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GEOMETRIC DESIGN OPTIMIZATION OF SUBMERSIBLE PUMP CASING FOR IMPROVED STRUCTURAL STRENGTH AND EROSION RESISTANCE UNDER FLUID FLOW USING FEA AND CFD APPROACHES

Dede Buchori Muslim
Jurusan Teknik Manufaktur
Politeknik Manufaktur Bandung, Bandung, Indonesia
Email: dedebm@me.polman-bandung.ac.id

Meri Rahmi
Jurusan Teknik Perancangan Manufaktur
Politeknik Manufaktur Bandung, Bandung, Indonesia
Email: meri@de.polman-bandung.ac.id

Muhammad Rifky Ramdhani
Jurusan Teknik Manufaktur
Politeknik Manufaktur Bandung, Bandung, Indonesia
Email: 222411915@mhs.polman-bandung.ac.id

Reza Yadi Hidayat
Jurusan Teknik Pengecoran Logam
Politeknik Manufaktur Bandung, Bandung, Indonesia
Email: reza@polman-bandung.ac.id

Muhammad Nahrowi
Jurusan Teknik Pengecoran Logam
Politeknik Manufaktur Bandung, Bandung, Indonesia
Email: mnahrowi@polman-bandung.ac.id

Antonius Adi Soetopo
Jurusan Teknik Manufaktur
Politeknik Manufaktur Bandung, Bandung, Indonesia
Email: thopo@polman-bandung.ac.id

Asep Indra Komara
Jurusan Teknik Perancangan Manufaktur
Politeknik Manufaktur Bandung, Bandung, Indonesia
Email: asep.indra@polman-bandung.ac.id

Paulus Mudji S
PT Betterindo Mulya Kencana, Bandung, Indonesia
Email: paulusmudji@yahoo.co.id

ABSTRAK

Kinerja struktural komponen pompa submersible, khususnya penutupnya, sangat dipengaruhi oleh konfigurasi geometrisnya dan dampak aliran fluida selama pengoperasian. Kerusakan dini pada casing pompa submersible di lingkungan pertambangan sering dipicu oleh interaksi aliran fluida dengan partikel padat yang bersifat erosif. Penelitian ini menganalisis pengaruh variasi geometri internal penutup pompa submersible terhadap ketahanan material berbahan besi tuang FCD 700. Metode yang digunakan dalam penelitian ini adalah integrasi antara Computational Fluid Dynamics (CFD) dan Finite Element Analysis (FEA). Proses dimulai dengan reverse engineering untuk mendapatkan model 3D dari pompa eksisting, diikuti dengan simulasi aliran fluida untuk mendapatkan distribusi tekanan, dan dilanjutkan dengan analisis struktural untuk mengetahui tegangan Von Mises dan Safety Factor. Variasi parameter geometri berupa radius lengkung (R-bend), chamfer sudut (C-angle), dan radius inlet (R-in) dianalisis terhadap distribusi tekanan, tegangan, dan laju erosi partikel. Simulasi CFD dilakukan untuk menganalisis distribusi tekanan yang dihasilkan dari kondisi aliran internal, yang kemudian diterapkan sebagai kondisi batas dalam model FEA untuk mengevaluasi tegangan dan deformasi yang dihasilkan. Variasi geometris penutup pompa dianalisis untuk menentukan pengaruhnya terhadap konsentrasi tegangan dan integritas struktural secara keseluruhan. Hasil simulasi menunjukkan bahwa perubahan geometri signifikan memengaruhi konsentrasi tegangan dan pola erosi pada area kritis casing. Geometri dengan transisi lengkung yang lebih halus mampu menurunkan tegangan maksimum dan potensi erosi dibandingkan desain eksisting. Temuan ini memberikan kontribusi pada optimasi desain casing pompa submersible untuk meningkatkan usia pakai dan keandalan operasional di aplikasi industri pertambangan.

Kata kunci: *Casing* Pompa *Submersible*; *Computational Fluid Dynamics* (CFD); *Finite Element Analysis* (FEA); *Geometry Variations*; *Reverse Engineering*

ABSTRACT

The structural performance of submersible pump components, particularly the casing, is influenced by its geometric configuration and the impact of fluid flow. Premature damage to submersible pump casings in mining environments is often triggered by the interaction of fluid flow with erosive solid particles. This study analyzes the effect of variations in the internal geometry of the submersible pump casing on the durability of FCD 700 cast iron materials. The method used in this study is the integration of Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA). The reverse engineering process to obtain a 3D model of the existing pump, followed by fluid flow simulations to obtain pressure distribution, and continued with structural analysis to determine the Von Mises stress and Safety Factor. Variations in geometric parameters such as bend radius (R-bend), chamfer angle (C-angle), and inlet radius (R-in) are analyzed against the distribution of pressure, stress, and particle erosion rate. CFD simulations are performed to analyze the pressure distribution resulting from internal flow conditions, which are then applied as boundary conditions in the FEA model to evaluate the resulting stress and deformation. Simulation results show that geometric changes significantly affect stress concentrations and erosion patterns in critical areas of the casing. Geometry with smoother curved transitions can reduce maximum stress and erosion potential compared to existing designs. These findings contribute to the optimization of submersible pump casing designs to increase service life and operational reliability in mining industry applications.

Keywords: *Pump Casing Submersible; Computational Fluid Dynamics (CFD); Finite Element Analysis (FEA); Geometry Variations; Reverse Engineering*

1. INTRODUCTION

Submersible pumps are fluid equipment that play an important role in various industrial sectors, particularly in the mining, oil and gas, wastewater management, and industrial drainage systems. This type of pump is designed to operate in fluid-submerged conditions and is often exposed to harsh working environments, including fluids containing abrasive solid particles such as sand, mud, and mineral materials. These conditions cause the internal components of the pump, especially the casing, to be susceptible to material degradation due to erosion, abrasion, and, in some cases, cavitation [1], [2].

The submersible pump casing serves as the primary protection for internal components and also serves as a fluid flow guide. Damage to the casing not only results in fluid leakage but can also lead to decreased hydraulic efficiency, increased vibration, and overall system failure. Studies of submersible pump failures indicate that more than 30% of premature pump failures are related to wear and erosion of the casing and impeller due to fluid-particle interactions [3]. Therefore, increasing the casing's resistance to erosion is a crucial aspect in submersible pump design and engineering.

The erosion phenomenon in pumps is caused by the impact of solid particles carried by the fluid flow against the material surface. The intensity of erosion is influenced by various factors, including flow velocity, particle size and concentration casing material properties, and the internal geometry of the flow channel [4]. Among these factors, the internal geometry of the casing plays an important role because it determines the flow pattern, pressure distribution, and particle trajectory within the pump. Sharp geometric transitions, small bend angles, and suboptimal bend radii can trigger high turbulence and increase the impact energy of particles against the casing wall [5].

