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Research Article

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Posted Date: October 29th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11167396/v1>

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Additional Declarations: No competing interests reported.

A Corrosion-to-CFD Framework for Quantifying Surface-Roughness Effects on a 316L Stainless-Steel Centrifugal Pump in Saline Service

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Abstract

Corrosion roughening of wetted pump surfaces may shift the near-wall shear, turbulence, secondary flow, and hydraulic-loss balances in a centrifugal pump. The traceability of the temporal evolution of the corrosion state to a level of a pump CFD is proven to be elusive for saline service centrifugal pumps. In one previous experimental case, a pump built of 316L SS was exposed for 200 h to 30-ppt synthetic seawater, exhibiting a development of the electrical-input pump efficiency, flow rate, and head, respectively from 70.6, to 58.0, 1.50, to 1.38, and 12.0, to 10.7 m.

Arithmetic surface roughness, R_a , in turn, developed from 0.8, to 3.4, and the RMS vibration from 0.20, to 0.75 mm/s [1].

Applying the current framework, one treats these R_a growths as exposure-indexed surface-condition descriptors instead of direct measurements of every wetted pump wall. The framework seeks a reproducible corrosion-to-CFD pathway through five exposure-indexed states, S0-S4. The modeling safeguard differentiates between the acquired values of R_a from the corresponding values of equivalent sand-grain roughness, k_s , as $k_s = R_a$, with as an uncertain, pump-specific factor as opposed to a universal constant. The proposed CFD modeling method includes three-dimensional,

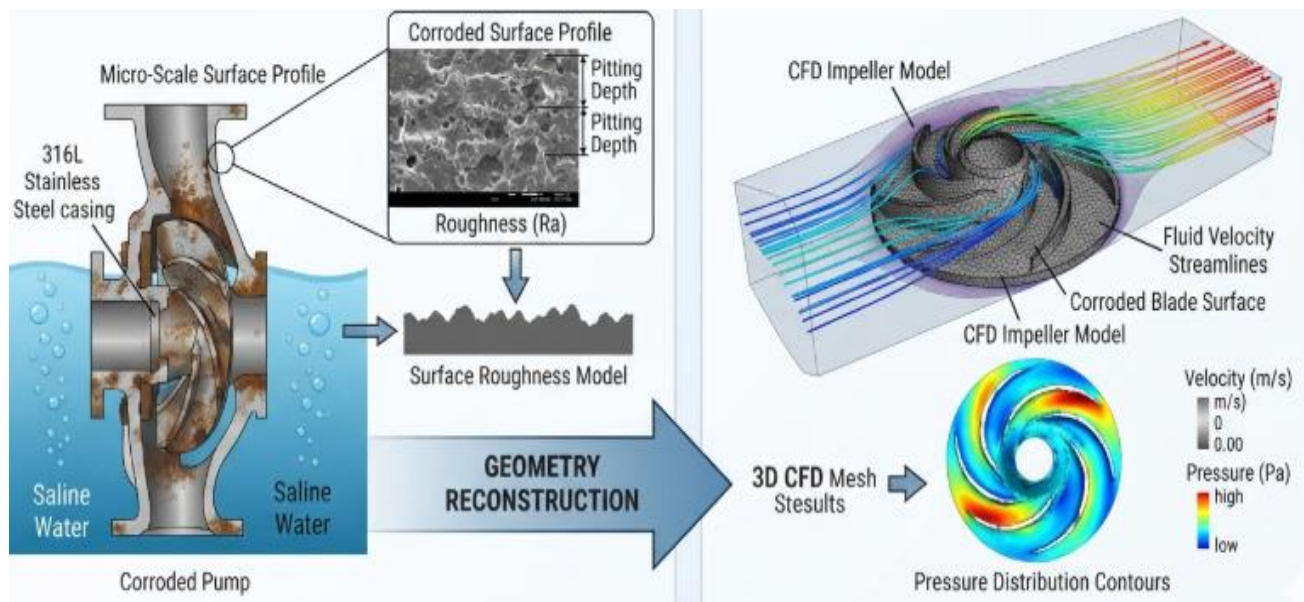
incompressible RANS with SST k- ω and k- ϵ turbulence models, rotating/stationary interfaces, mesh- and time-step verification, multi-point characteristic-curve generation, roughness transfer sensitivity testing, and local roughness regime evaluations.

The key endpoint is the head loss, which future CFD simulations can attribute to roughness alone with, thus enabling an estimation of the roughness-induced head loss percentage of the 1.30-m head decline.

The residual loss will be assigned to other degradation mechanisms, e.g., clearance or wear ring gaps, leakage, pitting, geometry distortion, and unbalanced impeller. No solver-dependent CFD results are included, as the original pump CAD geometry and CFD were not available. The paper is therefore formulated as a methodology.

Keywords: centrifugal pump; corrosion; surface roughness; saline service; seawater; computational fluid dynamics; SST k- ω ; equivalent sand-grain roughness; hydraulic efficiency; digital twin.

Graphic Abstract



Research Highlights

- A corrosion-to-CFD framework links measured saline degradation to hydraulic performance modelling.
- Time-resolved surface roughness is converted into five exposure-indexed candidate CFD states.
- An uncertain transfer factor separates measured arithmetic roughness, R_a , from CFD equivalent roughness, k_s .
- The framework uses local k_s^+ assessment to determine the applicable hydraulic roughness regime.
- A head-based metric separates roughness-attributable losses from residual degradation mechanisms.
- The approach establishes a reproducible pathway for future CFD quantification of corrosion-associated pump degradation.

1. Introduction

Seawater cooling, ballast, firewater, produced-water, offshore, and other saline processing applications commonly use centrifugal pumps. In these situations, the particular point of operation and the geometry of the pump do not govern the hydraulic performance as much as the condition of the wetted surfaces. Saltwater with high chloride concentrations tends to break down passive films and promote pitting and crevice corrosion; deposits, erosion, scaling, and metal loss can change the texture of the surface and the local flow passages [1,16-18]. In a turbulent flow internal passage, a change in the condition of the surface could affect the wall shear, momentum transfer, boundary layer development, and the local flow separation characteristic, which can influence head and efficiency [2-7].

A prior experimental study determined a time-resolved degradation path for a 316L stainless-steel centrifugal pump operating in 30-ppt synthetic seawater for 200 hours. The actual electrical-input pump efficiency ranged from 70.6 to 58.0%, while the RMS vibration grew from 0.20 to 0.75 mm/sec. Roughness increased from $R_a = 0.8$ to 3.4 μm , pit density increased to 68 pits/ mm^2 , and mean pit diameter increased to 132 μm at 200 hours [1]. This experiment established a coupled corrosion / performance trajectory but did not decouple the extent to which the hydraulic decline was specifically due to roughness-mediated fluid losses versus geometry change, leakage, clearance growth, or mechanical imbalance.

Reliable published CFD investigations of roughness on centrifugal pump performance are available [2-4,10,11,15]. These are of direct relevance to the present study. Güngör et al. report an experimental-CFD study of an API 610 BB3 multistage centrifugal pump; by use of measured roughness and prescribed equivalent sand-grain roughness values, with SST $k-\omega$ and rough-wall treatment, they compare numerical and experimental Q-H and Q-efficiency characteristics and are able to report on wall shear stress and turbulent kinetic energy [15].

