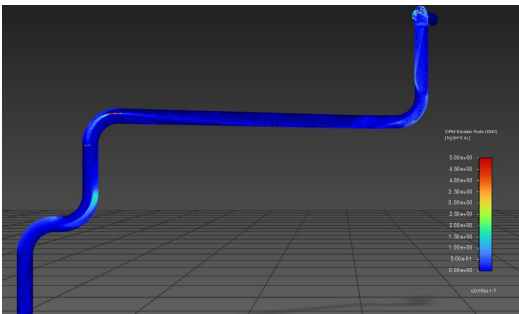
Elbow contour – Type B, 0.5D, radius 1250



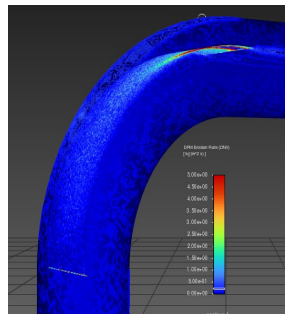
Erosion contour results along the pipe, variation C, at 0.5D and a radius of 1400



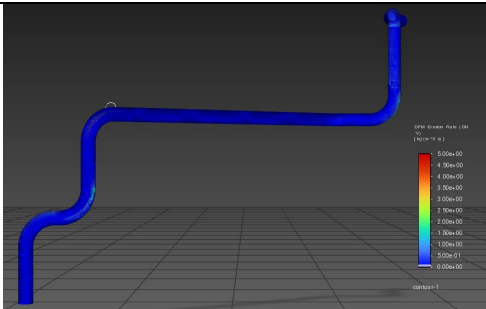
Elbow contour, C-type variation, 0.5D, radius 1400



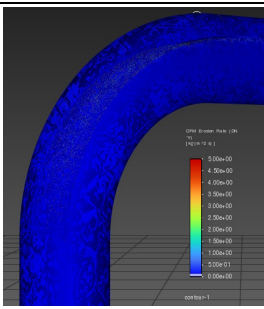
Erosion contour results along the pipe for variation D at a 0.75D radius of 1100



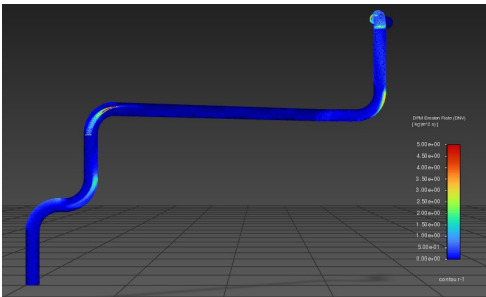
Elbow contour, 0.75D diameter variation, radius 1100



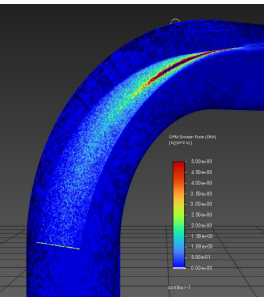
Erosion contour results along the pipe, Variation E, at 0.75D radius 1250



Elbow contour, E 0.75D variation, radius 1250



Erosion contour results along the pipe for Variation F at 0.75D and a radius of 1400



Elbow contour – Type F, 0.75D, radius 1400

The erosion rate distribution obtained from the simulation in Table 5 shows a non-uniform pattern along the pipe wall, but the erosion rate drops drastically in the elbow with the addition of a vane until the erosion rate becomes very low. With the addition of a vane in the elbow, the affected erosion location is on the added vane because it protects the outer pipe wall. This result is consistent with the DNV erosion model due to the flow direction that occurs in the elbow not following the bend in the elbow, but instead directly hitting the pipe wall ([Velasco et al., 2025](#); [Veritas, 2007](#)).

