Optimization of the marine fuel system (MGO/HFO, MFP–HFO, separation): the influence of fuel preparation modes on engine reliability and consumption

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Abstract. The study provides a broad analysis of approaches to optimizing marine fuel systems in the context of tightening environmental requirements in the 2024–2025 period. The purpose of the study is to identify patterns in the influence of fuel preparation modes (HFO, MGO, MFP-HFO) and the effectiveness of centrifugal separation on the operational reliability of main engines, as well as on the value of specific fuel consumption. As the methodological basis, a systematized review of specialized publications, a comparison of key technical parameters of equipment, and a practice-oriented analysis of cases of implementing digital systems for control and monitoring of tanks were used. The totality of the obtained data indicates that stabilization of the temperature regime of separation at 98°C with simultaneous limitation of throughput to 70% ensures removal of up to 85% of abrasive catalytic fractions, thereby statistically reducing the probability of scuffing formation on cylinder liners. Additionally, it is shown that replacing manual procedures for monitoring petroleum product levels with redundant computer-based measuring systems leads to an increase in accounting accuracy up to 98.3% relative to traditional measurements. The formulated hypothesis about the key significance of fuel cleanliness as one of the determining factors for achieving limiting values of effective engine efficiency above 53% is confirmed through analysis of tribological characteristics and wear parameters. The conclusions substantiate the expediency of integrating adaptive control of separation processes with digital monitoring of condition and levels in tanks as a systemic solution aimed at increasing the durability of the cylinder–piston group and reducing operational risks. The presented results have applied significance for marine engineers, technical managers of shipping companies, and specialists engaged in the design and modernization of modern marine power plants.

Keywords: marine fuel system, fuel separation, heavy fuel oil (HFO), marine gas oil (MGO), catalytic fines, cylinder wear, FuelEU Maritime, digital tank measurement system, engine reliability, energy efficiency.

Introduction

In 2025, the maritime industry is undergoing the most large-scale technological shift of the past century, which is determined not only by fleet renewal and the digitalization of operations, but also by intensified regulatory pressure in the field of environmental protection. The research relevance of the topic is determined by the entry into force of global and regional environmental mechanisms, including the extension of the EU Emissions Trading System (EU ETS) to shipping from 2024 and the launch of the FuelEU Maritime regulation from January 2025 [1]. Against this background, the bunker market in 2025 is estimated at 172.5 billion USD, and the total volume of maritime trade has exceeded 11.5 billion t. [3]. At the same time, the decarbonization trajectory does not exclude the preservation of traditional fuel practices: as of 2024, more than 5,000 vessels are equipped with scrubber installations, which makes it possible to continue operating high-sulfur fuel oil (HSFO), which forms a significant share of current costs [1, 2].

The key scientific uncertainty is associated with insufficient predictability of the tribological behavior of new blended fuels, primarily VLSFO and MFP-HFO, in the friction units of main engines. According to the 2024 data of the classification society DNV, an increase in the number of emergency incidents by 15% is noted, with 60% of episodes directly correlating with failures of engine-room equipment and damage to the cylinder–piston group arising due to unsatisfactory fuel preparation [5, 6]. The established technological separation schemes, originally oriented toward grades that are relatively stable in composition, demonstrate limited effectiveness when operating with unstable blends characterized by increased concentrations of catalytic fines (cat fines).

The study carried out within the framework of the work is **aimed** at substantiating a set of technical and operational solutions that make it possible to optimize fuel systems in order to reduce wear intensity and increase the overall energy efficiency of the vessel.

The scientific novelty consists in the quantitative establishment of a relationship between the hydraulic regimes of separation and the degradation rate of the surface layer of cylinder liners during operation on low-sulfur blends.

The proposed hypothesis proceeds from the fact that achieving the design reliability of modern high-compression engines becomes feasible only when the catalytic fine content at the engine inlet is reduced to a level of less than 15 ppm, which, in turn, requires a combination of automated control of separation processes with digital monitoring of tank condition.

Materials and Methods

The methodological framework of the study was formed on the basis of a multifactor consideration of marine fuel preparation processes with an emphasis on the interrelationship between preparation regimes, fuel characteristics, and purification parameters. A systematic review of specialized publications indexed in Scopus and Web of Science, devoted to simulation-based design optimization (SBDO), was applied as the basic research instrument. This approach ensured the identification of dominant directions in the development of methods for controlling variable parameters of fuel systems and made it possible to relate them to changes in hydrodynamic conditions that determine separation efficiency.