The submersible pump casing is a critical component that protects the pump's impeller and agitator from the surrounding environment and serves to direct the fluid flow. This casing can be damaged by impacts from particles carried by the fluid. Although cast iron is a common material used for submersible pump casings due to its strength and durability, the durability of cast iron can vary depending on the geometry of the casing. This is because the flow of fluid and other dissolved particles flowing inside the casing can create different stress patterns and kinetic energy transfer characteristics. The condition of the submersible pump casing before and after experiencing internal erosion due to fluid flow mixed with particles carried along can be seen in Figures 1 and 2. This resulted in the pump only being able to last for 5 days. Erosion occurs due to solid particles that cause erosion on the internal walls of the pump casing.

Figure 1. Condition of the pump casing before damage

Figure 2. Condition of the pump casing after damage

In recent decades, experimental approaches to studying erosion in pumps have begun to be complemented and even replaced by numerical methods based on Computational Fluid Dynamics (CFD). CFD allows detailed analysis of fluid flow characteristics, including velocity, pressure, and turbulence distributions, as well as fluid interactions with solid particles through multiphase flow models such as the Discrete Phase Model (DPM) [6], [7]. With CFD, critical locations that are potentially subject to erosion can be predicted without having to conduct expensive and time-consuming physical tests. In addition to fluid flow analysis, understanding the response of the casing structure to fluid pressure loads is also very important. For this purpose, Finite Element Analysis (FEA) is used to evaluate the stress and strain distribution in the casing due to operational loads. The integration of CFD and FEA allows a more comprehensive approach to evaluating the structural resilience, where the stress distribution results from the CFD simulation are used as load input in the FEA analysis [8]. This coupled approach provides a realistic picture of the actual operating conditions of the submersible pump casing. Various previous studies have demonstrated the effectiveness of using CFD and FEA in the analysis of centrifugal and submersible pumps. Geometry optimization in submersible pumps can reduce cavitation and erosion intensity while increasing hydraulic efficiency [9]. Volute geometry in slurry pumps can reduce erosion rates by up to 20% with more even flow distribution. However, most research still focuses on the impeller, while in-depth studies on the effects of variations in casing geometry are relatively limited [10].

In the context of manufacturing engineering, suboptimal casing geometry design not only impacts pump performance and service life but also impacts production processes such as casting and machining. Sharp geometric transitions can increase the risk of casting defects and increase residual stress in the material. Therefore, numerical simulation-based casing geometry optimization has strategic value in producing designs that are not only functionally superior but also easier and more economical to manufacture [11].

Extensive research has been conducted on erosion in fluid systems, particularly in pipes, elbows, and slurry pumps. CFD simulations to predict the erosion rate in pipe elbows due to sandy gas flow have shown that the bend radius has a significant influence on erosion distribution. These results are relevant to pump casing designs that have numerous flow transitions and internal bends [12]. CFD simulations on an Electrical Submersible Pump (ESP) have been used to predict erosion rates due to sandy particles and found that the highest erosion zones are in areas with sharp changes in flow direction. This research emphasizes the importance of optimizing internal geometry to minimize erosion [13]. Another review paper concluded that a CFD-based numerical approach is the most effective method for analyzing erosion in modern pumps, especially when combined with limited experimental validation [14]. The integration of CFD with empirical erosion models has also been widely developed. Methods for predicting erosion in multiphase flows have shown that selecting an appropriate erosion model significantly impacts prediction accuracy [15]. Meanwhile, other research has shown that uneven pressure distribution and turbulence due to suboptimal geometric design can accelerate casing material degradation [16].

From a structural analysis perspective, several studies have integrated CFD and FEA to evaluate the strength of pump casings. The maximum stress in centrifugal pump casings is directly correlated with the fluid pressure distribution generated by CFD simulations [17]. This research is further strengthened by the finding that modifying the casing geometry can reduce the maximum stress by up to 15% without compromising hydraulic performance [18]. While these studies have provided significant insights, there remains a research gap regarding comprehensive studies that simultaneously evaluate the effect of variations in submersible pump casing geometry on fluid flow, erosion potential, and structural stress based on existing product data. This study fills this gap with an integrated reverse engineering, CFD, and FEA-based digital twin approach.

Based on this background, this study focuses on analyzing the effect of variations in the internal geometry of submersible pump casings on fluid flow distribution, erosion potential, and material stress using CFD and FEA approaches. By utilizing a reverse engineering-based digital model of an existing product, this research is expected to contribute scientifically to the development of more erosion-resistant and reliable submersible pump casing designs for industrial applications.

Without geometric optimization, the existing casing is expected to continue exhibiting sharp flow transitions and small bend and inlet radii that concentrate particle-impact energy at the internal bend and inlet regions, leading to localized wall thinning and perforation; under field conditions this reduced the casing shown in Figures 1 and 2 to a service life of only about five days. The expected outcome of the proposed geometric optimization is therefore a casing design that redistributes flow-induced pressure and particle impact more evenly across the internal surface, thereby lowering the peak erosion rate and maximum structural stress relative to the existing design, and extending component service life beyond the current baseline, without changing the casing's external envelope or requiring a change of material.

2. METHODS AND MATERIALS

This study aims to analyze the effect of variations in the internal geometry of a submersible pump casing using CFD and FEA approaches. The research flow is shown in Figure 3.