Max Erosion Rate Distribution on the Vane

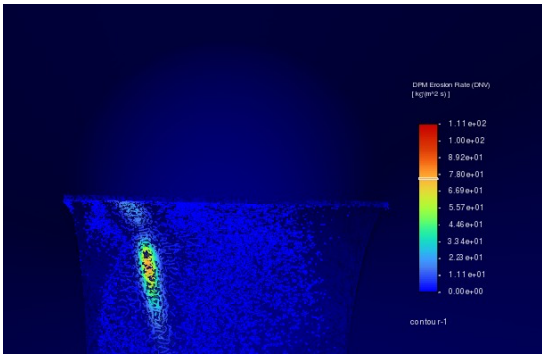


Figure 13. Max erosion results of vane elbow at 0.5D Radius 1100

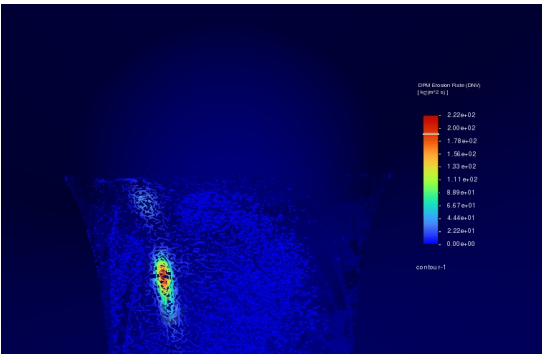


Figure 14. Max erosion results of vane elbow at 0.5D Radius 1250

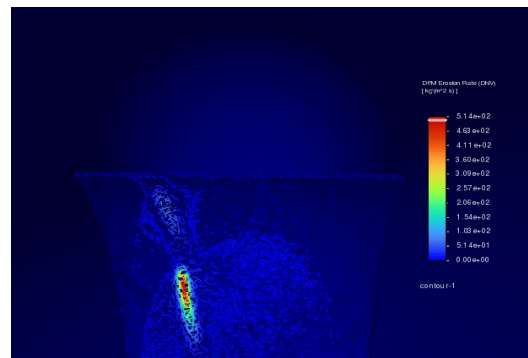


Figure 15. Max erosion results of vane elbow at 0.5D Radius 1400

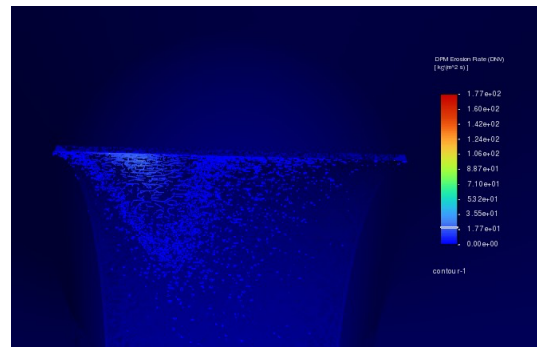


Figure 16. Max erosion results of vane elbow at 0.75D Radius 1100

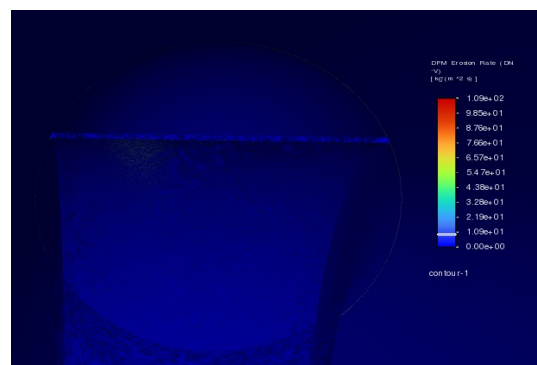


Figure 17. Max erosion results of vane elbow at 0.75D Radius 1250

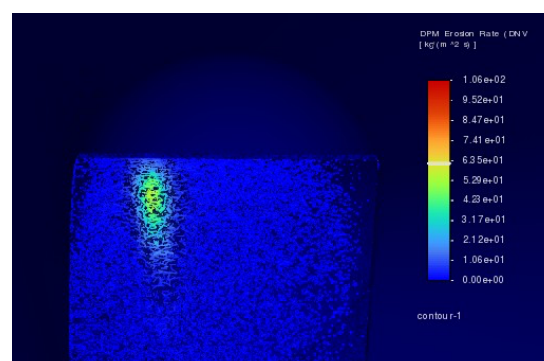


Figure 18. Max erosion results of vane elbow at 0.75D Radius 1400

Figures 13 to 15 display the erosion contour of the vane in the elbow pipe at position 0.5D or located in the middle of the pipe with several radius alternatives. By placing the vane at position 0.5D, the erosion results on the inner part of the vane experienced a very significant increase, with the highest at radius 1400 where the area inside the elbow pipe experienced constriction. Meanwhile, Figures 16--18 display the erosion contour of the vane in the elbow pipe at position 0.75D or located at 0.75 of the inner pipe diameter. With the placement of the vane at 0.75D, the erosion results on the inner part of the vane increased but were still within reasonable limits,

because the vane functions to protect the outer diameter of the elbow pipe.

Analysis of Erosion Rate and Remaining Life Based on Patch Variables

Table 6

Erosion Rate Results in the Coal Pipe for Variations A to F

Variation	Patch	Erosion Rate (kg/m ² s)	Mass loss (kg/m ² yr)	t (mm/yr)	Remaining life (yr)
A (0.5D R1100)	A	0.18	72.31	0.72	27.66
	B	0.02	8.03	0.08	248.92
	Vane	75.278	30241.62	302.42	0.07
B (0.5D R1250)	A	0.15	60.26	0.60	33.19
	B	0.04	16.07	0.16	124.46
	Vane	191.13	76783.13	767.83	0.03
C (0.5D R1400)	A	0.1	40.17	0.40	49.78
	B	0.05	20.09	0.20	99.57
	Vane	514.24	206586.91	2065.87	0.01
D (0.75D R1100)	A	0.25	100.43	1.00	19.91
	B	0.01	4.02	0.04	497.84
	Vane	21.29	8552.88	85.53	0.23
E (0.75D R1250)	A	0.07	28.12	0.28	71.12
	B	0.01	4.02	0.04	497.84
	Vane	9.67	3884.75	38.85	0.51
F (0.75D R1400)	A	0.03	12.05	0.12	165.95
	B	0.01	4.02	0.04	497.84
	Vane	62.43	25080.16	250.80	0.08