The source corpus was formed according to the principle of comparing regulatory, industry, and academic materials. Industry analytical reports of leading organizations (DNV, Lloyd's Register, UNCTAD) were used, containing updated information on accident rates, transportation volumes, and fuel quality indicators in 2024–2025. Scientific articles and engineering reviews were involved that disclose the physical mechanisms of abrasive wear and generalize the results of testing modern control systems. The regulatory contour of the study is defined by the international standards ISO 8217:2024 and ISO 13739:2020, regulating requirements for the characteristics of marine fuels and bunkering procedures. A substantial place is occupied by documents that set the framework for safe operation and environmental compliance, including ISGOTT (6th edition) and MARPOL Annex VI, which establish global requirements for pollution prevention and formalize a safe ship–shore interface.

The theoretical part relies on fundamental tribological regularities for interpreting the processes occurring in the friction zone and under high-temperature exposure in the combustion chamber, including an explanation of lubrication regime transitions and factors of accelerated degradation of contact surfaces.

Results and Discussion

The global maritime logistics system in 2025 operates under the necessity of simultaneously ensuring the economic performance of transportation and compliance with tightening environmental constraints, violation of which is accompanied by sanction and financial consequences. The total volumes of dry cargo transportation in 2023 reached 7,2 billion tons, whereas the tanker segment exceeded 2,2 billion tons of petroleum products [4]. Such a demand configuration supports a stable need for traditional types of bunker fuel (HSFO, VLSFO); however, in parallel, an accelerated trajectory of expansion of the market for sustainable marine fuels (Sustainable Marine Fuel) is being formed, for which a compound annual growth rate at the level of 51,5% is projected up to 2034 [12].

Particular attention should be paid to low-viscosity marine fuel MGO, which retains the status of one of the key instruments for compliance with sulfur content requirements, primarily within emission control areas (ECA). In the largest bunkering hub of Singapore, MGO sales in 2024 reached the maximum value of 54,92 million tons, which is associated with an increase in container traffic and the need to comply with sulfur limits in regulated waters. At the same time, the regulatory architecture of FuelEU Maritime increases pressure on the fuel policy of shipowners, forming a practical need for the use of biofuel blends, including MFP-HFO — a composition of a fuel oil base with a biodiesel component or FAME [17].

Table 1 presents comparative physicochemical indicators of marine fuels.

Table 1. Comparative physicochemical indicators of marine fuels (compiled by the author on the basis of [12, 17]).

Parameter	**HSFO (Heavy Fuel Oil)**	**VLSFO (Very Low Sulfur Fuel Oil)**	**MGO (Marine Gas Oil)**	**MFP-HFO (Bio30)**
Sulfur content, % by mass	up to 3.50	up to 0.50	up to 0.10	0.35 - 0.45
Density at 15°C, kg/m³	980 - 1010	920 - 970	820 - 860	935 - 965
Kinematic viscosity at 50°C, cSt	180 - 700	10 - 380	2 - 6	30 - 320
Lower heating value, MJ/kg	39.45	40.50	42.70	39.45
Cost (average 2024), €/t	550 - 620	720 - 810	940 - 1050	812

As follows from the data of Table 1, the use of the Bio30 blend, containing 30% biofuel and 70% fuel oil, ensures the achievement of a zero compliance balance with the FuelEU Maritime requirements without the need to pay penalty charges; however, the level of operating expenditures (OPEX) under such a fuel solution remains higher in comparison with the operating mode on pure HFO [17]. The reliability of fuel operations is largely determined by the quality of personnel training: at the Kherson State Maritime Academy (KSMA), the educational process at the Faculty of Marine Power Engineering in the specialty 271.02 is built in strict accordance with the provisions of the STCW Convention and is aligned with the IMO model courses 7.02 (for the chief and second engineer) and 7.04 (for the watchkeeping engineer), which forms prerequisites for international recognition of qualification documents and labor mobility in various segments of the fleet [14]. The functional role of the 3rd engineer on board covers critically important elements of ensuring the sustainability of the fuel system: standing an engine-room watch, traditionally falling within the intervals 00:00–04:00 and 12:00–16:00; servicing auxiliary machinery, including fuel and lube oil separators, auxiliary boilers, and sewage treatment plants; maintaining inventory records in the Planned Maintenance System (PMS) with simultaneous monitoring of the operating parameters of the high-pressure fuel pumps; as well as ensuring compliance with MARPOL requirements when performing fuel operations. In operational interaction, the 3rd engineer in fact performs the functions of the key assistant to the second engineer, concentrating on the technical serviceability of purification systems and on preparing the main engines for maneuvering modes [7-11].