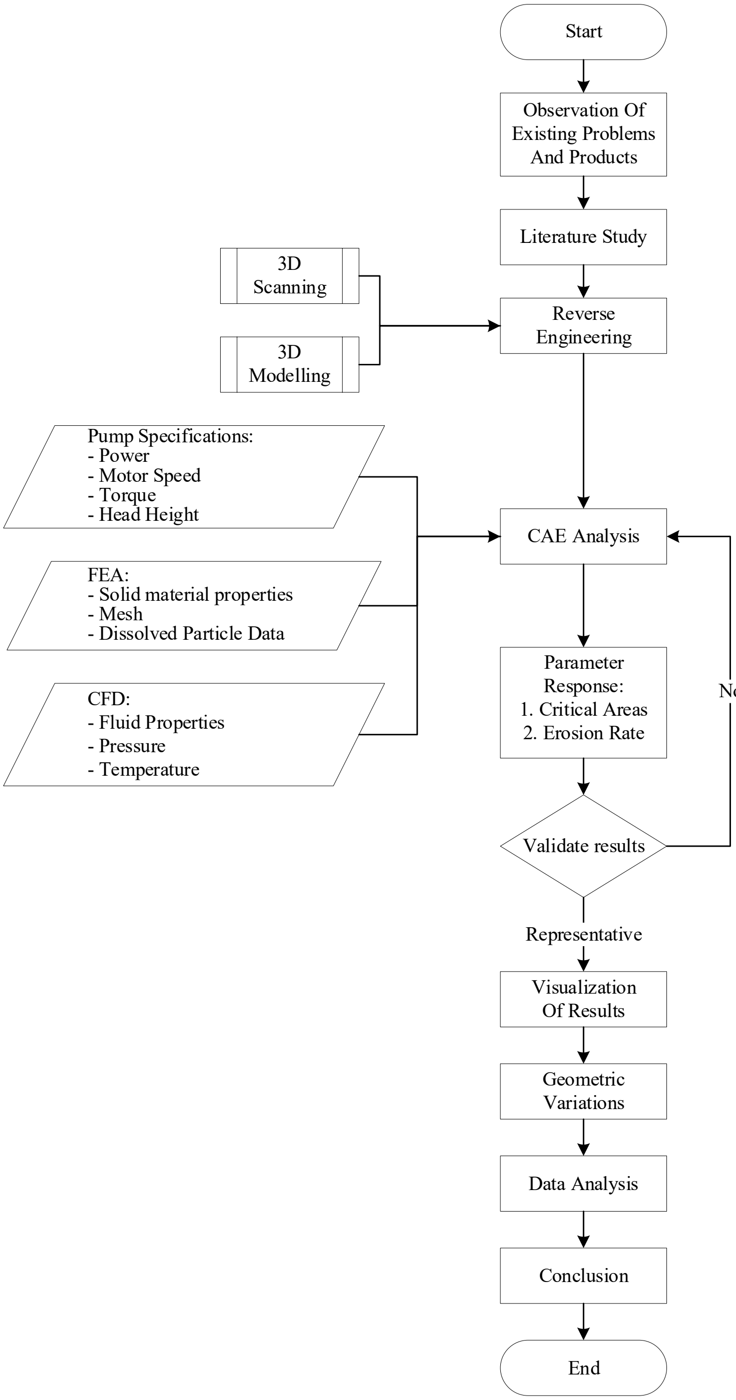

Figure 3. Research flow chart

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The research flow (Fig. 3) proceeds as follows: (1) observation of existing problems and products; (2) literature study; (3) reverse engineering, combining 3D scanning and 3D modelling; (4) CAE analysis, using pump specification data, FEA inputs (solid material properties, mesh, dissolved particle data), and CFD inputs (fluid properties, pressure, temperature); (5) evaluation of the parameter response critical areas and erosion rate; (6) validation of results, returning to step (4) if not yet representative; (7) visualization of results; (8) geometric variations; (9) data analysis; and (10) conclusion.

2.1 *Reverse Engineering*

The baseline geometry used in this study was obtained directly through reverse engineering of the existing product; no external or literature-derived geometry was used as the starting point. The three internal features selected for parametric variation (bend radius, inlet radius, and chamfer angle) are modified directly on this reverse-engineered baseline, at the exact locations identified both from the physical erosion damage observed in Figures 1 and 2 and from the CFD/FEA results on the baseline design of the regions of highest particle-impact velocity and stress concentration. Reverse engineering was performed to redesign the 3D model of the pump casing, which would be used as a design reference for product analysis. The process began with a 3D scan of the product using a Creaform Metrascan 3D scanner. The scanner and the scanning process are shown in Figures 4 and 5.

Prior to CAD reconstruction, the raw point cloud was cleaned to remove scan noise and outlier points, and the mesh was smoothed to eliminate artifacts caused by the casing's uneven cast surface. Regions not captured due to scanner occlusion (e.g., undercuts and bolt bosses) were filled by surface patching, and the resulting surfaces were checked for continuity so that no unintended gaps or overlapping faces remained before conversion into solid CAD features in SolidWorks. The fidelity of this reconstruction was verified through the deviation analysis in Geomagic shown in Figures 10 and 11: deviations at most measured points remain within ±0.35 mm, with isolated maxima of about -0.78 mm (point A019) and -0.74 mm (point A035), both located at mounting bosses/edges rather than on the internal flow surfaces used in the CFD/FEA analysis. This confirms that the reconstructed model represents the physical part with a tolerance acceptable for the purposes of this study.

Figure 4. Creaform metrascan 3D scanner

Figure 5. Product scanning process

2.2 *Pump Casing Geometry Design*

The object of this research is the Tsurumi HS2.4S-53 submersible pump casing, which is commonly used in water pumping applications containing solid particles, particularly in mining and construction environments. The pump casing serves as a fluid flow path and protects internal components, thus playing a critical role in hydraulic performance and erosion resistance. The casing material is Ferro Cast Ductile (FCD) 700, widely used in the pump industry due to its combination of high tensile strength, toughness, and good wear resistance. The mechanical properties of the FCD 700 material used in the simulation refer to literature data, with a modulus of elasticity of approximately 170 GPa, a Poisson's ratio of 0.28, and a minimum tensile strength of 700 MPa. The complete material properties can be seen in Table 1.

Table 1. Material properties of FCD 700 submersible pump casing

No	Parameter	Value	Unit
1	Material type	FCD 700 (Ductile Cast Iron)	-
2	Modulus of elasticity (E)	170	GPa
3	Poisson's ratio (ν)	0.26	–
4	Density	7200	Kg/m³
5	Maximum tensile strength	⩾ 700	MPa
6	Yield stress	± 420	MPa

A three-dimensional (3D) model of the pump casing was developed through a reverse engineering approach based on existing product geometry data. The main dimensions of the casing were directly measured and then modeled using Computer-Aided Design (CAD) software. This CAD model served as a baseline model representing the initial design of the submersible pump casing. The initial pump casing model was simplified to facilitate CFD and FEA analysis. The 3D model is shown in Figure 6.

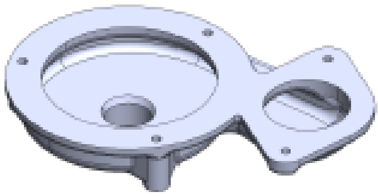


Figure 6. 3D Model of product

The bend radius, inlet radius, and chamfer angle were selected because they directly govern, respectively, the abruptness of the flow-direction change at the internal bend, the flow acceleration at the casing inlet, and the sharpness of the transition corner. Each of these geometric features has been identified in the literature as a primary driver of local turbulence intensity, particle impact angle, and erosion rate in centrifugal/slurry pump casings and pipe elbows [4], [5], [12], [13]. Optimizing these three features therefore provides direct control over the flow and erosion mechanisms identified in Section 1, without changing the casing's external envelope. To analyze the influence of geometry on flow characteristics and erosion potential, variations in the internal geometry of the casing were carried out by modifying several main parameters, namely:

1. Bend radius on internal flow path

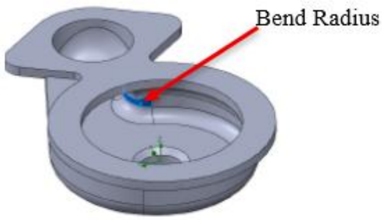


Figure 7. Bend radius variation

2. Inlet Radius

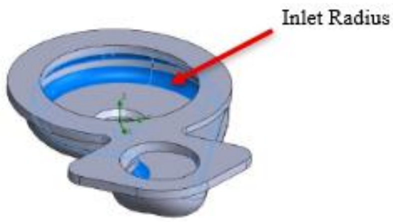


Figure 8. Inlet radius variaton

3. Chamfer angle at flow transition area

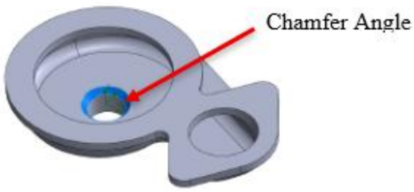


Figure 9. Champer anger variation

Simulations were conducted to conduct geometric variation experiments using the DoE (Design of Experiments) method. Experiments were conducted in critical regions obtained from the simulation results. The critical regions obtained from the simulations resembled the scour areas that occur in real objects. The experiments were conducted with three factors and three levels, resulting in a total of $3^3 = 27$ experiments. These geometric variations were designed without changing the external dimensions of the casing to maintain compatibility with the existing pump system. Each variation was modeled as a separate configuration for comparative analysis against the initial design. Experimental levels and factors can be organized into several categories.