Table 6 shows a comparison of erosion rate, mass loss, eroded thickness, and estimated remaining life for six vane configurations (combinations of 0.5D and 0.75D positions with R1100, R1250, and R1400 radii) at three different patches (A, B, and vane), where Patch B consistently shows the best erosion resistance due to its position on the inner side of the elbow, while Patch A experiences higher erosion because it is located on the outer side of the pipe, and the inner part of the vane experiences the most extreme erosion, tens to even hundreds of times higher than the other two patches, because it functions as a protector that directly receives coal particle impacts, so the remaining life of the vane only lasts a few months while Patches A and B can last tens to hundreds of years. From all variations analyzed, the 0.75D vane position with radius 1250 or matching the pipe elbow radius proved most effective in reducing erosion because it does not cause flow constriction on the inner side of the pipe so that the coal-air mixture flow can flow more smoothly and evenly.

Discussion

The CFD simulation results in this study show that the dominant erosion mechanism in the elbow coal pipe is inertial impaction, where coal particles with high density are unable to follow the flow streamlines when passing through sharp bends, thus hitting the outer elbow wall with significant velocity and impact angle. This phenomenon aligns with the findings of various previous studies confirming that solid particles in gas-solid flow in pipe elbows tend to migrate to the outer wall due to centrifugal and inertial forces ([Hong et al., 2021, 2023](#)). In the context of the coal pipe system in a coal-fired power plant, the characteristics of this gas-solid two-phase flow become a critical factor determining erosion distribution and component service life.

The selection of the realizable k-ε turbulence model in this study proved suitable for predicting flow in complex geometries such as elbows. This model has been widely validated in numerical studies of solid particle erosion in piping systems and has proven to provide adequate accuracy in predicting secondary flows and velocity distributions in bend areas ([Othayq et al., 2023](#); [Yudhatama et al., 2018](#)). The validation results in this study showed a relative error of 4.53% for Patch A, which is still below the 10% threshold generally accepted in numerical simulations based on empirical models ([Khoiriyah et al., 2025](#)).