El Mansour et al. found that in a CFD study of the flow in a seawater centrifugal pump, the hydraulic efficiency decreased with R_a [11].

These studies demonstrate that roughness-performance CFD is feasible but they do not recreate the time-indexed corrosion trajectory of the single stage pump in the present investigation [11,15].

Another problem is the meaning of roughness: R_s and s , R_a as a statistical surface-height parameter, while a special local roughness parameter termed as hydraulic surrogate developed for rough-wall flow models. They are not constant and may be related by roughness morphology, roughness density, roughness slope, roughness skewness, roughness kurtosis and flow regime [5,6,12,13]. Ma et al. have

shown that a number of surface descriptors may be important for the estimation of the equivalent sand-grain roughness, and a universal conversion cannot be assumed [12].

Hence, the goal is not simply to come up with a roughness figure and produce a second efficiency curve, but rather to build a traceability chain linking the corrosion state as measured directly to the wall state as a number, and then to the hydraulic performance. This type of design constraints the problem to the following three questions: (i) how to define the measured corrosion trajectory in CFD; (ii) how much of the observed performance degradation is due to roughness; and (iii) what residual degradation is due to effects requiring explicit geometry or structural modeling.

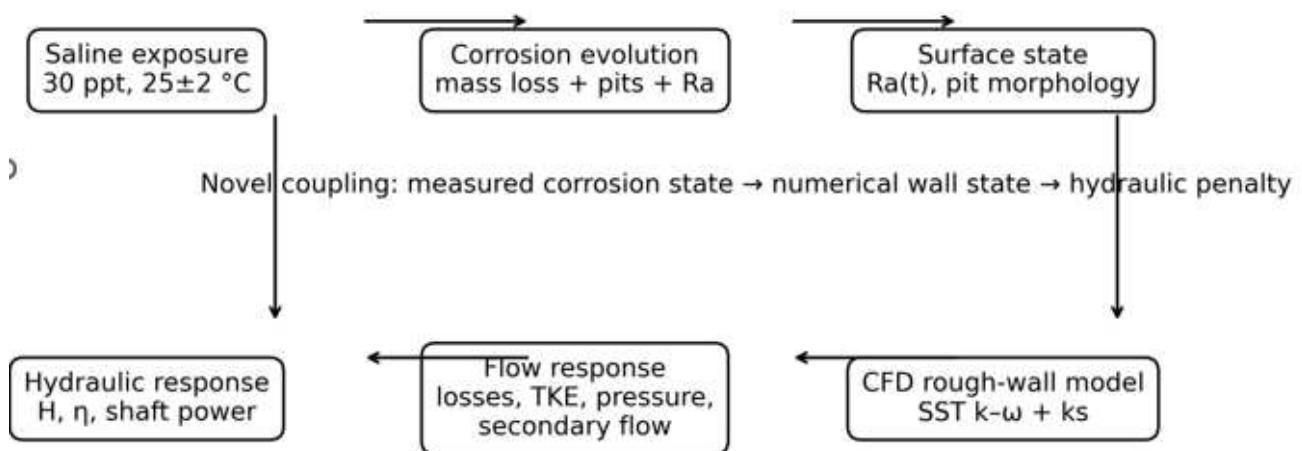


Fig. 1. Integrated corrosion-to-hydraulics framework. The framework provides an approach for connecting observed exposure to saline environments and numerical wall states to changes in hydraulic response. At present, the computational fluid dynamic results are not populated until the specific pump geometry and simulations are available

The research gap does not exist at the level of the broad conclusion that roughness influences pump performance, since this broad conclusion is itself supported by CFD and experimental-CFD literature [2-4,11,15]. The narrower research gap at the level of the study follows from the traceable conversion of an experimentally quantified corrosion trajectory into exposure-indexed CFD wall states with explicit uncertainty in the R_a to k_s transfer, and with an attribution structure that separates roughness-mediated hydraulic loss from residual damage. The three contributions of the paper are: (1) the distribution of the experimental corrosion trajectory into five exposure-indexed states; (2) explicit uncertainty in roughness transfer through the parametric relation $k_s = \alpha R_a$ rather than a fixed universal conversion to k_s ; (3) head-based attribution and residual decomposition to separate the effects of roughness-mediated hydraulic loss from those requiring additional geometric or mechanical insights. These contributions are presented at the framework and data-translation level, with the execution of the CFD, the numerical verification, and the experimental validation deferred to future work.

Table 1. Research Gaps, Framework Treatments, and Resulting Methodological Contributions

Research gap	Framework treatment	Resulting contribution
Roughness prescribed as an arbitrary CFD input	Use the measured 0–200 h R_a trajectory as the exposure-indexed backbone.	Time-indexed corrosion-to-CFD boundary states.
R_a and k_s treated as interchangeable	Define $k_s = \alpha R_a$ and sweep α rather than assuming $\alpha = 1$.	Separates surface metrology from hydraulic roughness.
Corrosion and pump hydraulics investigated separately	Use the published corrosion/performance trajectory as the reference envelope.	Mechanistic corrosion-to-hydraulics attribution.

Single-point CFD can conceal off-design behaviour	Evaluate 0.60–1.40Qdes across the characteristic curve.	Operating-point-dependent assessment.
Global efficiency does not identify local loss mechanisms	Post-process wall shear, TKE, pressure loss, separation and secondary flow.	Local-to-global loss decomposition.
Digital-twin models require interpretable degradation states	Define five exposure-indexed states S0–S4.	CFD-ready degradation state vector.
Morphology-rich models can exceed available measurements	Use α mapping as the primary model and morphology as a future extension.	Higher fidelity without unsupported inference.
Electrical-input efficiency is not identical to CFD hydraulic efficiency	Separate electrical-input/system efficiency from hydraulic efficiency and shaft power.	Consistent experimental–CFD comparison.
Head degradation used as the primary attribution metric	Compare measured 1.30 m head decline with roughness-only CFD head decline.	Avoids mixing experimental electrical-input efficiency with CFD hydraulic efficiency.
Roughness regime not assumed a priori	Evaluate $ks^+ = ks \, u\tau/v$ for each CFD state and report the resulting regime.	Prevents unsupported use of fully rough correlations or wall treatments.

Table 1 summarizes how the proposed framework addresses key limitations in existing corrosion-to-CFD approaches and translates them into traceable methodological contributions.

2. Materials and Methods

2.1 Experimental reference system

The numerical framework is anchored to the published experimental system rather than an unrelated synthetic pump case. The pump was a 316L stainless-steel centrifugal pump with a nominal head of 12 m, nominal flow rate of 0.00150 m³/s and a 0.25 kW electric motor. The fluid was 30-ppt synthetic seawater maintained at 25 ± 2 °C. Flow, head, input power, electrical-input pump efficiency and vibration were recorded at 50 h intervals over 200 h. The experimental campaign used triplicate measurements and reported approximately $\pm 2.5\%$ uncertainty for flow and head [1].

