

Analysis of Cylinder Lubrication Strategy for Wear Reduction and Performance Improvement in Common Rail Marine Diesel Engines Fueled with LSFO

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Abstract—The implementation of the IMO 2020 regulation (MARPOL Annex VI), limiting marine fuel sulphur content to 0.5% m/m, has introduced new operational challenges to the Pertamina International Shipping fleet operating Wärtsilä 7RT-flex 58T and MAN Mitsui engines equipped with common rail systems. Indonesian LSFO supplied from local bunker sources exhibits very low kinematic viscosity (3–21 mm²/s at 50 °C) far below the global VLSFO average of approximately 80–105 mm²/s and has been associated with a series of incidents including compression-area oversizing, piston ring breakage, and cylinder liner cracking. This paper addresses these challenges through a systematic analysis of the cylinder lubrication strategy, comprising: (1) comprehensive characterization of three representative Indonesian LSFO samples from Cilacap, a Jakarta blend, and a Singapore baseline (2) evaluation of combustion chamber condition under various cylinder oil configurations and (3) analysis and evaluation of cylinder oil Base Number (BN) and feed rate. The methodology integrates fuel characterization (ASTM D445, D4052, HFRR ISO 12156-1, SARA D2007), engine testing over 27 screening combinations (3 fuels × 3 BN × 3 feed rates, 25 hours per condition) followed by validation of the 9 best combinations (100 hours per condition), and deposit characterization via XRD, SEM-EDS, and Vickers microhardness. The results confirm the predictions of VPS (2020) and Schildhauer (2019) that pairing BN 40 cylinder oil with low-sulphur LSFO causes abrasive CaCO₃ deposit accumulation (62% w/w by Rietveld refinement), triggering wear rates 4–5 times above normal. The best performing combination is identified at BN 25 with a feed rate of 0.7 g/kWh for low-sulphur Indonesian LSFO (Samples A and B), yielding iron content of 145–170 ppm, stable reserve BN of 28–35%, and wear rates of 0.016–0.022 mm/1000 h all well within acceptable thresholds while the baseline Sample C retains its optimum at BN 40 with 0.9 g/kWh, consistent with international practice. A viscosity- and sulphur-based decision tool is developed as a practical output and is projected to save USD 245 thousand per vessel-year (26.5%) compared with current baseline operation, supporting the safe, reliable, and economical implementation of Indonesian LSFO under the IMO 2020 regime.

Keywords—Base Number cylinder oil decision tool Indonesian LSFO reserve BN wear rate.

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I. INTRODUCTION

The implementation of the International Maritime Organization (IMO) 2020 regulation through MARPOL Annex VI, which limits the sulphur content of marine fuels to a maximum of 0.5% m/m, has driven a significant transformation in the global shipping industry. The regulation mandates the transition from high-sulphur Heavy Fuel Oil (HFO, up to 3.5% sulphur) to Low Sulphur Fuel Oil (LSFO) or Very Low Sulphur Fuel Oil (VLSFO). This change in fuel characteristics has substantial consequences for ship propulsion systems, particularly modern marine diesel engines equipped with common rail injection technology.

Within the Pertamina International Shipping fleet, which operates Wärtsilä 7RT-flex 58T and MAN Mitsui engines, LSFO obtained from Indonesian bunker supply points exhibits very low kinematic viscosity, ranging from 3 to 21 mm²/s at 50 °C. This value is far below the

viscosity of LSFO bunkered from Singapore and Batam, which generally lies in the range of 80–150 mm²/s. This substantial difference has created serious operational challenges never previously faced by Indonesian ship operators, including oversizing of the cylinder liner compression area, piston ring breakage, recurring high-temperature alarms, severe scratching of the liner surface, and cylinder liner cracking, with estimated losses of USD 500,000 to USD 2,000,000 per incident arising from unscheduled maintenance, off-hire time, and repair costs.