The application of the DNV (Det Norske Veritas) erosion model in this simulation provided realistic and consistent erosion distribution predictions with field conditions. The DNV model is known for its ability to account for the effects of impact velocity and particle impact angle simultaneously, making it suitable for predicting erosion in solid particle transport systems. In similar research conducted by Ahmad et al. (2026) and Krisnanda et al. (2019), the DNV model also showed good accuracy in predicting erosion hotspot locations in gas-solid pipe elbows. The erosion distribution pattern produced in this study, namely the highest erosion concentration on the outer wall of the outer elbow diameter, is also consistent with experimental results reported by Bandanadaja et al. (2019) and Nursyifaulkhair et al. (2025) in studies of abrasive particle erosion on steel materials.

The grid independence test analysis conducted ensured that the simulation results did not depend on the mesh density used. Mesh M4 with 980,990 elements was chosen as the optimal mesh because it showed changes in results below 1% compared to finer meshes. This approach is consistent with best practices in CFD simulation of gas-solid flow, where selecting the appropriate number of elements is crucial for maintaining a balance between accuracy and computational efficiency. Mesh quality with an average skewness of 0.1063 and average orthogonality of 0.9876 indicates that the computational domain has met the quality standards required by ANSYS (2017) for accurate internal flow simulation (Zhang et al., 2026).

The addition of a vane in the elbow coal pipe proved to significantly reduce the erosion rate on the outer pipe wall by diverting coal particle impacts to the inner surface of the vane. The working principle of the vane as a flow deflector is consistent with the concept of using guide vanes in piping systems aimed at redistributing particle momentum and reducing impact angles against pipe walls (Duarte et al., 2016; Li et al., 2022). Research by Xu et al. (2016) also confirmed that adding deflectors or inserts in elbows can significantly reduce the erosion rate of the outer wall, although on the other hand it causes erosion concentration on the insert element itself (Xu et al., 2025). This finding reinforces the results of this study which show that the vane takes over the function as a sacrificial component that protects the main elbow wall.

Comparison between vane positions at 0.5D and 0.75D shows significant differences in flow characteristics. Placing the vane at position 0.5D (middle of the pipe) causes greater constriction of the flow cross-section so that the flow velocity on the inner side of the pipe increases drastically, especially with larger radius vanes (R1400). This velocity increase ultimately contributes to increasing particle kinetic energy and exacerbating erosion on the inner surface of the vane. This flow acceleration phenomenon due to cross-section constriction is explained as one of the factors that directly increases erosion intensity through the exponential relationship between impact velocity and material erosion rate. Conversely, placing the vane at position 0.75D provides a wider flow space on the inner side of the pipe so that excessive acceleration does not occur in the main flow.

Variations in vane radius have a complex influence on erosion patterns. At position 0.5D, increasing the radius from R1100 to R1400 actually drastically increases erosion on the vane, because a larger radius causes narrower flow constriction on the inner side so that coal particles hit the inner surface of the vane with higher angles and velocities. This shows that the geometry of the elbow must be designed so as not to create local acceleration zones that actually worsen erosion. Meanwhile, at position 0.75D, the R1250 radius variation gave the most optimal results because it produced smaller impact angles and more uniform velocity distribution compared to R1100 and R1400 at the same position.

Research Implications

Theoretically, the results of this study reinforce the understanding of the inertial impaction erosion mechanism in gas-solid flow in pipe elbows and show that the DNV erosion model combined with the Discrete Phase Model (DPM) approach is able to predict erosion distribution with adequate accuracy for industrial-scale coal pipe systems. The findings regarding the influence of vane position and radius on flow acceleration patterns and particle impact angles enrich the literature on flow director-based erosion mitigation, which has so far been more widely studied in oil and gas industry applications, thus serving as a reference for erosion research in other solid particle transport systems with similar flow characteristics.

