SECTION 9.
ENERGY AND POWER ENGINEERING

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THEORETICAL ANALYSIS OF THE EFFICIENCY OF MARINE DIESEL FUEL ALTERNATIVES

Abstract. *This study presents a theoretical investigation into the impact of various fuel types, including alternative and low-sulfur options, on the effective performance indicators of marine diesel engines. The primary objective is to identify the most efficient fuel type through mathematical modeling, thereby avoiding financial and time losses associated with physical testing. Calculations were conducted in the MATLAB environment for the 8ChSPN 18/22 engine, utilizing specific algorithms based on thermodynamic laws. Results indicate that standard diesel and gas turbine fuels provide the highest efficiency in terms of power output and fuel consumption. Conversely, the use of biodiesels leads to a reduction in effective power and an increase in brake specific fuel consumption. Ultimately, the study concludes that fuel selection must be based on a multi-factor approach considering technical-economic criteria and International Maritime Organization (IMO) environmental regulations.*

Introduction. This article presents a theoretical study of the impact on the performance indicators of marine diesel engines when operating on alternative low-sulfur fuels. In the modernizing world, alongside technological advancement, issues such as environmental pollution and global warming—manifested by rising average temperatures—are also developing. One of the sectors affected by this is maritime transport. Considering that approximately 75% of global transportation is carried out by sea, the scale of this issue becomes clear [1-13].

This suggests that even minimal changes can lead to significant economic fluctuations. When switching from one fuel to another, assuming all other conditions remain constant, it is observed that annual costs may differ by approximately 1 million USD [14-22]. The aim of this article is to determine the most cost-effective fuel based on theoretical analysis without incurring financial and time losses. For a healthier and safer future, it is essential to take necessary steps to minimize environmental damage across all sectors [23-29].

In scientific literature, the modeling of diesel engines has mainly developed in three directions [30-38]:

The first direction is based on classical thermodynamic approaches and describes the processes occurring inside the cylinder through differential equations representing the variation of pressure and temperature over time. These models enable analytical analysis of the engine cycle and are widely used to calculate key operational parameters such as power output, efficiency, and specific fuel consumption.

The second direction is characterized by numerical modeling and the use of computer-based simulation methods. In this approach, thermodynamic processes are modeled considering different fuel types, load regimes, and combustion characteristics. These simulation models are important not only for analyzing mechanical parameters but also for evaluating the composition of combustion products and their environmental impact.

The third direction involves modern control and optimization approaches. In this field, statistical models, neural networks, and artificial intelligence methods are used to analyze the nonlinear and dynamic behavior of the engine and to develop optimal control algorithms. These models enable not only prediction but also real-time control and adaptive regulation under varying operating conditions.

Methodology. In this study, several additions and modifications were applied to the model presented in [39-51], enabling the required experimental simulations to be conducted in a software environment. It should be noted that the adequacy of the original model has been verified [52-57]. However, since the program lacks explanations and is highly multi-parametric, careful attention and precision are required during calculations.

The engineering model used was developed in the MATLAB environment [58-66]. Its compatibility with real engine parameters was validated by comparison with the nameplate data of the Wartsila 6L20 diesel engine [67-73], and in this study, it was applied to the 8ChSPN 18/22 diesel engine.

Within the research framework, the operational and economic performance of the selected engine when operating on different fuels was evaluated using additional parameters introduced into the model. Eight different fuel types were selected and labeled as 1–8 (Table 1).

A computational algorithm based on mathematical modeling was developed to calculate the working cycle of the marine diesel engine and implemented in MATLAB. The model is based on the first law of thermodynamics, the conservation of mass, and the ideal gas equation of state. The resulting differential equations were treated as first-order and solved numerically using the Euler integration method [74-85].

Table 1

Average Elemental Composition and Lower Heating Value of Fuels. Fuels Considered (1–8)

Fuel	C	H	S	O	QH (MJ/kg)
Diesel fuel	0.863	0.133	0.003	0.001	42.654
Gas turbine fuel	0.846	0.12	0.028	0.005	41.271
Marine fuel oil (F-12)	0.865	0.122	0.008	0.005	41.418
Furnace fuel oil 40 (low sulfur)	0.879	0.109	0.005	0.007	40.768
Furnace fuel oil 40 (sulfurous)	0.865	0.108	0.02	0.007	40.287
Furnace fuel oil 40 (high sulfur)	0.851	0.107	0.035	0.007	40.078
Biodiesel – Soya	0.772	0.121	0.107	0.001	37.200
Biodiesel – WCO	0.768	0.12	0.012	0.002	36.843

Calculations were carried out through time discretization using Δ steps. During crankshaft rotation, the internal energy, temperature, volume, and pressure of the gas inside the cylinder were updated sequentially. Changes in internal energy were determined by considering mass inflows and outflows, heat released during combustion, heat losses through the walls, and mechanical work performed by the gases.

The current temperature was calculated based on changes in internal energy using average molar heat capacities at constant volume, while pressure was determined using the ideal gas equation. The piston position was calculated based on the geometry of the crank-slider mechanism, and cylinder volume and heat transfer surface areas were updated at each step.

Heat exchange between gases and cylinder walls during intake, compression, combustion, and expansion phases was modeled using an empirical heat transfer coefficient. Mechanical work was calculated using the pressure-volume relationship via trapezoidal integration.

Heat release during combustion was described using the empirical Vibe function. Combustion distribution, duration, and heat utilization were determined using empirical relations for nominal operating conditions. The composition of the working mixture (CO_2, H_2O, O_2, N_2, and fuel vapors) was updated continuously, and temperature-dependent heat capacities were calculated [86-89].