Table 2. Exposure-Indexed Experimental Reference States for the Corrosion-to-CFD Framework

Exposure (h)	State	Q (m³/s)	H (m)	Ra (μm)	Pit density (pits/mm²)	Mean pit diameter (μm)	RMS vibration (mm/s)	Electrical- input efficiency (%)
0	S0	0.00150	12.00	0.8	0	—	0.20	70.6
50	S1	0.00147	11.65	1.4	12	45	0.34	66.8
100	S2	0.00144	11.35	2.1	28	78	0.47	63.5
150	S3	0.00141	11.00	2.8	46	105	0.61	60.2
200	S4	0.00138	10.70	3.4	68	132	0.75	58.0

Table 2 summarizes the measured parameters for the following hydraulic, surface-condition and vibration states (S0-S4) in the five 200-hour saline-service test exposure-indexed states. These states provide the experimental reference trajectory for the later corrosion to CFD modelling.

The reported Ra surface roughness is simply an exposure-indexed surface-condition descriptor, and should not be interpreted to hold for the spatially-resolved roughness of all wetted pump surfaces. Pump efficiency in table 2 is the electrical-input/system efficiency, as the initial computation used measured electrical-input power.

Interestingly only the 316L pump was hydraulically tested. The bronze and carbon-steel samples were tested using corrosion-coupon immersion, and so cannot be used as an alternative pump CFD material within this study [1]. Their published corrosion rates are probably corrosion contextual material data rather than pump CFD hydraulic validation data. The surface descriptions from the coupons are also probably exposure-indexed condition indicators rather than actual data from each moving internal pump wall.

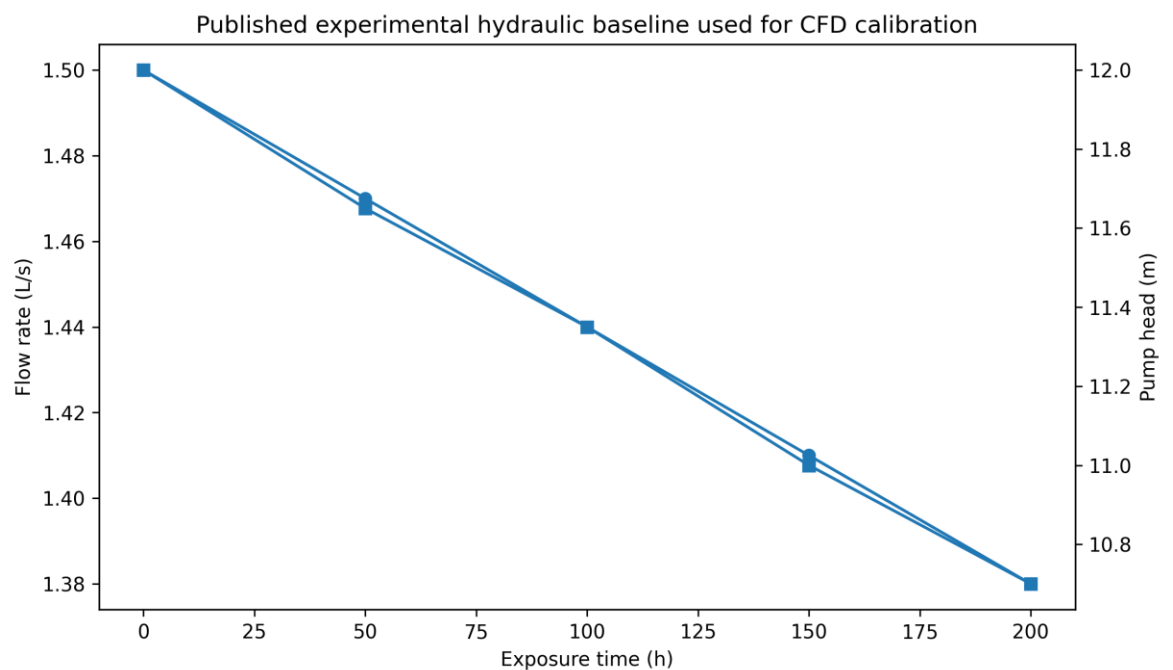


Fig. 2. Experimental degradation trajectory of the 316L centrifugal pump during 200 h saline exposure.

Figure 2 shows the actual degradation trend, which represents the test results boundary envelope for the corrosion-to-CFD framework. This trajectory experienced more than 200 hours of 30-ppt synthetic seawater exposure, resulting in a drop in pump head, flow rate, and electrical-input/system efficiency, along with an increase in surface roughness and RMS vibration. This trend may serve as the measured boundary for comparison with the roughness-only CFD predictions that will come in the future.

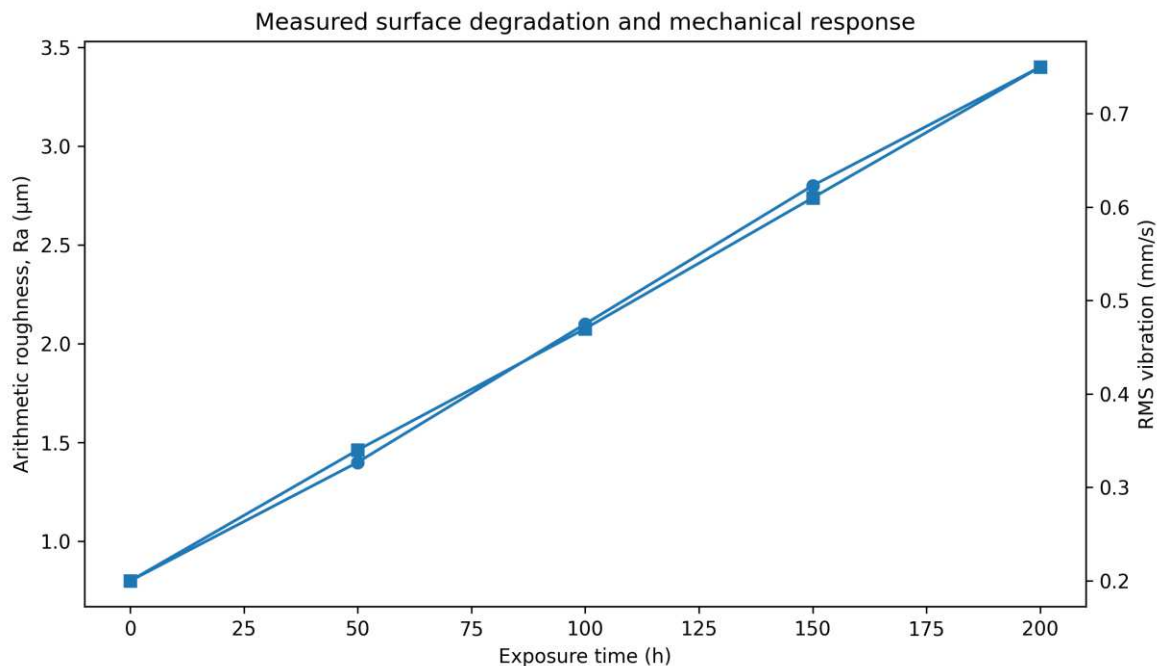


Fig. 3 Evolution of measured surface roughness and RMS vibration during saline exposure [1]

Figure 3: Variation of arithmetic surface roughness (Ra) and root mean square (RMS) vibration against exposure time. These trend lines show that Ra increased from 0.8 μm at 0 hours to 3.4 μm at 200 hours while RMS vibration increased from 0.20 to 0.75 mm/s. These parallel trend lines offer experimental evidence of progressive surface deterioration and the onset of degraded surface

condition resulting in greater mechanical or hydraulic disturbance between the saline solution and the surface as a function of exposure time. [1] In the presented approach, with increasing exposure time, the arithmetic average surface roughness (R_a) is used as surface-condition descriptor while vibration serves as support evidence of erosion.