Bunkering procedures in international practice are regulated by the standard ISO 13739:2020 Petroleum products — Procedures for the transfer of bunkers to vessels, which, in conjunction with the ISGOTT 6 guidance, establishes the priority of the closed method of fuel receiving and the mandatory use of safety checklists (Bunker Checklist) as an instrument of risk controllability [9, 18]. The distribution of responsibility within the operation corresponds to the requirements of the ISM Code, clause 12: the master bears integral responsibility for the safety of the vessel and the prevention of pollution, the chief engineer carries out direct management of the process, ensuring the correct configuration of valves and the taking of representative samples, whereas the bunker fuel supplier is responsible for the quality of the product and the preparation of the Bunker Delivery Note (BDN) [9]. Separately, the requirement to retain fuel samples for 12 months is emphasized, which provides a procedural possibility for arbitral analysis when non-compliance with the parameters of ISO 8217 is identified [10]. In the domain of ship tank measurements, digitalization has led to the institutionalization of Automatic Tank Gauging (ATG) systems: the transition from manual sounding with a sounding tape to instrumental solutions, including the SELMA and Emerson Rosemount platforms, makes it possible to achieve measurement accuracy at the level of 98,3%. The modern measuring architecture usually combines hydrostatic sensors for ballast and service tanks, maintaining stability of readings under heel; 80 GHz radar level gauges for non-contact control in heavy fuel tanks and tanks with oil-containing cargoes, insensitive to variations in the density of the vapor phase; as well as electro-pneumatic systems implementing the bubbling principle and technologically optimal for sewage water and bilge wells. The results of the Aradel Holdings (2025) case study additionally confirm that the implementation of digital tank calibration databases reduces the probability of transcription errors and increases the efficiency of Hydrocarbon Accounting procedures [20].

Below, Figure 1 presents the evolution of the thermal efficiency of diesel engines.

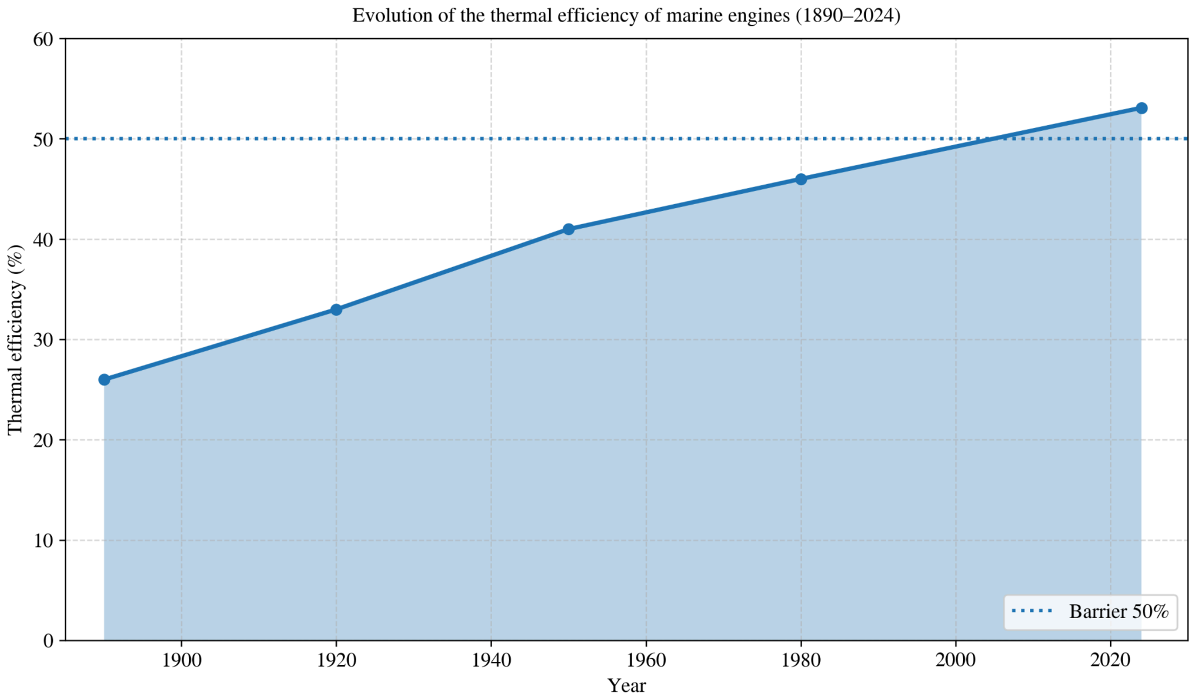

Fig. 1. Evolution of thermal efficiency of diesel engines (compiled by the author based on [4, 21])