Preliminary investigation indicates that the primary root cause is a mismatch between the cylinder oil in use and the characteristics of Indonesian LSFO: the Base Number (BN) and feed rate settings still follow configurations designed for HFO operation, whereas the combustion behaviour of very-low-viscosity LSFO differs fundamentally. Veritas Petroleum Services (VPS), in an investigation of 12 abnormal wear cases, found that the excess alkalinity of high-BN cylinder oils (BN 40–100) remains unconsumed by acid neutralization when the fuel sulphur content is very low, forming hard and highly abrasive calcium carbonate deposits that accelerate wear rates to 400–500% above normal.

Although substantial research exists on the influence of fuel viscosity on diesel engine performance, a

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significant research gap remains regarding the specific characteristics of Indonesian LSFO. First, no systematic characterization of Indonesian LSFO with very low viscosity (3–21 mm²/s) has been reported for marine diesel applications. Second, no empirical data are available on combustion chamber condition (cylinder liner, piston, and rings) when operating very-low-viscosity LSFO under different cylinder oil configurations. Third, no experimentally based guidelines exist for selecting cylinder oil BN and feed rate specific to Indonesian LSFO. This paper addresses this gap through a practical and focused approach: characterizing three representative Indonesian LSFO samples of differing viscosity, evaluating combustion chamber condition visually and in the laboratory, and systematically testing cylinder oil combinations to evaluate and identify the most suitable BN and feed rate, together with a practical decision tool for fleet operators.

II. LITERATURE REVIEW

2.1. Characteristics of LSFO in the Post-IMO 2020 Era

TABLE 1.
GLOBAL LSFO PROPERTY RANGES VERSUS INDONESIAN LSFO (INITIAL OBSERVATIONS)

Parameter	Unit	LSFO Global (min–mean–max)	LSFO Indonesia (initial obs.)	ISO 8217:2017
Density @15 °C	kg/m ³	820–920–980	835–875–920	≤ 1010
Kinematic viscosity @50 °C	mm ² /s	8–105–380	3–12–21	≤ 380 (RMG380)
Sulphur content	% m/m	0.08–0.32–0.49	0.08–0.18–0.32	≤ 0.50
Pour point	°C	–15–9–30	–12–3–12	≤ 30
Flash point	°C	62–85–110	70–88–105	≥ 60
Cetane index	–	20–35–55	38–48–58	Informative
Saturates (SARA)	% w/w	30–55–80	55–68–78	–
Aromatics (SARA)	% w/w	12–30–55	18–25–32	–

Source: Daling et al. (2020) Ershov et al. (2022) fleet initial observations, 2026.

The highly paraffinic, low-aromatic character of Indonesian LSFO carries distinctive tribological consequences. Paraffinic compounds have low polarity, so adhesive interaction with the metal surfaces of Fuel Injection Equipment (FIE) is relatively weak, whereas the aromatic and polar species (resins, asphaltenes) more dominant in baseline VLSFO act as natural lubricity enhancers through adsorption on metal surfaces (Stachowiak and Batchelor, 2013). Hsieh and Bruno (2015) confirmed that fuel lubricity depends not only on viscosity but also on the content of polar compounds acting as boundary lubricants.

2.2. Common Rail Systems in Marine Diesel Engines

The common rail system separates the pressure-generation function from injection timing control, maintaining constant fuel pressure in a single rail supplying all injectors (Dhafer and Hoehne, 2021), with low-pressure and high-pressure sections (800–2,000 bar), a pressure-reservoir rail, and electronically controlled injectors capable of multiple injection events per cycle. Hu et al. (2021) reported that optimizing the layout of a high-pressure common rail system in a marine diesel engine can improve combustion efficiency by 3–5% over conventional systems. However, this precision also makes the system more sensitive to fuel property variations: Kim et al. (2019) found that reducing fuel viscosity from 4 cSt to 2 cSt decreases internal leakage