2.2 Measurement-to-model distinction

The experimental and numerical variables are clearly defined. The indications given are: saline exposure measurement, degradation state inferred, numerical wall state determined, and CFD comparison of hydraulic response against measured pump performance. Note that a coupon surface and a rotating impeller surface each experience varying hydrodynamic, mechanical, and electrochemical conditions [1,16-18]. As a result, the five states reported in Table 2 are indexed by exposure condition and cannot be asserted to involve uniformly matching values of R_a on all internal wetted surfaces.

This distinction is important for scientific interpretation of the results. The CFD model is an attribution model of roughness related hydraulic loss, and probably not a complete corrosion damage model because the CFD does not model the growth of clearance, the detailed local geometry of a pit, removal of material, modification of leakage paths, distortion of the impeller and mechanical imbalance.

2.3 Governing equations and performance definitions

The working fluid is treated as incompressible and Newtonian. The mean continuity equation is:

$$\nabla \cdot \mathbf{U} = 0 \quad (1)$$

Momentum equations are generally presented in their standard form (incompressible) with the Reynolds stresses modeled with the SST k- turbulence model [8]. For rotating turbomachinery, it is important to clarify whether a transient sliding-mesh approach or a multiple-reference-frame/frozen-rotor approach is used- a generic source term may not be adequate for reproducibility.

For matched inlet and outlet reference planes, the CFD total-head definition is:

$$H = (p_{t,out} - p_{t,in})/(\rho g) \quad (2)$$

where p_t is total pressure, the experiment head needs to be zeroed against a reference plane and pressure definition before validation. Further, if experimental measurement is taken with static pressure taps, documenting the velocity-head terms and measurement-plane geometry is preferable to assuming automatic equality.

.Hydraulic efficiency is defined from shaft power as:

$$\eta_h = \rho g Q H / P_{\text{shaft}}, \text{ with } P_{\text{shaft}} = T_{\text{CFD}} \omega \quad (3)$$

The preceding experiment calculated efficiency using electrical input power. Therefore, the experimentally reported 70.6–58.0% values are referred to here as electrical-input/system efficiency, η_{sys} , not hydraulic efficiency. A consistent relation is:

$$\eta_{\text{sys}} = \rho g Q H / P_{\text{electrical}} = \eta_h \eta_{\text{mech}} \eta_{\text{motor}} \quad (4)$$

A direct comparison between CFD hydraulic efficiency and experimental electrical-input efficiency is therefore inappropriate unless motor and mechanical losses are independently accounted for or the

experimental data are transformed to a shaft-power basis. This correction removes a major source of terminology and validation error.

2.4 Time-indexed roughness representation

For degradation state *i*, the measured arithmetic roughness is *Ra_i*. The primary executable wall representation is:

$k_{s,i} = \alpha Ra_i$ (5)

The dimensionless transfer parameter α is a modelling parameter, not a universal physical constant. Its purpose is to represent uncertainty in converting a statistical physical roughness descriptor into the hydraulic equivalent used by the CFD wall treatment [5,6,12,13].

Table 3. Exposure-Indexed Surface-Condition States and Corresponding CFD Roughness Inputs

State	Time (h)	Measured Ra (µm)	CFD wall variable	Interpretation
S0	0	0.8	$k_s = \alpha \times 0.8$	Near-baseline
S1	50	1.4	$k_s = \alpha \times 1.4$	Early degradation
S2	100	2.1	$k_s = \alpha \times 2.1$	Intermediate degradation
S3	150	2.8	$k_s = \alpha \times 2.8$	Advanced degradation
S4	200	3.4	$k_s = \alpha \times 3.4$	End-state degradation

Table 3 defines the five exposure-indexed surface-condition states, S0-S4, that map the observed corrosion trajectory to forward CFD roughness conditions. The measured, arithmetic roughness *Ra* can be mapped to the equivalent sand-grain roughness *ks* as *ks* = *Ra*, which is defined to be an

uncertain pump-specific transfer parameter. Thus, the obtained k_s values are model-defined inputs to the CFD simulation, not observational measurements. These states provides a common time reference set for subsequent CFD simulations and allows analysis of the conversion from R_a to k_s .

2.5 α strategy and morphology-informed extension

The initial sensitivity design uses $\alpha = 1, 2, 3$ and 4 . These values are deliberately described as sensitivity cases rather than physically established conversions. A more defensible staged design is: (i) $\alpha = 1$ as a lower-bound direct mapping; (ii) $\alpha = 0.5, 1, 2, 3$ and 4 for sensitivity; and (iii) if sufficient pump performance and geometry information become available, estimation of a best-fit, pump-specific α that minimises discrepancy against the experimentally comparable metric. The fitted value must not be described as a universal conversion factor.

Table 4. Sensitivity Design for the Roughness-Transfer Parameter α and Corresponding CFD

Roughness Range

α	Interpretation	k_s range for $R_a = 0.8\text{--}3.4\ \mu\text{m}$
0.5	Lower sensitivity case	0.4–1.7 μm
1.0	Direct mapping case	0.8–3.4 μm
2.0	Moderate morphology amplification	1.6–6.8 μm
3.0	Higher morphology amplification	2.4–10.2 μm
4.0	Upper sensitivity case	3.2–13.6 μm

Table 4 defines sensitivity cases for converting measured arithmetic roughness, R_a , to equivalent sand-grain roughness, k_s , using $k_s = \alpha R_a$. The parameter α is treated as an uncertain, pump-specific transfer factor rather than a directly measured quantity. For $R_a = 0.8\text{--}3.4\ \mu\text{m}$, the selected α values

produce k_s ranges of 0.4–13.6 μm . These cases form a deterministic sensitivity envelope for subsequent CFD analysis and are not experimentally established hydraulic roughness values.

Where three-dimensional surface scans become available, the single-parameter mapping can be extended to a morphology-aware function, for example:

$$k_s/R_a = f(R_q/R_a, R_z/R_a, S_k, K_u, \lambda_c, PD, D_p) \quad (6)$$

where R_q is RMS roughness, R_z is peak-to-valley roughness, S_k is skewness, K_u is kurtosis, λ_c is a characteristic correlation length, PD is pit density and D_p is mean pit diameter. This extension is consistent with literature showing that equivalent roughness depends on multiple surface descriptors [12,13]. It remains a future model extension unless the required topographic data are available.

2.6 Roughness regime and dimensionless roughness

The hydraulic significance of an imposed k_s depends on the local friction velocity and therefore cannot be established from dimensional R_a alone. For each roughened CFD case, the local roughness Reynolds number shall be calculated as $ks^+ = ks \, u\tau/\nu$, where $u\tau = (\tau_w/\rho)^{1/2}$ is the local friction velocity, τ_w is wall shear stress, ρ is fluid density and ν is kinematic viscosity. The completed CFD study should report the distribution of ks^+ over the roughened wetted surfaces, together with representative minimum, median and maximum values. Conventional classifications often distinguish hydraulically smooth, transitional and fully rough behaviour using approximate ks^+ ranges; however, the exact applicability depends on the wall-function formulation and local flow conditions. The present framework therefore does not assume a priori that any S0–S4 state is fully rough. In particular, the use of fully rough correlations from the literature must be justified against the computed ks^+ regime rather than inferred from R_a alone [5,6,7,12].