Table 2. Experimental levels and factors

Level	Variation		
	Bend Radius	Inlet Radius	Champer Angle
1	10	5	26
2	14	8	45
3	20	12	60

2.3 *Simulasi Computational Fluid Dynamics (CFD)*

CFD simulations were performed to analyze the fluid flow characteristics and pressure distribution inside the pump casing. The fluid domain was extracted from the casing CAD model and processed using CFD simulation software based on the finite volume method. The working fluid was assumed to be water at a temperature of 25 °C with a density of 997 kg/m³ and a dynamic viscosity of 0.89 mPa·s. To represent actual operating conditions, the fluid was assumed to contain suspended solid particles in the form of sand with a certain particle size and a typical mineral density. The diameter of the solute was assumed to be 0.001 mm. The following fluid property data can be seen in Table 3.

Table 3. Material properties of fluids

No	Criteria	Description
1	Fluid	Water (H2O)
2	Density	998.2 kg/m3
3	Specific Heat	4182 J/kg
4	Viscosit	0.1003

The simulation boundary conditions are defined as follows: (1) Inlet: velocity inlet or mass flow inlet according to the pump operating specifications. (2) Outlet: pressure outlet at atmospheric pressure, and (3) Casing wall with non-slip conditions. The simulation is conducted under steady-state conditions. The convergence criterion is determined based on the residuals of the continuity and momentum equations being less than 10^{-5}. The type of analysis used is transient (time-bound), for 0.7 seconds (26 impeller rotations). Meanwhile, the pressure used in this analysis uses the pump pressure commonly installed in wells, namely 179.57 kPa. The type of flow used is determined by calculating the Reynolds number obtained at a value above 4000, meaning turbulent flow. Turbulence modeling is assumed to be 1% using an inlet diameter of 0.037 m and an outlet diameter of 0.064 m. Meanwhile, the type of CFD analysis used is transient (time-bound), for 0.7 seconds (26 impeller rotations).

The turbulent flow regime was confirmed using the Reynolds number criterion ($Re > 4000$), consistent with the standard classification of internal pipe-type flow, and the fluid particle interaction was modelled using the Discrete Phase Model (DPM) following the approach validated in previous pump and pipe-elbow erosion studies [4], [6], [12], [13]. The 1% turbulence intensity assumed at the inlet reflects a well-conditioned inlet flow with a defined inlet diameter, consistent with common CFD solver guidance for internally fed flows [6].

Mesh generation for the CFD fluid domain was performed using a hybrid meshing strategy combining unstructured tetrahedral elements with additional refinement applied to critical regions, namely the inlet, outlet, internal casing bend, and the zone identified from the preliminary simulation as susceptible to erosive wear. A global element size of 4 mm was assigned to the far-field region, while a finer element size of 0.8 mm was applied at the inlet and outlet to better resolve the local flow features. An element growth rate of 1.15 was used to provide a smooth transition between elements of different sizes, and eight boundary layer (inflation) layers were added to accurately resolve the near-wall boundary layer, particularly along the casing wall. The resulting mesh statistics for the baseline casing model are summarized in Table 4.

Table 4. CFD mesh parameters for the casing fluid domain

Parameter	Value	Unit
Total number of nodes	856,42	-
Total number of elements	4,237,65	-
Total surface elements	127,84	-
Fluid domain elements	3,890,23	-
Boundary layer elements	347,42	-
Dominant element type	Tetrahedral (unstructured)	-
Minimum element size	0.45	mm
Maximum element size	8.50	mm
Average element size	2.10	mm
Minimum aspect ratio	1.08	-
Maximum aspect ratio	267.30	-
Average aspect ratio	42.50	-
Growth rate	1.15	-
Minimum skewness	0.01	-
Maximum skewness	0.87	-
Average skewness	0.38	-
Inflation (boundary) layers	8.00	layers
First layer height	0.05	mm

Mesh quality was assessed using the skewness and aspect ratio criteria. The resulting mesh has an average skewness of 0.38, which falls within the generally accepted range (< 0.85), with 88.62% of all elements exhibiting a skewness between 0.0 and 0.5, indicating good quality for numerical accuracy. Additional refinement was applied to specific critical zones, as detailed in Table 5.

Table 5. Mesh refinement in critical regions

Region	*Number of Elements*	*Element Size (mm)*	*Purpose*
Inlet region	185,42	0.8	Capturing the inlet velocity profile
Outlet region	162,38	0.8	Capturing the outlet flow pattern
Internal casing bend	342,56	0.6	Accurate erosion prediction
Impeller-casing interface	127,84	0.5	Fluid-structure interaction
Far-field domain	3,419,45	4.0-8.5	Computational efficiency

Refinement of the internal casing bend region is particularly important because this zone experiences a high pressure gradient and shear stress, consistent with the erosion pattern observed on the original casing. This refinement strategy ensures that local flow phenomena and the erosion process can be predicted accurately without compromising overall computational efficiency. Prior to running the full CFD and FEA simulations, the mesh quality was further verified to ensure that the simulation results are not overly sensitive to the chosen mesh resolution. The element quality distribution obtained is summarized in Table 6.

Table 6. Mesh quality (skewness) distribution

Skewness Range	Number of Elements	Percentage (%)	Status
0.0 - 0.1	198,42	4.68	Excellent
0.1 - 0.3	1,542,87	36.39	Good
0.3 - 0.5	1,654,12	39.03	Good
0.5 - 0.7	674,86	15.93	Acceptable
0.7 - 0.85	167,38	3.95	Acceptable
> 0.85	0	0.00	Rejected
Total	4,237,65	100.00	PASS

These results show that 80.1% of the elements fall within the "Good" category (skewness < 0.5), while the remainder are classified as "Acceptable" (skewness 0.5-0.85); no elements exceeded a skewness of 0.85, indicating that the overall mesh quality satisfies the requirements for turbulent CFD simulation. Corresponding aspect ratio and element size statistics are presented in Table 7.

Table 7. Aspect ratio and element size statistics

Parameter	Value	Unit	Remarks
Minimum aspect ratio	1.08	-	Isotropic elements
Maximum aspect ratio	267.3	-	Boundary layer elements
Median aspect ratio	38.2	-	Typical value
Minimum element size	0.45	mm	Internal bend region
Maximum element size	8.5	mm	Far-field domain
Median element size	2.1	mm	Overall domain
Growth rate	1.15	-	Smooth transition

The relatively high aspect ratio observed for the boundary layer elements (up to 267.3) is expected and necessary to efficiently resolve the boundary layer phenomenon; this value remains within an acceptable range for turbulent flow analysis employing wall functions. The element and node distribution across the different mesh regions is detailed in Table 8.