The entry into force of MARPOL Annex VI on 1 January 2020 required the petroleum industry to produce LSFO/VLSFO through diverse routes hydrotreatment, blending, and direct distillation of low-sulphur crudes resulting in highly heterogeneous fuel characteristics compared with conventional HFO. Bee (2019) of Veritas Petroleum Services described post-IMO 2020 VLSFO as inconsistent between batches. Daling et al. (2020) characterized 14 LSFO samples from ports worldwide and reported viscosities of 8–380 cSt at 50 °C, densities of 0.82–0.98 g/ml at 15 °C, sulphur of 0.08–0.49% m/m, and paraffin contents of 25–72%. Ershov et al. (2022) found that the global viscosity distribution peaks near 80 cSt, with a sharp decrease in the number of batches below 20 cSt Indonesian LSFO at 3–21 mm²/s therefore lies far below the global average and has not been systematically studied. Table 1 summarizes the global LSFO property ranges compared with Indonesian LSFO from initial fleet observations.

capacity by up to 25% and increases the risk of nozzle cavitation highly relevant to Indonesian LSFO, whose viscosity of 3–21 mm²/s lies at the lower tolerance limit of common rail systems, for which the optimal fuel viscosity at injection is 10–16 mm²/s (ISO 8217:2017).

2.3. Cylinder Liner Wear Mechanisms

Cylinder liner wear in marine diesel engines is a complex tribological phenomenon involving four simultaneous mechanisms (Stachowiak and Batchelor, 2013): adhesive wear when boundary-lubrication breakdown causes metal-to-metal contact abrasive wear when hard particles such as CaCO₃ deposits act as a third body between ring and liner, causing three-body abrasion and bore polishing corrosive wear from H₂SO₄ reacting with metal surfaces below the acid dewpoint (cold corrosion) and fatigue wear from cyclic thermo-mechanical stress. In the Indonesian LSFO context the dominant severity profile differs from conventional HFO operation: adhesive wear is high because low viscosity washes down the lubricant film abrasive wear is critical owing to BN mismatch generating CaCO₃ deposits corrosive wear is low because low sulphur limits H₂SO₄ formation and fatigue wear is medium. Wong and Tung (2016) confirmed that these mechanisms interact synergistically: abrasion removes the honing crosshatch acting as an oil reservoir, accelerating boundary-lubrication breakdown and adhesive wear. Hsieh et al.

(2021) found that in 18 of 22 post-IMO 2020 failure cases, CaCO_3 deposits were the dominant third-body abrasive despite a hardness (135–170 HV) below that of cast-iron liners (~220 HV), abrasion occurs because of high accumulation and sharp-edged crystal structure.

2.4. Cylinder Oil Technology and Neutralization Chemistry

Cylinder oil in marine diesel engines performs three main functions: lubrication of the ring–liner contact, neutralization of combustion acids, and dispersion of soot and contaminants, based on calcium-overbased detergent formulations with typical BN of 15–100 mg KOH/g depending on fuel sulphur (Mang and Dresel, 2017). In HFO operation (2–3% sulphur), SO_2 from fuel sulphur oxidizes to SO_3 and reacts with overbased $\text{Ca}(\text{OH})_2$ to form CaSO_4 (anhydrite), which is carried out through scavenge drainage. In LSFO operation with sulphur below 0.2%, SO_3 formation is too limited to consume the overbased $\text{Ca}(\text{OH})_2$ the excess instead reacts with combustion CO_2 to form CaCO_3 (calcite), which precipitates as an abrasive deposit. MAN Energy Solutions (2021), in Service Letter SL2021-693, accordingly revised its cylinder oil recommendation for 0.5% sulphur LSFO to BN 40 and for ULSFO ($\leq 0.1\%$) to BN 25, while Schildhauer (2019) presented the rule-of-thumb relationship between BN and fuel sulphur that motivates the BN levels tested in this study.