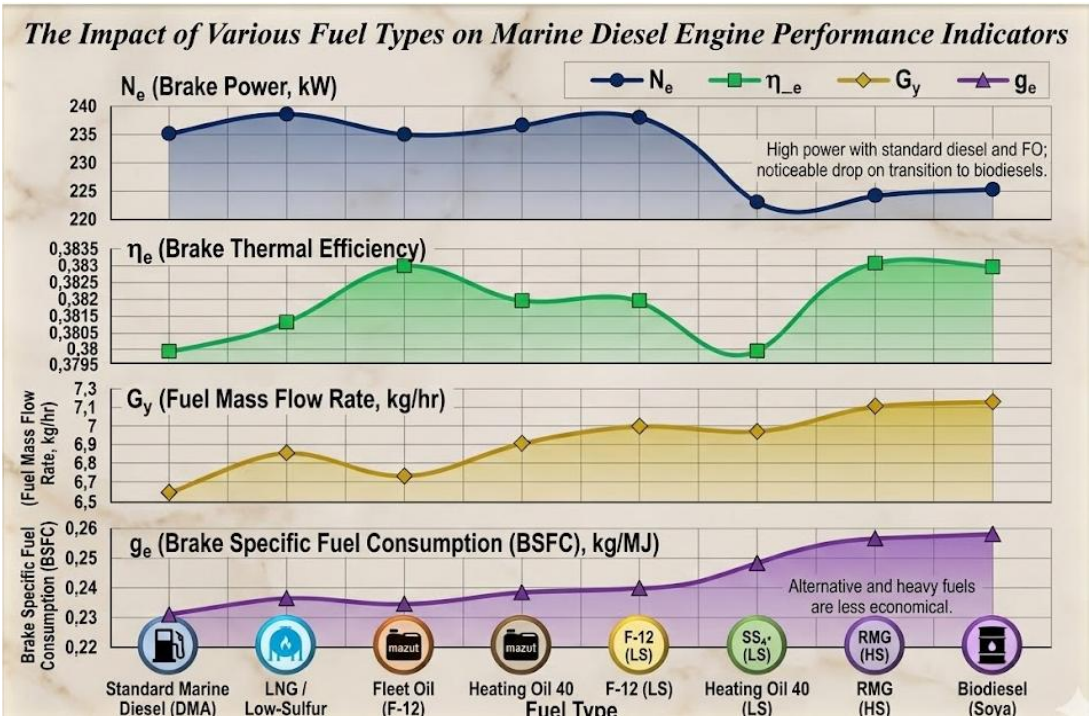

Fig. 1. **Dependence of hourly fuel consumption, effective specific fuel consumption, effective power, and efficiency on fuel type**

Key parameters such as injection pressure, injection timing (advance angle), and fuel density were considered. Their effects on combustion duration, ignition delay, heat utilization, and engine performance indicators were evaluated through numerical experiments.Simulations were conducted in MATLAB under nominal conditions. Variations in injection pressure, timing, and fuel density were analyzed to determine cylinder pressure and temperature profiles, as well as key indicators such as mean effective pressure, power, torque, and specific fuel consumption.

Results and Discussion. Comparative analysis shows that fuel type directly affects engine performance.

Effective power (N_e): Diesel fuel, marine fuel oil, and low-sulfur fuels show similar high values (≈235–240 kW). Biodiesel results in a noticeable decrease in power.

Specific fuel consumption (g_e): Lowest for diesel and gas turbine fuels. It increases with sulfur content and when switching to biodiesel, reducing efficiency.

Hourly fuel consumption (G_f): Higher for heavy and high-viscosity fuels, indicating more fuel is required to produce the same power.

As a result, diesel and gas turbine fuels are superior in terms of efficiency and economic performance. Heavy and alternative fuels (biodiesel) reduce effective power, increase fuel consumption, and make engine operation more demanding.

Therefore, fuel selection should be based on both technical and economic criteria.

Beyond the basic performance indicators, the modeling revealed significant variations in the cylinder pressure and temperature profiles depending on the fuel's physicochemical properties. When operating on heavy fuel oils (e.g., Furnace fuel oil 40) and biodiesels, the variations in fuel density and viscosity inherently affect the atomization process during injection. According to the simulation data, this leads to a prolonged combustion duration and a slight shift in the peak pressure away from the top dead center. Although the injection parameters were kept constant for baseline comparisons, this altered combustion phasing explains the underlying thermodynamic reasons for the observed drop in efficiency and the increase in specific fuel consumption for these alternative fuels.

Furthermore, interpreting these results strictly through an economic and power-generation lens provides an incomplete picture without considering the stringent International Maritime Organization (IMO) environmental regulations. While standard diesel demonstrated optimal efficiency, the elemental composition of high-sulfur fuels poses a direct challenge to compliance with IMO 2020 sulfur caps. Conversely, although biodiesels and low-sulfur furnace oils showed reduced effective power, their chemical structure (lower carbon and sulfur fractions) theoretically guarantees a significant reduction in SOx and, potentially, particulate matter emissions. This highlights a critical trade-off identified by the mathematical model: achieving environmental compliance inevitably requires accepting a certain degree of performance degradation unless engine calibration parameters—such as injection timing and injection pressure—are specially optimized for the alternative fuel in question. Therefore, the study demonstrates that a direct "drop-in" replacement of standard marine diesel with alternative fuels is thermodynamically sub-optimal, emphasizing the need for a multi-factor optimization approach rather than a simple fuel substitution.

Conclusions. Selecting the most environmentally and economically efficient fuel is a multi-factor problem and must also consider production processes and compliance with International Maritime Organization requirements.

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