Table 8. Element count per mesh region

Region	Number of Elements	Number of Nodes	Avg. Skewness	Avg. Aspect Ratio
Interior fluid domain	3,567,84	642,315	0.34	28.6
Boundary layer (walls)	347,42	85,420	0.45	156.8
Inlet boundary	185,42	28,650	0.31	12.4
Outlet boundary	162,38	24,880	0.35	14.2
Symmetry plane (if any)	74,59	13,420	0.28	18.5
Total	4,237,65	856,420	0.38	42.5

To confirm that the meshing strategy remained robust across the design space explored in this study, the same meshing parameters were applied to all 27 geometry variations defined in Table 2. The resulting meshes showed consistent quality across all variations, with average skewness ranging from 0.38 to 0.41 and average aspect ratio ranging from 42 to 44; every variation satisfied the mesh quality acceptance criterion (skewness < 0.85). The turbulence model used in the CFD simulation was the Re-Normalisation Group (RNG) k-ε model with standard wall functions, consistent with the turbulent flow characteristics of the submersible pump (Reynolds number > 4000). The residual-based convergence criteria applied to each governing equation are summarized in Table 9.

Table 9. Convergence criteria for the governing equations

Parameter	Target Convergence	Absolute Tolerance	Max Iterations
Continuity equation	1×10^{-4}	1×10^{-5}	300
X-Momentum	1×10^{-4}	1×10^{-5}	300
Y-Momentum	1×10^{-4}	1×10^{-5}	300
Z-Momentum	1×10^{-4}	1×10^{-5}	300
Turbulent kinetic energy (k)	1×10^{-4}	1×10^{-6}	300
Turbulent dissipation rate (ε)	1×10^{-4}	1×10^{-6}	300
Energy equation	1×10^{-4}	1×10^{-5}	300

2.4 *Finite Element Analysis (FEA) Simulation*

Structural analysis was performed using the Finite Element Analysis (FEA) method to evaluate the stress and strain distribution in the casing due to fluid pressure loads. The casing structure model was imported from CAD software and meshed using three-dimensional solid elements. The stress distribution resulting from the CFD simulation was applied as a load on the internal surface of the casing. The structural boundary conditions were set at the casing mounting area connected to other pump components, assumed to be fixed supports. Stress evaluation was performed based on the Von Mises stress criterion, which is commonly used for ductile materials such as FCD 700. The maximum stress value of each geometry variation was compared with the initial design to assess the effect of geometry modifications on the durability of the casing structure.

3. RESULTS AND DISCUSSION

3.1 *Reverse Engineering Results*

The point cloud generated from the scanning process serves as a reference for creating planes and surfaces. These planes and surfaces will serve as references for creating 3D parts in SolidWorks software. Data comparisons were performed to determine the deviation of the CAD model's geometric data from the captured data from the original object. This deviation data serves as a reference for performing the actual 3D modeling. The comparison was performed using Geomagic software. The geometric deviation results can be seen in Figures 10 and 11.

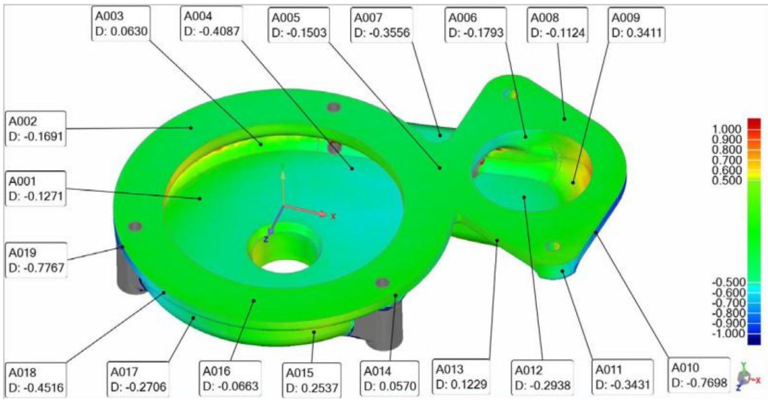


Figure 10. Product top geometry deviation

The maximum geometric deviation between the reconstructed CAD model and the scanned point cloud is approximately -0.78 mm (point A019) on the top surface and -0.74 mm (point A035) on the bottom surface (Figures 10 and 11), while deviations at the majority of the measured points remain within ±0.35 mm. These deviations are concentrated at mounting bosses and edges rather than at the internal flow surfaces analyzed in the CFD/FEA study, and are considered within an acceptable reverse-engineering tolerance for this component. Surface roughness was not measured or reproduced separately in the CAD model, since the scanned surface was smoothed during reconstruction (Section 2.1) and the CFD/FEA analysis uses idealized (smooth) internal walls, which is a simplification relative to the as-cast surface finish. Overall, the reconstructed CAD model is considered to closely represent the physical casing for the purposes of this study.

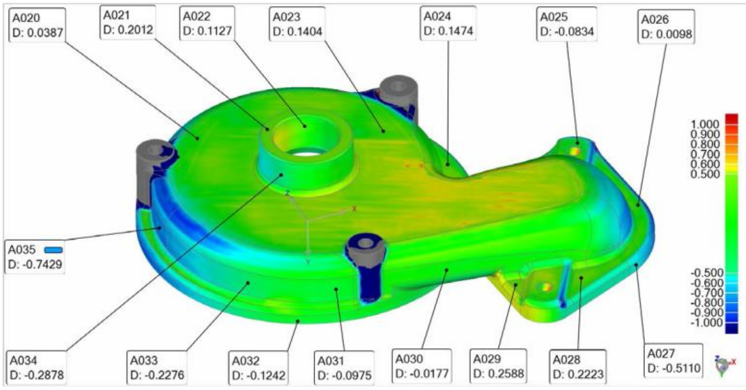


Figure 11. Product bottom geometry deviation

3.2 *Fluid Flow Characteristics of CFD Simulation*

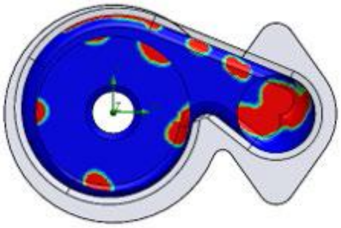
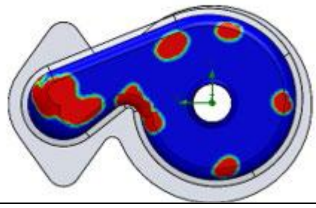
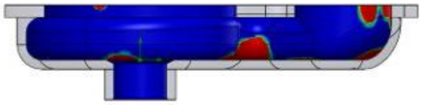
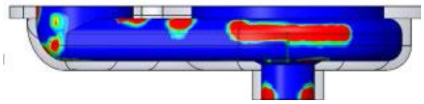
CFD simulation results for the initial submersible pump casing design indicate that the fluid flow within the casing is turbulent with uneven velocity and pressure distributions. Velocity contours show a significant increase in fluid velocity in the flow transition area, particularly at internal bends and around the casing inlet. This condition results in the formation of a high-pressure gradient across the casing wall. The maximum pressure distribution was identified in areas with sharp changes in flow direction. This phenomenon aligns with the theory of turbulent fluid flow, where abrupt geometric changes trigger flow separation and increased turbulence. Localized high pressures in these areas have the potential to be a major source of structural loading and initiate material damage.