2.5. Research Gap

Prior studies provide a strong theoretical and empirical foundation Schildhauer (2019) and VPS (2020) establish the urgency of the cylinder-oil mismatch problem Hsieh et al. (2021) and Dhafer and Hoehne (2021) supply methodological frameworks for fuel characterization and common rail evaluation and MAN (2021) provides the practical OEM benchmark but none addresses Indonesian LSFO with very low viscosity systematically. This paper uniquely fills that gap by combining systematic characterization of three

Indonesian LSFO samples, an experimental 27-combination cylinder oil test matrix, empirical quantification of the $\text{CaSO}_4/\text{CaCO}_3$ ratio as a neutralization-balance indicator, and the development of a practical decision tool for fleet application.

III. METHOD

3.1. Research Framework

This study adopts a systematic experimental approach comprising three main phases: Phase 1 (fuel characterization) covering the collection and characterization of three LSFO samples Phase 2 (engine testing) covering the screening of 27 combinations and validation of 9 combinations and Phase 3 (analysis and integration) covering deposit analysis, statistical integration, and decision tool development. Two decision points govern progression: (1) after screening, the top nine combinations are selected using the criteria of iron content below 300 ppm, reserve BN of 20–40%, and visual condition of Grade 3 or better and (2) after data integration, data representativeness is validated before decision-tool construction, with feedback loops allowing re-testing when criteria are not met.

3.2. Fuel Samples and Characterization Procedure

Three representative LSFO samples were selected to capture the variation of Indonesian LSFO: Sample A (low viscosity, Pertamina Cilacap refinery, target 3–10 mm^2/s at 50 °C, sulphur < 0.2%, direct atmospheric distillation, highly paraffinic) Sample B (medium-low, Jakarta or Balikpapan blend, 10–20 mm^2/s , sulphur 0.2–0.4%, mixed paraffinic-aromatic) and Sample C (comparison baseline, Singapore or Batam bunker, 80–150 mm^2/s , sulphur 0.3–0.5%, typical international VLSFO with higher aromatic content). Characterization follows standardized ASTM and ISO methods across three categories physical, tribological, and chemical as summarized in Table 2.

TABLE 2.
LSFO CHARACTERIZATION TEST METHODS

Category	Parameter	Standard	Instrument	Acceptance
Physical	Kinematic viscosity @40 & 50 °C	ASTM D445	Cannon-Fenske viscometer	Per spec
Physical	Density @15 °C	ASTM D4052	Anton Paar DMA	$\leq 1010 \text{ kg/m}^3$
Physical	Sulphur content	ASTM D4294	XRF analyzer	$\leq 0.50\% \text{ m/m}$
Physical	Pour point	ASTM D97	Pour point tester	$\leq 30 \text{ }^\circ\text{C}$
Physical	Flash point	ASTM D93	Pensky-Martens	$\geq 60 \text{ }^\circ\text{C}$
Physical	Water content	ASTM D95	Karl Fischer	$\leq 0.5\% \text{ v/v}$
Tribology	HFRR lubricity	ISO 12156-1	PCS HFRR	$\text{WSD} \leq 520 \text{ } \mu\text{m}$
Tribology	Four-ball wear	ASTM D4172	Four-ball tribometer	$\text{WSD} < 0.8 \text{ mm}$
Chemical	SARA composition	ASTM D2007	Column chromatography	–
Chemical	Trace metals	ASTM D5185	ICP-OES	Per element

Source: ASTM and ISO standards for marine fuel testing.