2.7 Pump geometry and CFD domain

To support a completed CFD paper, the geometry of the tested pump is needed. The experimental hardware described above does not provide a complete computer-aided design (CAD) model, so key parameters such as impeller diameter, number of blades, blade angles, blade thickness, impeller width, hub and shroud geometries, volute dimensions, tongue/cutwater geometries, inlet and outlet dimensions, clearances, and the definition of the rotating region, must be provided from pump drawing, measured components, or manufacturer literature. It is indicated in the manuscript that no geometry has been fabricated.

Further, it is likely that the defined final computational domain will have an inlet pipe, rotating impeller region, stationary volute/diffuser region, and outlet pipe.

Numerical formalisms should be chosen based on the desired accuracy: steady multiple-reference-frame/frozen-rotor formalisms may be sufficient for preliminary constant-characteristic-curve calculations and testing; however, a transient sliding-mesh formalism should be employed for blade-passage unsteadiness, secondary flow, or local loss investigations. Finally, the paper must state which formalism resulted in the published outcome [9,14,15].

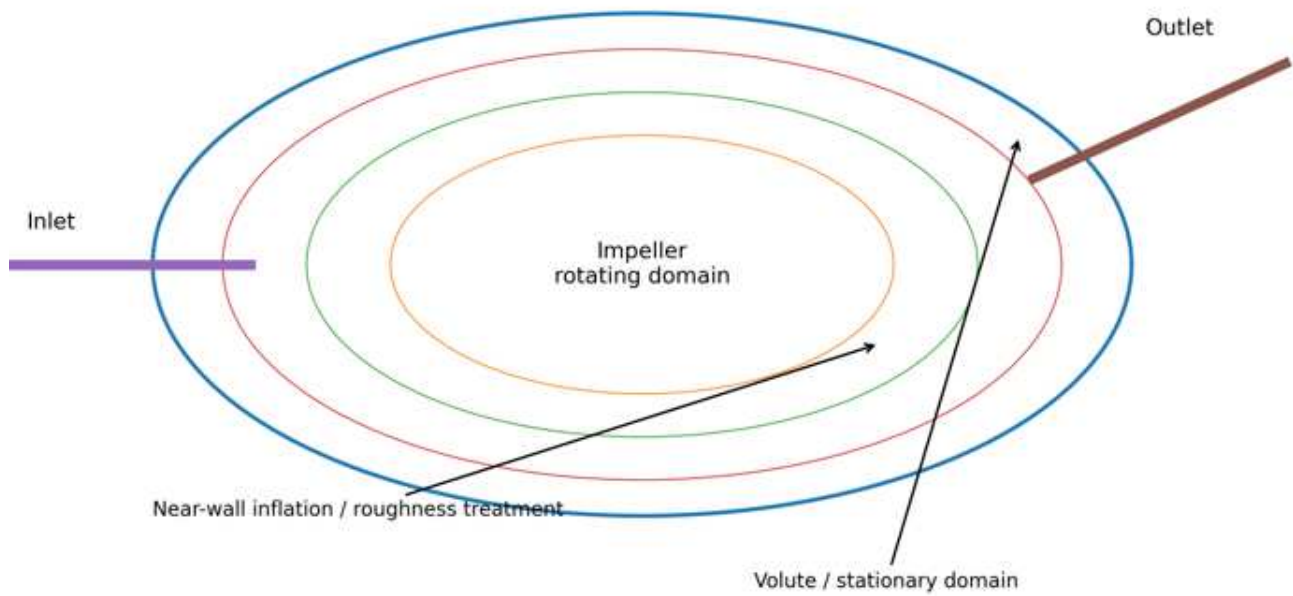


Fig. 4. Conceptual CFD domain and rotating–stationary interface for the proposed pump model

The diagram 4 above illustrates an illustration of the CFD modelling framework which consists of the rotating impeller region, the stationary flow area, and the interface inbetween the stationary and the rotation. This configuration represents the computing framework for the upcoming future simulation. Although it does not represent the actual geometry of the pump upon which the experiment was conducted.

3.8 CFD reproducibility and verification specification

Table 5. Minimum Reproducibility and Verification Requirements for the Proposed CFD Study

CFD item	Required reporting	Verification/acceptance requirement
Fluid	Measured/traceable density and viscosity for 30-ppt synthetic seawater at the test temperature.	Document source and temperature; use consistent properties in all states.
Solver	Software name and version; pressure–velocity coupling; spatial discretisation; precision.	Full settings must be reproducible.
Turbulence	SST $k-\omega$ and near-wall treatment.	Residual convergence plus stability of Q, H and torque.
Rotating treatment	Sliding mesh or MRF/frozen rotor; interface type.	Interface conservation and torque stability.
Rough-wall treatment	Exact equivalent-sand-grain roughness wall formulation.	Report k_s , y^+ , roughness regime and implementation details.
Mesh	Cell count, inflation layers, first-layer height, growth rate, skewness, orthogonal quality and aspect ratio.	At least three systematically refined meshes; head and torque changes below a predefined tolerance.
Time step	Time step, steps/revolution and blade-passing resolution.	At least three time-step levels; monitored quantities independent within predefined tolerance.

Convergence	Residual criteria and monitored engineering quantities.	Mass imbalance preferably $<0.1\%$; Q, H and torque stable over the averaging interval.
Validation	Experimental Q–H and comparable efficiency/power metrics.	Report MAE, RMSE, MAPE and maximum deviation with experimental uncertainty.

Table 5 indicates the required modelling, reporting, and verification requirements for a full CFD implementation of the proposed framework. The specifications cover fluid properties, solver setup, treatment of turbulence and rotating-region, rough-wall model implementation, mesh and time-step independence, convergence, and comparisons with experimental data. They are presumably structured to meet the mark of establishing that the following CFD results are repeatable, independently verifiable, and referenceable to the experimental data.

3.9 Mesh, y^+ and time-step independence

No less than three refined meshes should be generated with regard to the analyses in the CFD, the evaluation of the mesh should be established by parameters such as head, torque / shaft power, and representative local flow parameters and not just cell count. Near-wall resolution should match the rough-wall treatment used; if the low y^+ approach is employed, resolution of the viscous sublayer is necessary, but if the wall functions are employed the y^+ should be consistent with the formulation and roughness model. A table of the distribution and statistics of the y^+ distribution across the roughened wetted surfaces should be provided rather than a single number. Practical sensitivity of rough wall SST k- for numerical implementation has been noticed [7].

It is suggested that time step independence is shown independently of the spatial independence. The transient should record blade-passing frequency, time step, steps/revolution, revolutions lost during start-up and revolutions used in cycle averaging. It is also suggested that convergence is not guaranteed by the residuals simply dropping below a prescribed value and it is recommended that Q , head, torque and other quantities be statistically stationary.