Aluminosilicate catalytic fines (Al+Si), formed at oil refineries as a by-product of catalytic cracking processes, are considered one of the most hazardous factors of damage to the cylinder–piston group. Particles in the 1–75 μm range, possessing high hardness and an angular morphology, become embedded in the surface layer of cylinder liners and initiate an intensive abrasive wear mechanism [19, 22]. The ISO 8217 standard permits the content of such impurities at a level of up to 60 ppm; however, in operational practice, OEM criteria are significantly stricter: to minimize the risk of accelerated wear, it is necessary to reduce the concentration to values below 15 ppm before the fuel enters the engine inlet [23].

Below, Figure 2 presents the efficiency of Cat Fines removal depending on the regime (compiled by the author on the basis of [23-25]).

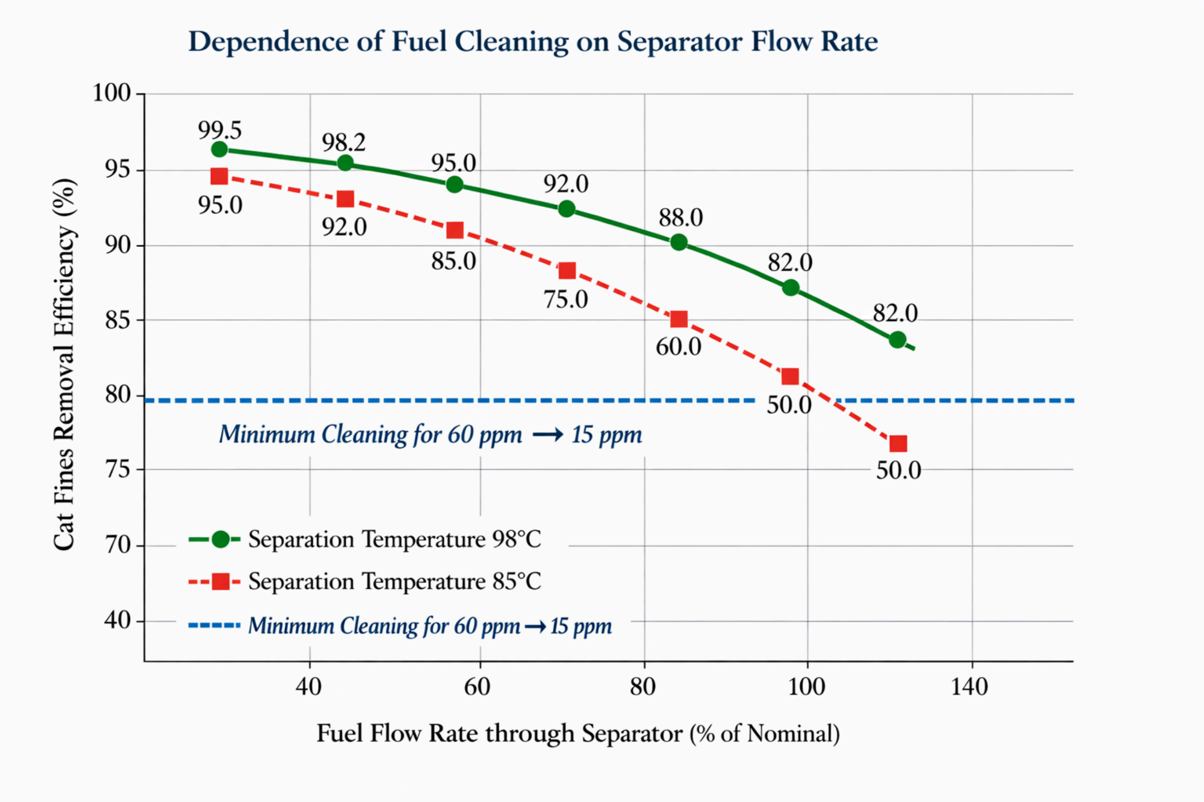

Fig. 2. Efficiency of Cat Fines removal depending on the regime (compiled by the author on the basis of [23-25]).