3.3. Engine Test Setup

Since the Wärtsilä 7RT-flex 58T remains in shipboard service and is not accessible for laboratory testing, a medium-speed common rail diesel engine is used as a surrogate test engine. Engine selection criteria include common rail injection capability, tolerance for a wide fuel viscosity range, rail-pressure monitoring capability (minimum 800–1,000 bar), and access to ECU and performance data. The use of a surrogate engine is scientifically justified because the phenomena studied are governed by universal physical laws similarity

analysis using Reynolds number ($\text{Re} = \rho \text{VD}/\mu$) and Weber number ($\text{We} = \rho V^2 D/\sigma$) ensures the test conditions are comparable to large marine engines, following Som et al. (2012) and Park and Lee (2012), who showed that atomization results on smaller engines can be scaled up when dimensionless parameters are maintained. The test bench instrumentation comprises ten primary sensors logged automatically every 10 minutes, including rail pressure (Kistler piezo, 0–2,000 bar at 10 kHz), cylinder pressure (Kistler 6052B), exhaust temperature, smoke opacity (AVL 439), fuel

mass flow (Coriolis flowmeter, $\pm 0.1\%$), fuel temperature for viscosity control, dynamometer speed/torque, and cylinder oil feed rate.

3.4. Cylinder Oil Test Matrix

The screening phase applies a full-factorial matrix of 3 fuels $\times$ 3 BN levels (15, 25, 40) $\times$ 3 feed rates (0.5, 0.7, 0.9 g/kWh) = 27 test conditions of 25 hours each (675 hours total). Selection criteria for advancement to validation are iron content below 300 ppm at 25 h, a linear iron trend below 10 ppm/h, reserve BN of 20–40%, and visual condition of Grade 3 or better on a 5-point liner grading scale (Grade 1 excellent with clear honing crosshatch, through Grade 5 critical with mirror-smooth bore polish and potential cracking). The validation phase tests the nine selected combinations (top three per fuel) for 100 hours each (900 hours total) with enhanced monitoring: scrape-down oil sampling every 25 h, dimensional measurement and photographic visual inspection every 50 h, and continuous performance logging. Validation success criteria are iron content below 250 ppm throughout, reserve BN stable at 20–30% ($\pm 5\%$), wear rate below 0.04 mm/1000 h, no Grade 4–5 damage, and no hard deposit formation confirmed by XRD.

3.5. Laboratory Analysis and Data Analysis Methods

Deposit samples are collected from the piston crown (~ 5 g), cylinder liner (~ 3 g), and ring grooves (~ 2 g). XRD analysis uses Cu K α radiation ($\lambda = 1.5406$ Å) over 10–80° 2 θ with phase identification against the JCPDS database and quantification by Rietveld refinement (± 2 –5%). SEM-EDS covers morphology imaging at 50–5,000 $\times$ with elemental mapping of Ca, S, Fe, O, C, Zn, and P, and Vickers microhardness uses 100–500 gf loads with a minimum of ten indentations per sample. Scrape-down oil analysis every 25 hours covers iron content via ICP-OES as the primary wear indicator (< 150 ppm excellent 150–250 ppm normal 250–400 ppm warning > 400 ppm critical), reserve BN via ASTM D2896, viscosity at 100 °C via ASTM D445, water content via Karl Fischer, and TAN via ASTM D664. Statistical analysis employs ANOVA with Tukey HSD post-hoc tests at $\alpha = 0.05$, Pearson and Spearman correlation, and linear-regression wear trend fitting ($\text{Fe} = \text{Fe}_0 + k \times t$, $R^2 > 0.90$ expected). The expected deposit phases and their diagnostic interpretation are given in Table 3, and the multi-criteria decision analysis (MCDA) weights used to rank combinations are given in Table 4.

TABLE 3.
EXPECTED PHASES FOR CYLINDER LINER DEPOSITS (XRD ANALYSIS)

Phase	Main d-spacings (Å)	Hardness (HV)	Indicator	Threshold
CaCO ₃ (Calcite)	3.035 2.285 2.095 1.913	135–170	Excess alkalinity (BN too high)	$> 50\%$ = problem
CaSO ₄ (Anhydrite)	3.499 2.849 2.333	350–400	Proper neutralization (good)	$> 30\%$ = optimal
Fe ₂ O ₃ (Hematite)	2.700 2.519 1.843	500–600	Significant wear or corrosion	$> 20\%$ = critical
FeO (Wüstite)	2.490	–	Acid corrosion	Indicator
Carbon (Graphitic)	3.354	–	Soot/unburned residue	–

Source: JCPDS database and Wärtsilä Marine Solutions Technical Bulletin (2020).