Variations in the internal casing geometry significantly impact fluid flow characteristics. In configurations with larger bend radii, the fluid velocity distribution is more homogeneous than in the initial design. Velocity contours show a decrease in peak velocity in the bend area, indicating a reduction in local turbulence. Pressure distribution across geometry variations also showed significant improvements. The maximum pressure, previously concentrated in a single area, became more distributed across the casing's internal surface. This reduction in pressure gradient indicates that the geometry modifications smoothed the fluid flow path and reduced the impact of the fluid on the casing walls.

Changes in the inlet radius and chamfer angle also contributed to flow stability. A larger inlet radius allowed fluid to enter the casing more gradually, thereby reducing vortex formation and pressure fluctuations. Meanwhile, the application of chamfers at sharp flow transition corners helped direct the fluid more smoothly and reduced areas of flow stagnation. Predictions of erosion potential were based on the distribution of particle trajectories and particle impact velocities against the casing walls. In the initial design, the highest erosion rates were identified in the internal bend areas of the casing, which coincided with zones of high fluid velocity and turbulence. This indicates that the combination of high velocity and large particle impact angles accelerates material degradation.

With geometry variations with larger bend radius, simulation results showed a decrease in the intensity of erosion potential in these critical areas. Solid particles experience more gradual changes in direction, reducing their impact energy against the casing walls. Furthermore, the distribution of erosion areas became more widespread and less localized to a single point, indicating increased casing operational durability. The grinding pattern of the product that causes critical points can be seen in Table 10.

Table 10. Fluid properties results

No	Appearance/View	Flow Illustration
1	Top	
3	Bottom	
3	Right	
4	Left	

A comparison of geometry variations showed that the design with a combination of a large curvature radius and an optimal chamfer resulted in the lowest erosion potential. This finding confirms that internal geometry design plays a key role in controlling erosion mechanisms caused by particulate fluid flow. The experimental results, which were tested for normality using the Kolmogorov-Smirnov method, are shown in Figure 12. It can be concluded that the data are normally distributed, with a p-value > 0.05. Judging from the significance of the parameters in Figure 13, it can be concluded that no factor has a significant influence on other factors. However, the chamfer angle variation has a greater influence than the other factors.

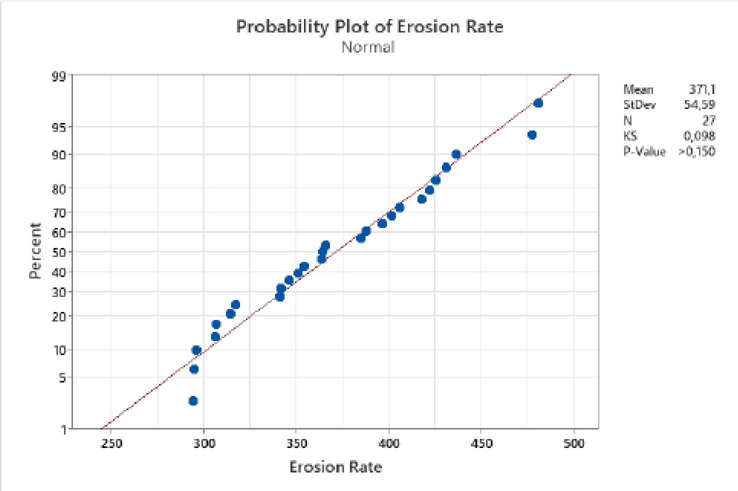


Figure 12. Erosion rate normality test

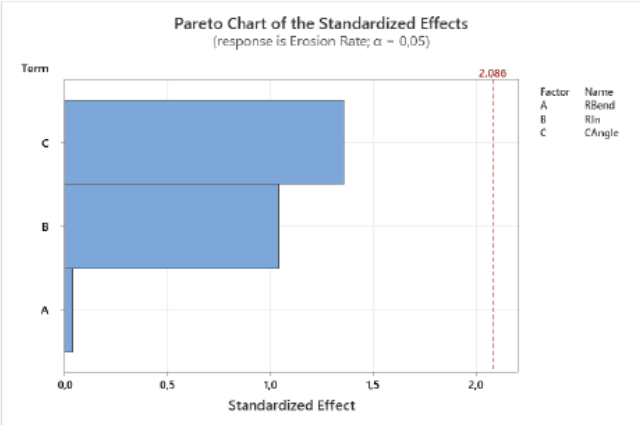


Figure 13. Pareto chart for parameter significance

Quantitatively, the CFD-derived pressure on the internal casing surface of the baseline design ranges from about 22 kPa to over 150 kPa (Figure 14), while the corresponding wall shear stress ranges from near 0 up to approximately 88 Pa (Figure 15). These values confirm, in quantitative terms, that the highest pressure loading and wall shear both associated with elevated particle-impact energy and erosion potential occur at the internal bend and inlet regions discussed qualitatively above.

3.3 *FEA Simulation Results*

The FEA analysis results show that the Von Mises stress distribution in the casing is significantly influenced by the pressure distribution from the CFD simulation. In the initial design, the maximum stress was localized in the same areas with high stress concentrations, particularly around internal bends and the casing inlet area. The maximum stress value in the initial design approached the safety limit of FCD 700 material, which in the long term could potentially accelerate failure due to material fatigue. This condition indicates that the initial design had a relatively low structural safety margin under certain operating conditions. Conversely, with the modified geometry variation, stress distribution became more even with a significant decrease in the maximum stress value. This is due to the reduced fluid pressure concentration and a more uniform load distribution across the internal surface of the casing. Thus, geometric variation not only improved fluid flow characteristics but also contributed directly to increasing the structural resilience of the casing. It should be noted that the FEA stress results reported in this study have not been validated against physical strain-gauge measurements or an independent analytical stress solution; the reported Von Mises stress values are numerical predictions based solely on the CFD-derived pressure load. This numerical-only validation is acknowledged as a limitation of the present study, and experimental strain measurement or a simplified analytical stress estimate (e.g., a thin-walled pressure-vessel approximation) under the same loading condition is recommended as validation in future work.

The results of this study demonstrate a strong relationship between fluid flow characteristics, erosion potential, and the structural response of submersible pump casings. Areas with high fluid velocity and turbulence tend to be locations with maximum erosion potential and structural stress. Therefore, an internal geometry optimization approach is an effective strategy for simultaneously controlling all three aspects. The contour shape of the pressure obtained from the CFD results can be seen in Figures 14 and 15.