The analysis results presented in Figure 2 indicate that when the separator operates at the maximum throughput (100% flow), the degree of extraction of solid inclusions decreases below the threshold 85%, which is regarded as the minimum acceptable level for reducing fuel with an initial Al+Si concentration of 60 ppm to operationally safe values [23]. Additional deterioration is observed when the temperature is reduced to 85 °C: the separation efficiency decreases to approximately 50%, which effectively predetermines the accelerated development of damage and leads to engine failures within a horizon of several weeks [15]. At the same time, the transition to low-sulfur fuels (VLSFO) has formed a different category of risks associated with the absence of so-called beneficial corrosion: due to reduced acidity, microcavities that promote retention of the oil film do not form on the liner surfaces, which increases the probability of polishing of the working surface to a mirror state and the subsequent development of scuffing. Along with this, the digitalization of tank measurement loops, despite the increase in accuracy and controllability, is accompanied by cyber risks; the recommendations of the IMO and ABS on cybersecurity emphasize the need to protect data on stability and fuel levels from unauthorized access [9, 13, 16].

Table 2 presents the risk matrix of fuel preparation.

Table 2. Risk matrix of fuel preparation (according to IMO/ISO 2025 standards)

Risk factor	Consequence for the engine	Regulatory limit	Minimization method
Catalytic fines	Abrasive wear of cylinder liners	< 15 ppm (inlet to main engine)	Flow rate < 70%, T = 98°C
Incompatibility of batches	Filter clogging, sludge	ISO 8217 (Compatibility)	Preliminary testing
Water in fuel	Injector corrosion, cavitation	< 0.5% (settling tank)	Effective draining, separation
High Methane Slip	Environmental penalties under EU ETS	FuelEU Maritime	Combustion optimization (EGR)

Thus, it can be stated that maritime logistics in 2025 is developing under dual pressure, namely the need to maintain the economic efficiency of transportation while environmental requirements are simultaneously being tightened, where non-compliance is transformed into direct penalty and sanction costs: against the background of stable demand for traditional bunker fuels (HSFO/VLSFO) at the scale of global carriage (7,2 billion t of dry cargo and >2,2 billion t of tanker cargoes), an accelerated trajectory of transition to sustainable marine fuels is being formed (projected CAGR 51,5% up to 2034). Within the practical framework of compliance with sulfur restrictions, MGO remains a key instrument (including within ECA), as illustrated by peak sales in Singapore in 2024 (54,92 million t); however, the regulatory framework of FuelEU Maritime is already shifting shipowners' fuel policy toward bio-blends: according to the comparison of properties, the Bio30/MFP-HFO blend makes it possible to achieve the required zero compliance balance without penalties, but increases OPEX relative to operation on HFO. It is substantiated that the reliability of fuel operations is determined not only by the choice of fuel, but also by the quality of personnel training and the distribution of functions: training under STCW and IMO model courses forms personnel resilience, while the 3rd engineer acts as a critical link in ensuring the serviceability of purification/separation systems and compliance with MARPOL during bunkering. The operational bunkering process is structured by ISO 13739:2020 and ISGOTT/ISM (closed receiving, checklists, responsibility of the master/chief engineer/supplier, retention of samples for 12 months for arbitration under ISO 8217), whereas the digitalization of gauging (ATG platforms) increases accounting accuracy to ~98,3% and reduces the probability of errors, but adds cyber risks. Finally, the technical and operational block establishes that the principal severe factor of damage to the cylinder–piston group remains cat fines (Al+Si): with the ISO 8217 permissible limit of 60 ppm, the operationally safe level at the engine inlet must be <15 ppm, which requires an appropriate separation regime (flow limitation and temperature regime), otherwise the cleaning efficiency falls below the threshold; in parallel, the transition to VLSFO forms specific risks of polishing/scuffing due to changes in lubrication conditions, and the resulting risk matrix (Table 2) consolidates the key threats (cat fines, incompatibility of batches, water, methane slip) into specific regulatory limits and practical mitigation measures.

Conclusion

The obtained results indicate that, under the realities of 2025, the adjustment and operational optimization of a marine fuel system should be structured on the unconditional fulfillment of the requirements of ISO 13739:2020 and ISO 8217:2024. A critical parameter of engine durability and fault tolerance is the separation regime: maintaining a temperature of approximately 98 °C at a hydraulic load not exceeding 70% of the nominal ensures a stable reduction of the content of catalytic particles to the safe threshold of 15 ppm. At the same time, the implementation of digital redundant loops for automatic tank level gauging (ATG) forms a measurement basis for high-accuracy accounting reaching 98,3%, which becomes of fundamental importance when fulfilling the requirements of FuelEU Maritime and the EU ETS. Against the background of increasing complexity of technological and regulatory contours, the training of engineering personnel in accordance with the STCW Convention retains a determining role in accident prevention and the prevention of petroleum product spills. The systematized provisions have applied value for ensuring fail-safe operation of vessels under conditions of an accelerating energy transition and the consistent tightening of environmental constraints.

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