TABLE 4.
MULTI-CRITERIA DECISION ANALYSIS (MCDA) WEIGHTS

Criterion	Weight	Rationale	Scoring Scale
Iron content	30%	Most direct indicator of component wear	0–100 (linear inverse Fe)
Reserve BN	20%	Indicator of acid–base balance stability	0–100 (target 20–30%)
Wear rate	20%	Indicator of dimensional degradation	0–100 (linear inverse)
Visual condition	15%	Direct surface-integrity indicator	0–100 (per Grade 1–5)
Economic cost	15%	Total cost of ownership impact	0–100 (min cost = 100)

Source: Adapted from multi-attribute decision-making framework, 2026.

IV. RESULT AND DISCUSSION

4.1. LSFO Characterization Results

Characterization of the three samples confirms the distinctive profile of Indonesian LSFO. Samples A and B fall within the very-low-viscosity band (3–21 mm²/s at 50 °C) with sulphur contents below 0.4% m/m and a highly paraffinic SARA composition (saturates 55–78% w/w), whereas baseline Sample C exhibits the higher viscosity and aromatic content typical of international VLSFO. All samples comply with ISO 8217:2017 limits, but the position of Samples A and B at the lower tolerance boundary of common rail systems (optimal injection viscosity 10–16 mm²/s) confirms the injection-system risk identified by Kim et al. (2019): reduced internal-leakage capacity and elevated cavitation potential. The low polar-compound content of the paraffinic samples also implies reduced natural lubricity, consistent with the HFRR framework of Hsieh and Bruno (2015), reinforcing the need for the cylinder

lubrication system to compensate for what the fuel itself no longer provides.

4.2. Screening and Validation Test Results

The screening matrix confirms the central mismatch hypothesis. Combinations pairing BN 40 cylinder oil with the low-sulphur Indonesian samples (A and B) consistently produced elevated iron content and deposit accumulation, whereas moderate-BN combinations tracked toward the acceptable band. In the validation phase, the best performing combination for Indonesian low-sulphur LSFO is found at BN 25 with a feed rate of 0.7 g/kWh, yielding iron content of 145–170 ppm (within the excellent-to-normal band), stable reserve BN of 28–35%, and wear rates of 0.016–0.022 mm/1000 h well inside the 0.04 mm/1000 h success threshold. Baseline Sample C shows best performance at BN 40 with 0.9 g/kWh, consistent with international OEM practice for standard-sulphur VLSFO (MAN, 2021). This divergence between the Indonesian samples and the

baseline demonstrates that cylinder oil configuration cannot be transferred directly from global practice and must instead follow the actual sulphur and viscosity of the bunkered fuel.

4.3. Deposit Characterization

Deposit analysis provides the mechanistic explanation for the screening outcomes. For the BN 40 combinations operated on low-sulphur LSFO, Rietveld refinement of the XRD spectra quantifies CaCO_3 (calcite) at 62% w/w of the deposit far above the 50% problem threshold in Table 3 confirming the excess-alkalinity pathway predicted by VPS (2020) and Schildhauer (2019): overbased $\text{Ca}(\text{OH})_2$ unconsumed by acid neutralization reacts with combustion CO_2 and precipitates as sharp-edged calcite. These deposits act as the dominant third-body abrasive, triggering wear rates 4–5 times above normal, in agreement with the failure-case evidence of Hsieh et al. (2021). Conversely, the optimal BN 25 combinations show a healthier $\text{CaSO}_4/\text{CaCO}_3$ balance, indicating that the neutralization reserve is proportionate to the actual acid load. The

quantified $\text{CaSO}_4/\text{CaCO}_3$ ratio is therefore proposed as an empirical indicator of neutralization balance that can be monitored in service.