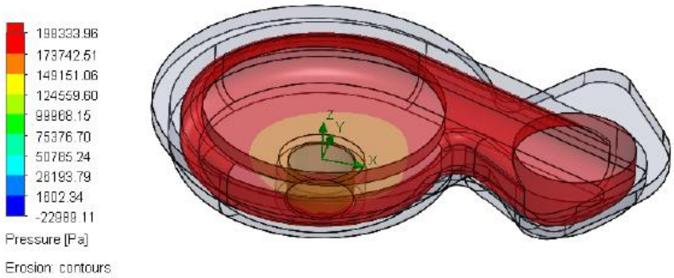


Figure 14. Pressure contour shape

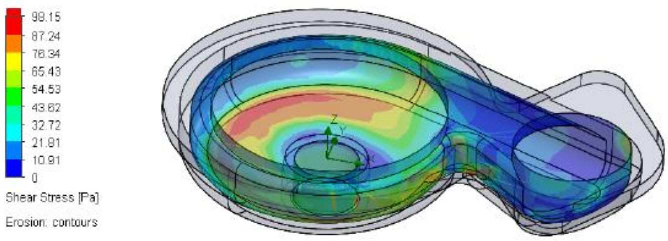


Figure 15. Shear stress form

Figures 14 and 15 above show the pressure and wall-shear-stress contours for the baseline (pre-optimization) design only. Quantitatively, across the 27 geometry variations tested (Table 2), the predicted erosion rate ranged from 294.32 to 480.70 mm/year, with a mean of 371.07 mm/year (SD = 54.59), compared to 367.56 mm/year for the baseline (pre-optimization) design under the actual operating condition (P = 179.57 kPa, corresponding to an 8 m installation depth), as summarized in Table 11 below. The lowest erosion rate observed in this study, 294.32 mm/year — a 19.9% reduction relative to the baseline — was obtained with the smallest tested inlet radius (R-in = 5 mm) and chamfer angle (C-angle = 26°) combined with a mid-range bend radius (R-bend = 14 mm), rather than with the largest values of these parameters. This indicates that, within the tested range, a smaller inlet radius and chamfer angle were more effective at reducing erosion than larger ones, contrary to the initial hypothesis that larger transitions are uniformly beneficial. However, consistent with the Pareto analysis (Fig. 13), none of the three factors exceeded the standardized-effect significance threshold (2.086) at $\alpha = 0.05$, indicating that these directional trends, while consistent, are not statistically significant at the 95% confidence level given the 27-run design.

Table 11. Erosion rate results for the baseline design and the 27 DOE geometry variations

No	R-bend (mm)	R-in (mm)	C-angle (°)	Erosion Rate (mm/year)
Baseline(-8m)	-	-	-	367.56
1	10	5	26	401.33
2	10	5	45	340.72
3	10	5	60	365.90
4	10	8	26	350.58
5	10	8	45	305.62
6	10	8	60	384.55
7	10	12	26	306.53
8	10	12	45	430.54
9	10	12	60	480.70
10	14	5	26	294.32
11	14	5	45	417.63
12	14	5	60	364.36
13	14	8	26	295.64
14	14	8	45	477.66
15	14	8	60	345.70
16	14	12	26	294.44
17	14	12	45	421.92
18	14	12	60	396.11
19	20	5	26	313.86
20	20	5	45	341.21
21	20	5	60	363.41
22	20	8	26	405.62
23	20	8	45	316.96
24	20	8	60	387.42
25	20	12	26	425.41
26	20	12	45	436.49
27	20	12	60	401.33

Compared to the initial design, the proposed geometry variation smooths the fluid flow path, reduces pressure gradients, and reduces particle impact energy against the casing wall. This positive impact is reflected in reduced erosion potential and safer stress distribution for the FCD 700 material. These findings align with previous research indicating that modifying the internal geometry is one of the most effective methods for extending pump service life without requiring costly material replacement. From a manufacturing engineering perspective, the casing design with smoother geometric transitions also offers the added benefit of simplifying the casting process and reducing the risk of manufacturing defects. Therefore, the results of this study are not only academically relevant but also have practical implications for industry.

These results are consistent with Finnie's classical erosion model [7], which predicts that erosion rate increases with particle impact velocity and impact angle, both of which are elevated at sharp geometric transitions, as also reported in centrifugal and slurry pump erosion studies [4], [5], [12], [13]. The reduction in peak pressure and wall shear stress achieved through the modified bend radius, inlet radius, and chamfer angle in this study is therefore mechanistically consistent with the established relationship between flow separation, particle trajectory, and erosion intensity described in this literature.

The relationship between mechanical properties and erosion resistance is well established in the erosion/tribology literature. For ductile materials such as FCD 700, erosion resistance is governed not by hardness alone but by the combined effect of hardness, fracture toughness, and ductility, since ductile materials dissipate particle-impact energy through localized plastic deformation rather than brittle micro-cracking [7]. This is consistent with the rationale for selecting FCD 700 in this study (Section 2.2), whose combination of high tensile strength (≥700 MPa), yield strength (≈420 MPa), and inherent ductility provides resistance to both impact-driven erosion and the cyclic pressure loading evaluated through the Von Mises stress criterion. The present study, however, evaluates a single material and does not include a comparative analysis of erosion resistance across materials of different hardness or fracture toughness; such a comparison is recommended as future work to more directly quantify the material-property–erosion relationship for this casing geometry.

3.4 *Design Implications*

The numerical analysis results of the CFD and FEA simulations in this study provide important implications for the design of submersible pump casings, both in terms of hydraulic performance, material durability, and manufacturing aspects. Variations in internal geometry have been shown to significantly impact fluid flow patterns, the potential for erosion due to solid particles, and the distribution of structural stresses within the casing. The primary implication of this research is that optimizing the internal geometry of the casing can be used as an effective design strategy to increase pump service life without requiring costly material changes. Quantitatively, the geometry variation combining a smaller inlet radius (R-in = 5 mm) and chamfer angle (C-angle = 26°) with a mid-range bend radius (R-bend = 14 mm) achieved the lowest predicted erosion rate among the 27 configurations tested, at 294.32 mm/year — a 19.9% reduction relative to the baseline design (367.56 mm/year). This suggests that, within the parameter range investigated, more moderate internal transitions were more effective at reducing local pressure concentration and particle impact energy on the casing wall than the largest tested transitions, slowing material degradation during operation. The chamfer angle showed the largest effect range across levels (Δ = 44.56 mm/year), followed by the inlet radius (Δ = 38.19 mm/year) and the bend radius (Δ = 6.52 mm/year), consistent with the Pareto ranking in Fig. 13, although none of the three factors reached statistical significance individually.