2.10 Multi-point characteristic-curve design

To avoid attributing performance degradation from a single operating point, the numerical campaign should cover 0.60, 0.80, 1.00, 1.20 and 1.40 times the nominal flow. With $Q_{des} = 0.00150 \text{ m}^3/\text{s}$, the target flow rates are 0.00090, 0.00120, 0.00150, 0.00180 and 0.00210 m^3/s . Head, shaft power and hydraulic efficiency must be noted for the state of degradation and for the value at each of the operating points. This is the method by which roughness response can be observed over the characteristic curve not just at the nominal point.

Table 6. Proposed Operating-Point Matrix for CFD Characteristic-Curve Assessment

Q/Q_{des}	$Q \text{ (m}^3/\text{s)}$	Required CFD outputs
0.60	0.00090	H, P_{shaft} , η_h , wall shear, TKE
0.80	0.00120	H, P_{shaft} , η_h , wall shear, TKE
1.00	0.00150	H, P_{shaft} , η_h , wall shear, TKE
1.20	0.00180	H, P_{shaft} , η_h , wall shear, TKE
1.40	0.00210	H, P_{shaft} , η_h , wall shear, TKE

The operating points, to be used in the subsequent computational fluid dynamics (CFD) calculations, shown in the rows of table 6 between 0.60 and 1.40 times the design flowrate. At each of the points, the head, shaft power, hydraulic efficiency, wall shear stress, and turbulent kinetic energy will be

calculated for each level of surface roughness. This matrix allows for analysis of the effect of corrosion wall roughness on pump performance over the entire range of pump operation and not for one flow condition.

3.11 Performance penalties and local-loss diagnostics

Once CFD results exist, head, efficiency and shaft-power penalties can be defined as:

$$\Pi_H = (H_0 - H_i)/H_0 \times 100 \quad (7)$$

$$\Pi_\eta = (\eta_0 - \eta_i)/\eta_0 \times 100 \quad (8)$$

$$\Pi_P = (P_i - P_0)/P_0 \times 100 \quad (9)$$

Where

- Π_H = head penalty relative to the baseline condition.
- H_0 = baseline pump head.
- H_i = pump head at degradation state i .
- Π_η = hydraulic efficiency penalty relative to the baseline condition.
- η_0 = baseline hydraulic efficiency.
- η_i = hydraulic efficiency at degradation state i .
- Π_P = shaft-power penalty relative to the baseline condition
- P_0 = baseline shaft power.
- P_i = shaft power at degradation state i .
- i = degradation-state index representing the CFD condition being evaluated

The local diagnostics may include wall shear stress, turbulent kinetic energy, pressure-loss pattern, recirculation/separation volume and secondary-flow strength. They may represent the physical bridge between the forced state of roughness and the global response of the pump [14,15].

$$\text{The sensitivity } S_{\eta,Ra} = \partial(\eta/\eta_0)/\partial(Ra/Ra_0) \quad (10)$$

Where

- $S_{\eta,Ra}$ = sensitivity of normalized hydraulic efficiency to normalized surface roughness.
- η = hydraulic efficiency at a particular roughness condition.
- η_0 = baseline hydraulic efficiency.
- Ra = arithmetic surface roughness at the condition being evaluated.
- Ra_0 = baseline arithmetic surface roughness.
- η/η_0 = normalized efficiency.
- Ra/Ra_0 = normalized roughness.
- ∂ = partial derivative, meaning the local rate at which normalized efficiency changes as normalized roughness changes

This should be calculated only after the CFD response surface has been executed and must not be presented as an experimental constant.

2.12 Hierarchical validation and uncertainty

Validation should be performed hierarchically starting with the numerical validation; this is the first level and comprises mesh independence, timestep independence, conservation of mass, residuals convergence, and torque stability. The second is the hydraulic baseline validation, using a smooth or near-baseline state, and the third is degraded-state validation (S1 – S4). The fourth is attribution, which involves comparing the measured total degradation to the roughness-only CFD degradation.

This hierarchy prevents a model being accepted as validated just because an operating point happens to match a measured quantity.

Pump performance comparisons should also carefully describe the test setup, reference plane, flow, head, power definitions, and associated uncertainty following the guidance of ISO 9906:2012 [22].

The principal comparison metrics are:

$$\text{MAE} = (1/n) \sum |y_{\text{CFD}} - y_{\text{exp}}| \quad (11)$$

$$\text{RMSE} = [(1/n) \sum (y_{\text{CFD}} - y_{\text{exp}})^2]^{1/2} \quad (12)$$

$$\text{MAPE} = (100/n) \sum |(y_{\text{CFD}} - y_{\text{exp}})/y_{\text{exp}}| \quad (13)$$

Should give an uncertainty alongside the number to be measured. Experimental source states an approximate flow/head uncertainty of 2.5% so numerical deviations may be treated as measurement uncertainties [1].

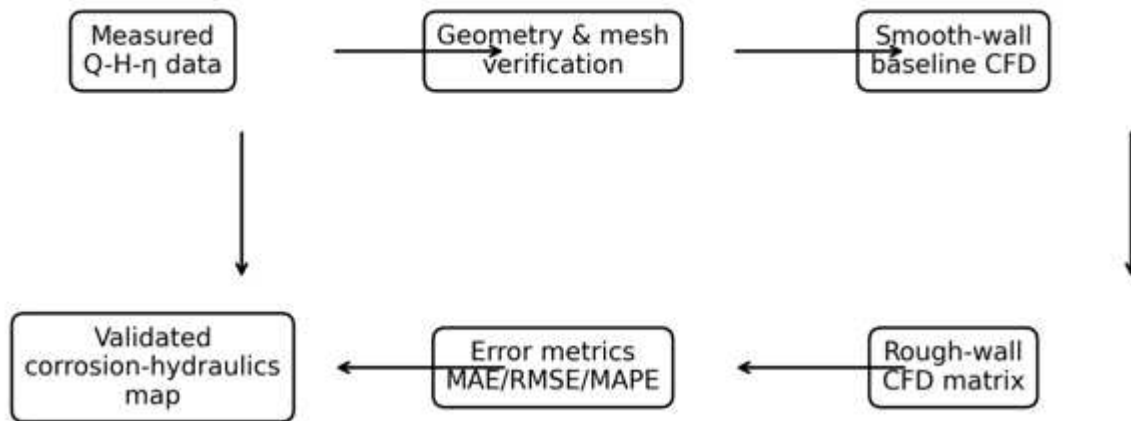


Fig. 5. Hierarchical validation workflow for the proposed CFD framework

The workflow in figure 5 illustrates the suggested stepwise approach for computational verification and validation of CFD. The first step involves the definition of the geometry and the numerical setup, which are then verified in terms of mesh, time-step and convergence tests. The baseline smooth-wall case is also compared to the available experimental Q-H data which indicate the model to be accurate. Subsequently, the validated model is used for roughness states, with the evaluation of results based on a number of error metrics.

3. Results and Discussion

3.1 Experimental degradation envelope

The experimental data handed down provides the measurable erosion range that the CFD model is to investigate. On average, over the 200 hours of service there was an increase of surface roughness of Ra from 0.8 to 3.4 μm (325%), pit density increased from zero at initial state, to 68 pits per mm and mean pit diameter from 45 μm at 50 hours to 132 μm at 200 hours, at maximum pit depth reached 210 μm at 200 hours [1].