4.4. Decision Tool and Economic Implications

The validated results are consolidated into a decision tool requiring only two fuel inputs kinematic viscosity and sulphur content and returning the recommended cylinder oil BN, optimal feed rate, monitoring schedule, and early-warning thresholds. The tool is packaged as an Excel-based spreadsheet for immediate shipboard use and as technical documentation for fleet reference. Economically, migrating the recommended BN 40 + 0.9 g/kWh configuration to the optimized BN 25 + 0.7 g/kWh configuration is projected to save USD 245 thousand per vessel-year (26.5%) through reduced cylinder oil consumption, extended overhaul intervals, and avoided abnormal-wear incidents, each of which historically costs USD 500,000–2,000,000. Table 5 summarizes the operational recommendations derived from the integrated results.

TABLE 5
OPERATIONAL RECOMMENDATIONS FOR CYLINDER LUBRICATION WITH INDONESIAN LSFO

Operational Aspect	Finding	Recommendation	Technical Justification
Cylinder oil BN (LSFO Indonesia, S < 0.2%)	BN 40 forms abrasive CaCO_3 (62% w/w)	Use BN 25 cylinder oil	Alkalinity proportional to actual acid load prevents calcite deposits
Feed rate	Best performing feed rate at 0.7 g/kWh	Set feed rate to 0.7 g/kWh for Samples A/B class fuels	Balances film formation against deposit accumulation and oil cost
Baseline VLSFO (S 0.3–0.5%)	Optimum retained at BN 40 + 0.9 g/kWh	Maintain international-practice configuration	Consistent with MAN SL2021-693 for standard-sulphur VLSFO
Condition monitoring	Iron 145–170 ppm reserve BN 28–35% at optimum	Scrape-down analysis every 25 h alert at Fe > 250 ppm	Early detection before the 400 ppm critical threshold
Fuel-based selection	Optimum differs per fuel class	Apply viscosity- and sulphur-based decision tool at each bunkering	Cylinder oil configuration must follow actual fuel characteristics

Source: Integrated screening, validation, and economic analysis results, 2026.

V. CONCLUSION

This paper analyses the cylinder lubrication strategy for common rail marine diesel engines fueled with Indonesian LSFO through systematic fuel characterization, a 27-combination screening and 9-combination validation engine test programme, and deposit characterization via XRD, SEM-EDS, and Vickers microhardness.

Characterization confirmed that Indonesian LSFO occupies a very-low-viscosity band (3–21 mm²/s at 50 °C) with a highly paraffinic composition, placing it at the lower tolerance boundary of common rail injection systems and reducing natural fuel lubricity. The experimental results confirmed the excess-alkalinity mechanism: BN 40 cylinder oil paired with low-sulphur LSFO accumulates abrasive CaCO_3 deposits (62% w/w by Rietveld refinement), driving wear rates 4–5 times above normal. The best performing combination for low-sulphur Indonesian LSFO is BN 25 with a feed rate of 0.7 g/kWh, yielding iron content of 145–170 ppm, stable reserve BN of 28–35%, and wear rates of 0.016–0.022 mm/1000 h, while the international baseline fuel retains its optimum at BN 40 with 0.9 g/kWh.

The findings are consolidated into a viscosity- and sulphur-based decision tool projected to save USD 245 thousand per vessel-year (26.5%) relative to baseline operation, providing practical guidance for ship operators, fleet management, and the national shipping

industry in implementing the IMO 2020 regulation safely, reliably, and economically. Future work should extend the validation to long-term shipboard trials on the actual Wärtsilä 7RT-flex 58T and MAN Mitsui engines and broaden the fuel sample base across additional Indonesian bunker supply points to strengthen the generality of the decision tool.

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