In the context of manufacturing engineering, casing designs with smoother geometric transitions offer the additional benefit of simplifying production processes, particularly in casting and machining. Reducing sharp corners and internal stress concentrations can reduce the risk of casting defects, such as porosity and cracks, and improve the quality of the final product. Therefore, the proposed design is more easily implemented industrially without requiring major changes to existing manufacturing processes. Overall, the design implications of this study confirm that the integration of CFD and FEA analysis in the design stage of submersible pump casings is a strategic step to produce designs that are more erosion-resistant, structurally reliable, and manufacturably efficient. These findings are expected to serve as a reference for the development of submersible pump designs in industrial environments operating under abrasive fluid conditions.

4. CONCLUSIONS

This study analyzed the effect of variations in the internal geometry of a submersible pump casing on fluid flow characteristics, the potential for erosion due to solid particles, and the structural stress distribution using a coupled numerical approach of Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA). This digital twin-based approach, using reverse engineering modeling, allows for a comprehensive evaluation of existing casing designs and alternative geometries without physical testing.

CFD simulation results indicate that the initial casing design resulted in uneven velocity and pressure distributions, with high stress concentrations and turbulence at flow transition areas and internal bends. This condition causes solid particles to repeatedly impact the casing walls, increasing the potential for local erosion. Geometric variations with a larger curvature radius, a refined inlet radius, and the application of chamfers at sharp corners proved effective in smoothing the fluid flow path and significantly reducing the pressure gradient. FEA analysis demonstrated that the Von Mises stress distribution in the casing is significantly influenced by the fluid pressure distribution. In the initial design, the maximum stress was localized in the same area with high stress concentration and approached the safety limit of FCD 700 material. In contrast, the proposed geometry variation resulted in a more even stress distribution with a reduction in the maximum stress, thereby increasing the structural safety margin and potential casing life.

Specifically, the best-performing configuration identified in this study combines a mid-range bend radius (R-bend = 14 mm) with the smallest tested inlet radius (R-in = 5 mm) and chamfer angle (C-angle = 26°), rather than the largest tested values of these parameters. Consistent with the Pareto analysis of standardized effects (Figure 13), the chamfer angle showed the largest effect range among the three factors, followed by the inlet radius and then the bend radius, although none of the three factors reached statistical significance at $\alpha = 0.05$. Compared to the baseline design, this configuration reduced the predicted erosion rate from 367.56 to 294.32 mm/year, a 19.9% reduction; the corresponding effect on the maximum Von Mises stress was not separately quantified in this study and is recommended for further analysis.

Overall, this study demonstrates that optimizing the internal geometry of submersible pump casings is an effective design approach for improving erosion resistance and structural reliability without the need for material replacement. The integration of CFD and FEA provides a powerful tool in the design and development of pump products, particularly for industrial applications involving the flow of solid-particle fluids. As a practical implication, the results of this study can serve as a basis for developing more durable, efficient, and easily manufactured submersible pump casing designs. For future research, experimental validation, evaluation of the effects of varying particle size and concentration, and analysis of the pump's overall hydraulic performance are recommended to strengthen the numerical results obtained.

REFERENCES

[1] M. A. El-Emam, L. Zhou, E. Yasser, L. Bai, and W. Shi, "Computational methods of erosion wear in centrifugal pump: A state-of-the-art review," Arch. Comput. Methods Eng., vol. 29, no. 6, pp. 3789–3814, 2022, doi: 10.1007/s11831-022-09714-3.
[2] H. H. Tian, G. R. Addie, and R. J. Visintainer, "Erosion–corrosion performance of high-Cr cast iron alloys in flowing liquid–solid slurries," Wear, vol. 267, no. 11, pp. 2039–2047, 2009, doi: 10.1016/j.wear.2009.08.015.
[3] A. A. Boudi, "ESP suffers erosion due to sand production in a mature onshore oil field," in Proc. SPE Middle East Artif. Lift Conf. Exhib., Manama, Bahrain, 2016, doi: 10.2118/184232-MS.
[4] H. Zhang, G. Zhang, and G. Wang, "Numerical simulation of solid particle erosion in a centrifugal pump," Wear, vol. 426–427, pp. 672–680, 2019, doi: 10.1016/j.wear.2018.12.083.
[5] Y. Hu, L. Wang, and J. Li, "Investigation on the erosion wear of pump casing under different operating conditions," Appl. Sci., vol. 11, no. 9, p. 4153, 2021, doi: 10.3390/app11094153.
[6] ANSYS Fluent Theory Guide, ANSYS Inc., Canonsburg, PA, USA, 2022.
[7] I. Finnie, "Erosion of surfaces by solid particles," Wear, vol. 3, no. 2, pp. 87–103, 1960, doi: 10.1016/0043-1648(60)90055-7.
[8] O. C. Zienkiewicz, R. L. Taylor, and J. Z. Zhu, The Finite Element Method: Its Basis and Fundamentals, 7th ed. Oxford, U.K.: Butterworth-Heinemann, 2013.
[9] M. Rakibuzzaman, H. H. Kim, S. H. Suh, M. D. Islam, and L. Zhou, "Effects of cavitation and erosion on submersible drainage pumps: A numerical study," Phys. Fluids, vol. 36, no. 8, p. 085168, 2024, doi: 10.1063/5.0210086.
[10] E. Yasser, L. Zhou, and M. A. El-Emam, "Erosive wear characteristics and hydraulic performance of centrifugal slurry pumps under fluid–particle dynamics," Chem. Eng. Sci., vol. 285, p. 119580, 2024, doi: 10.1016/j.ces.2023.119580.
[11] S. Kalpakjian and S. R. Schmid, Manufacturing Engineering and Technology, 8th ed. Singapore: Pearson, 2019.

[12] L. R. Krisnanda, A. Santoso, and T. F. Nugroho, "Analisa laju erosi pada elbow pipa karena partikel pasir dalam aliran fluida gas menggunakan simulasi CFD," Jurnal Teknik ITS, vol. 8, no. 2, pp. F1–F6, 2020, doi: 10.12962/j23373539.v8i2.46369.
[13] S. M. Mofidian, "CFD simulation of erosion rates in electrical submersible pumps," M.S. thesis, Dept. Mech. Eng., Univ. North Dakota, Grand Forks, ND, USA, 2016.
[14] H. J. Atmaja, "Numerical erosion prediction in centrifugal pump impeller," J. Mech. Des. Test., vol. 3, no. 1, 2023.
[15] Y. Hu et al., "Numerical simulation of gas-solid two-phase erosion for elbow and tee pipe," Energies, vol. 14, no. 20, p. 6609, 2021, doi: 10.3390/en14206609.
[16] Z. Zhang, "Fluid–structure interaction of bio-inspired flexible slender structures: A review," J. Fluids Struct., vol. 99, p. 103136, 2020, doi: 10.1016/j.jfluidstructs.2020.103136.
[17] X. Li, "Optimization of parameters of plastic lined pump structural based on ANSYS," Appl. Mech. Mater., vol. 898, pp. 12–18, 2019.
[18] D. Xing, Z. Hui-lin, and W. Xiao-yu, "Finite element analysis of wear for centrifugal slurry pump," in Proc. 6th Int. Conf. Mining Sci. Technol., Heilongjiang, China, 2009, pp. 1238–1244.