Within the same period, flow rate dropped from 1.50 to 1.38 L/sec and head pressure dropped from 12.0 to 10.7 m. In addition, the electrical-input pump efficiency drops 12.6 percentage points representing an estimated relative drop of 17.8% while the RMS vibration increases from 0.20 to 0.75 mm/sec [1]. These are indicative of a time-dependent deterioration trend, but confound surface roughness filtering effects from the hydraulic perspective.

Second, the previous experiment was found to have a statistically significant correlation between cumulative mass loss and efficiency for 316L ($R = 0.87$, $p < 0.05$) [1]. This correlation could arguably be considered as a coupled degradation, not definitive evidence that roughness is the only causative mechanism.

3.2 Corrosion–hydraulics state map

Table 7. Experimental Degradation States Defining the Proposed CFD Boundary Cases

State	Ra (μm)	Flow (L/s)	Head (m)	Electrical- input efficiency (%)	Vibration (mm/s)	Numerical interpretation
S0	0.8	1.50	12.0	70.6	0.20	Reference wall state
S1	1.4	1.47	11.65	66.8	0.34	Early degradation
S2	2.1	1.44	11.35	63.5	0.47	Intermediate state
S3	2.8	1.41	11.00	60.2	0.61	Advanced state
S4	3.4	1.38	10.70	58.0	0.75	End-state reference

Table 7 summarizes the quantified degradation states, which are used to characterize the limiting states for the corrosion-to-CFD framework. The five states, including the initial reference condition (S0) and the end state at 200 hours (S4), depict the evolution of the measured states; the experiment state reference trajectory of hydraulic performance, surface roughness, and vibration data; and the candidate states of roughness. Please note that this table contains experimental measurements and is not of any conclusive CDF results.

3.3 Primary head-based attribution metric

The principal quantitative endpoint is head degradation because head is directly comparable between the experiment and CFD when the measurement and numerical reference planes are made consistent.

The experimental decline is:

$$\Delta H_{\text{exp}} = H_{0,\text{exp}} - H_{200,\text{exp}} = 12.0 - 10.7 = 1.30 \text{ m} \quad (14)$$

For the roughness-only CFD campaign, the corresponding decline is:

$$\Delta H_{\text{rough}} = H_{0,\text{CFD}} - H_{200,\text{CFD}} \quad (15)$$

The roughness-attributable fraction is therefore:

$$F_{\text{H,rough}} = \Delta H_{\text{rough}} / \Delta H_{\text{exp}} = (H_{0,\text{CFD}} - H_{200,\text{CFD}}) / (H_{0,\text{exp}} - H_{200,\text{exp}}) \quad (16)$$

and the residual head degradation is:

$$\Delta H_{\text{residual}} = \Delta H_{\text{exp}} - \Delta H_{\text{rough}} \quad (17)$$

$F_{\text{H, rough}}$: the fraction of measured head loss decline that can be reproduced by a roughness-only CFD. This term does not indicate the fraction of corrosion damage covered and should not be interpreted as probabilities, reliabilities, or a causal coefficient that is a constant. Additionally, if residuals are negative or the residual is more than 1, one should explore the reference plane, the uncertainties, model-form error, and physics content that is omitted rather than truncate to a range that is physical.

Another efficiency attribution is a secondary issue. The experimental efficiency trajectory of 70.6-58.0% relates to the electrical-input/system efficiency, while CFD hydraulic efficiency uses shaft power. Thus an efficiency-attribution ratio can be reported only if the experimental result is

translated into a uniform shaft-power basis or the motor and mechanical loss components are characterized separately. A comparison of efficiencies is then possible.

$$F_{\eta,\text{rough}} = (\eta_{h,0,\text{CFD}} - \eta_{h,200,\text{CFD}})/(\eta_{h,0,\text{exp}} - \eta_{h,200,\text{exp}}) \quad (18)$$

Until a common ground is found the manuscript does not utilize the experimental electrical-input efficiency as the denominator in the CFD hydraulic-efficiency attribution metric. This maintains consistency between measured and numerical values and therefore removes another source of validation uncertainty.

3.4 Roughness-transfer sensitivity and response surface

The sensitivity campaign is recommended to test all seven variables for the same geometry, operating conditions, and solver settings over the full range of possible values. A suggested response matrix is to record head and if applicable hydraulic efficiency for S0-S4, at each value. The main attribution output is shown to be $F_{H,\text{rough}}$, and the sensitivity test is to show whether or not this is insensitive to reasonable roughness-transfer uncertainty. If this attribution varies strongly between values, it is suggested that this be documented in the paper, rather than selecting the one that best matches the database data.

After the numerical matrix is completed, the corrosion state can be normalised as:

$$D_c(t) = [Ra(t) - Ra_0]/[Ra_{200} - Ra_0] \quad (19)$$

and the hydraulic response can be represented as:

$$\eta/\eta_0 = F(D_c, \alpha, Q/Q_{\text{BEP}}, Re, N) \quad (20)$$

The response surface should be fitted only after the CFD matrix exists. Cross-validation should be used if a surrogate model is fitted, and numerical noise should not be interpreted as physical nonlinearity.

3.5 What is demonstrated in the present paper and what remains to be demonstrated

The current manuscript exposes three concepts. Firstly, the experimental trajectory published can be explicitly converted into five reproducible, exposure-indexed degradation states without the effort of recapitulating pump geometry or solver output. Secondly, the difference between the measured surface-roughness value (R_a) and its CFD-suit equivalent roughness (k_s) can be made explicitly explicit according to a parametric with morphological extension description.

Thirdly, a head-based attribution and residual-degradation formulation is expected to offer a traceable quantitative endpoint for subsequent CFD works.

The numerical solution alone has not been demonstrated: geometry reconstruction, mesh and time-step sensitivity, roughness-wall implementation, k_s^+ regime accounting, baseline and degraded state validation, multi-operating-point CFD, local-loss diagnostics, and the error and variance of $F_{H,rough}$. These are in the scope of what will still be required to be accomplished, rather than presented here.

3.6 Physical mechanisms to be tested

The proposed CFD analysis will investigate three main effects: 1. Roughness should increase wall shear, resulting in an increase in the turbulent momentum transfer. 2. Roughness should affect the separation and secondary flow structures, if any, within the impeller passage and volute. 3. The

effects are likely to be nonlinear, as the rough-wall effects are assumed to be controlled by the dimensionless roughness and the local flow conditions, rather than dimensional Ra [3-7,11,15].

Global performance modification should be connected to local loss modifications, pressure contours, wall-shear-stress fields and TKE distributions in order to establish a corresponding explanation. Besides, the most recent experimental-CFD investigation from Gngr et al. appears to be a very appropriate example of combining Q-H/Q- validation and wall shear and TKE diagnostics [15].

If a rough-wall CFD simulates only a fraction of the head loss, that portion should be retained as a residual degradation component, rather than compressed into a 'general effect'. Possible causes may be clearance growth, leakage, local pit shape, impeller distortion, mass imbalance, or inlet/outlet shape changes. From a scientific perspective, this residual figure is both an insight and path-forward, as it illustrates the physics that a future corrosion-aware digital twin must then incorporate. Hence, the staged modeling approach is: the experimental study identifies the corrosion/performance profile; this paper characterizes the corrosion-to-CFD mapping, and attribution; a future CFD study isolates the roughness contribution; and a digital twin incorporates residual geometrical and mechanical effects.