The 0.75D R1250 vane configuration showed the best performance among all variations

tested, with Patch A erosion rate of $0.07 \text{ kg/m}^2\text{s}$ and a remaining life of 71.12 years, much better than the configuration without a vane. Erosion on the vane itself was $9.67 \text{ kg/m}^2\text{s}$ with a remaining life of 0.51 years, indicating that the vane needs to be replaced periodically every few months, but this is far more economical than replacing the entire pipe elbow. The strategy of using easily replaceable sacrificial components to protect the main pipe structure has been recommended in various pipeline integrity management studies as a cost-effective solution to extend the operational life of piping systems (JIANG et al., 2026; Peng & Cao, 2016). In the context of coal-fired power plants, this approach is highly relevant given the relatively high cost of replacing elbow coal pipes and the operational impact of the resulting downtime (Atmaja et al., 2020; Prasetyo, 2024).

From the perspective of asset maintenance management, the results of this study provide an important contribution to PLTU Banten 3 Lontar. A deep understanding of erosion distribution and remaining life for each vane variation allows maintenance planners to develop more structured inspection and component replacement schedules. The CFD simulation-based approach for erosion prediction and maintenance planning has also been validated in previous studies as a reliable method to support Predictive Maintenance strategies in coal-fired generation systems (Jiang et al., 2026; Peng & Cao, 2016). By integrating numerical simulation results into the maintenance management system, the power plant can reduce the risk of sudden coal pipe leaks, which have been a major cause of plant capacity derating.

The results of this study reinforce the position of CFD simulation as a reliable and efficient tool in analyzing erosion phenomena in solid particle transport systems in steam power plants. The numerical approach used in this study was able to replicate actual operational conditions with acceptable accuracy, so it can serve as a scientific basis for technical decision-making related to coal pipe design modifications. In the future, the development of models that consider more representative particle size distribution and the influence of coal particle thermo-physical properties during the transport process will further improve the accuracy of erosion predictions (Duarte et al., 2016; Li et al., 2022; Xu et al., 2016). This research is expected to serve as a reference for the development of coal pipe design standards in Indonesian coal-fired power plants that are more resistant to erosion and more cost-effective in long-term maintenance.

CONCLUSION

Based on the CFD simulation of the elbow coal pipe at PLTU Banten 3 Lontar, the study demonstrates that erosion in the coal-air mixture transport system is predominantly associated with inertial particle impaction at the elbow. The CFD model showed a relative validation error of 4.53% at Patch A, indicating acceptable agreement with the field thickness measurement data. Among the six vane configurations evaluated, the 0.75D-R1250 configuration provided a favorable balance between reducing erosion on the main elbow wall and maintaining the flow characteristics of the coal-air mixture. This configuration produced an erosion rate of $0.07 \text{ kg/m}^2\text{s}$ at Patch A and an estimated remaining life of 71.12 years. The results indicate that vane position and radius influence both particle-flow behavior and erosion distribution, while the vane acts as a sacrificial component that receives a portion of the particle impact and consequently protects the main elbow wall.

Practically, the findings provide a numerical basis for prioritizing inspection and maintenance of high-erosion locations and for considering replaceable vane components in coal pipe erosion mitigation. However, the present study is limited by the use of a specific coal particle size and steady operating conditions, as well as the one-way coupling approach and the absence of direct experimental testing of the proposed vane configurations. Further research should therefore investigate a wider particle-size distribution, variations in operating conditions, two-way particle-fluid coupling, and experimental validation to improve the robustness and applicability of the erosion prediction and vane design recommendations for coal-fired power plant coal pipe systems.

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AUTHOR CONTRIBUTION STATEMENT

Ridha Adi Putranto: Conceptualization, methodology, CFD modeling and simulation, data analysis, visualization, and manuscript preparation. Muhammad Agung Bramantya: Supervision, validation, interpretation of results, and revision of the manuscript. Both authors contributed to the final review and approval of the manuscript.

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