3.7 Positioning relative to recent literature

The patent of novelty of the present work is more constrained than the prior art CFD studies of roughness effects on centrifugal pumps [2-4, 11, 15]. Specifically, the present work adds a time-indexed dimension to an experimentally-seen corrosion path in saline service and an unambiguous uncertainty in the transition from Ra to ks. It also adds a roughness-regime check and a head-based attribution that separates the roughness-mediated residual hydraulic loss from other mechanisms.

Gnagr et al. appear to have a very relevant experimental-CFD precedent because the API 610 BB3 study in the present work combined measured surface roughness, equivalent sand-grain roughness, SST k-model, rough-wall treatment, experimental validation, and a local-loss diagnostic [15].

Conversely, El Mansour et al. studied the roughness-related hydraulic conduct within the CFD framework for seawater pumps [11]. So the novelty of roughness-sensitive pump CFD is not to be found in the present study, but in the addition of a corrosion origin, time history, and attribution methodology.

3.8 Physical interpretation of α and scope of inference

It is also important to note that the parameter in this discussion is a model-form uncertainty parameter, not a material property. The sensitivity analysis test inputs are used as test numbers for the framework and are not the data source for an estimated probability distribution based on literature sources. The figures should not be used for comparison to another pump without validation.

This interpretation falls in line with the literature (as even cited in Figure 8) that suggests the equivalent sand-grain roughness is the consequence of multiple surface descriptors and roughness morphology [5,6,12,13].

The framework is intentionally limited to a single 316L pump and one controlled saline exposure. In contrast, it does not provide a universal degradation law for all centrifugal pumps, all stainless steels, or all seawater conditions.

4.9 Residual degradation and digital-twin interpretation

If the baseline CFD only captures part of the head loss observed, it should be left as an residual degradations, not overcompensated. Possible mechanisms may include clearance growth, leakage, local pit shape, blade tip distortion, mass imbalance and inlet/outlet geometry changes. The residual is of practical interest because it indicates what others physical phenomena a corrosion-informed digital twin would include. The staged approach is: experimental study – measured corrosion, performance path; this paper – how to translate corrosion to CFD and to assign cause; a further CFD study – allocate head degradation to roughness; and a digital twin, higher than- CFD – allocate remaining geometric and dynamic effects.

6. Limitations and Requirements for a Completed CFD Results Article

This current manuscript outlines a proposed methodology based on available publication data, and thus should be regarded as a work-in-progress with respect to the CFD results and not as a finalized one. The manuscript revealed four larger points of concern: (1) the experimental material does not incorporate the pump CAD geometry; (2) the presented Ra values serve as surface condition descriptors indexed by exposure; and, when the source was coupon-based, do not represent measurements of every rotating wetted pump wall and must therefore be identified explicitly, by a subsequent valid CFD validation publication, as the dedicated measurement surface; (3) the Ra to k_s conversion is model-dependent, thus the identification of the k_s^+ regime must be verified; and, (4) a solver-dependent CFD output has not been generated.

In addition, a traditional CFD paper should be written only after the geometry has been reconstructed, and the CFD campaign has been completed. The minimum set of simulations performed includes the baseline geometry and CAD verification, mesh independence at three levels,

time-step independence at three levels, document y^+ and ks^+ distributions, baseline Q-H and common-basis power/efficiency validation, S0-S4 rough-wall cases, sensitivity studies, multiple operating point characteristic curves, torque/shaft-power plots, wall shear analysis, TKE plots, pressure-loss and separation diagnostics, Uncertainty analysis, and the head-based roughness-attributable fraction $F_{h, rough}$.

On the other hand, the current framework deliberately avoids replacing estimated or fabricated CFD data. In the mildest form of this approach, the preservation of scientific standards can be achieved by maintaining an unambiguous division between the measured evidence, model inputs and all the future numerical outputs.

6. Conclusions

Corrosion-to-CFD methodology has been formulated for a 316L stainless-steel centrifugal pump exposed to 30-ppt synthetic seawater for 200 h. This methodology redefines the published experimental trajectory by decomposing it into five exposure-indexed states, while explicitly preserving the separation of measured degradation data from the CFD model's inputs and outputs [1].

The key methodological step is the direct distinction made between the measured arithmetic roughness, R_a , and the equivalent sand-grain roughness, ks , used in rough-wall CFD calculations. The relation $ks = R_a$ is maintained as a pump-specific modeling assumption with explicit sensitivity analysis, and then the necessary CFD simulation to infer ks^+ and the roughness regime is given. Morphology-based extrapolation is envisaged in situations where a sufficient three-dimensional surface-topography dataset is at hand.

The main quantity for the following CFD analysis is the head-based roughness-attributable fraction, $F_{H, rough}$, based on the head loss ratio between the roughness-only CFD calculation and the

measured head drop of 1.30 m. Efficiency attribution is a secondary consideration and requires a common shaft-power basis. The residual degradation term is kept for clearance, leakage, change of geometry due to pitting, imbalance and mechanisms other than roughness per se.

Recent papers have noted that roughness-sensitive centrifugal-pump CFD and seawater-pump research are mature research areas [11,15]. Therefore, the novelty of this method lies in the corrosion-based time-state representation, explicit Ra-to-ks uncertainty, roughness-regime identification, and attribution/residual framework rather than the general notion of roughness affecting pump performance.

The actual tested-pump geometry is not available and the CFD execution is not part of the provided experimental data set. Accordingly, no solver-dependent CFD values are reported. Therefore, the present manuscript is reported as a methodological approach. A future paper providing the CFD outcomes should verify and perform the numerical campaign sketched here, before providing any quantitative roughness-attribution values.

Declarations

Funding:No external funding was received specifically for the present analytical study.

Competing interests:The author declares no competing interests.

Author contributions: N.I.U. conceived the present analytical study, developed the Pump Degradation Index framework, performed the secondary analysis and prepared the manuscript.

Data availability: The experimental source study reports that supporting data and analysis code are available from the corresponding author upon reasonable request [1]. For a future completed CFD article, the geometry description, mesh statistics, solver settings, convergence histories, roughness cases and post-processing definitions should be provided to the extent permitted by intellectual-property constraints.

Ethics approval: Not applicable.

Consent to participate: Not applicable.

Consent for publication: Not applicable.

Nomenclature

Symbol / abbreviation	Meaning
CFD	Computational fluid dynamics
RANS	Reynolds-averaged Navier–Stokes
SST $k-\omega$	Shear-stress-transport $k-\omega$ turbulence model
Ra	Arithmetic average surface roughness
Rq	Root-mean-square roughness
Rz	Peak-to-valley roughness
Sk	Surface-height skewness
Ku	Surface-height kurtosis
k_s	Equivalent sand-grain roughness
PD	Pit density
D_p	Mean pit diameter
TKE	Turbulent kinetic energy
Q	Volumetric flow rate
H	Pump head
η_h	Hydraulic efficiency
η_{sys}	Electrical-input/system efficiency
P_{shaft}	Shaft power
α	Roughness-transfer parameter
BEP	Best-efficiency point
MAE	Mean absolute error
RMSE	Root-mean-square error

MAPE	Mean absolute percentage error
$u\tau$	Friction velocity
ν	Kinematic viscosity
ks^+	Roughness Reynolds number, $ks\ u\tau/\nu$
Re	Reynolds number

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