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Performance Mapping and Fuel Efficiency Analysis of an LSCS Piston Diesel Engine under Injector Pressure Variation for Marine Applications

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Abstract—Fuel efficiency and stable engine performance are important issues in small diesel engines used for marine auxiliary systems, generator sets, and small vessel applications. Injector pressure and combustion chamber geometry affect fuel atomization, air–fuel mixing, combustion quality, and fuel consumption. This paper aims to investigate the effect of injector pressure variation on the performance and fuel efficiency of a four-stroke single-cylinder diesel engine equipped with a Lateral Swirl Combustion System (LSCS) piston. The injector pressure was varied at 170, 180, and 190 bar. The engine was tested at speeds of 1000, 1200, 1300, and 1400 rpm under electrical loads of 2000, 3000, and 4000 W. The main parameters evaluated were output power, torque, brake specific fuel consumption (BSFC), brake mean effective pressure (BMEP), and performance map characteristics. The results show that injector pressure influenced the performance and fuel efficiency of the LSCS piston diesel engine. The 190 bar injector pressure produced the best overall performance, with a maximum power of 2.72 kW, maximum torque of 18.65 N·m, lowest BSFC of 371.06 g/kWh, and highest BMEP of 1.95 bar. Compared with the 180 bar setting, the 190 bar injector pressure increased power by 1.87%, increased torque by 1.96%, reduced BSFC by 7.32%, and increased BMEP by 2.09%. The performance map also showed that the 190 bar setting provided the most favorable operating region, with relatively low BSFC and higher BMEP. These findings indicate that suitable injector pressure combined with LSCS piston geometry can improve combustion effectiveness and fuel efficiency in small diesel engines for marine-related applications.

Keywords— LSCS piston; injector pressure; diesel engine; BSFC; BMEP; performance mapping; marine applications.

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I. INTRODUCTION

Fuel efficiency remains a critical issue in the operation of diesel engines for marine-related applications. In small vessels, auxiliary power units, and marine generator systems, diesel engines are commonly operated under fluctuating speed and load conditions. Advancing main diesel injection and raising intake temperature at small loads improves misfire and raises effective power by ~5.9%, but increases NOx[1]. These operating patterns require stable combustion performance, adequate torque response, and efficient fuel utilization. Dual injector systems using a small pilot before main injection can raise thermal efficiency by ~6.1% and cut NOx by ~22% at low load[2]. Increasing injection pressure in ammonia–diesel dual-fuel operation raises mean effective pressure, thermal efficiency, and reduces specific fuel consumption[3]. Therefore, improving the combustion characteristics of small diesel engines is relevant not only for increasing engine performance, but also for reducing operational fuel consumption in maritime sectors[4]. Optimized cross spray and synchronous injection can raise indicated thermal efficiency by 3.2% and reduce BSFC by ~4.5% vs pure diesel, while improving combustion stability at high methanol share[5].

One of the important factors influencing diesel engine performance is the interaction between fuel injection characteristics and in-cylinder air motion. The quality of fuel atomization, spray distribution, and air–fuel mixing determines how effectively the chemical energy of the fuel is converted into useful mechanical output. When the injected fuel is not properly atomized or mixed with compressed air, the combustion process

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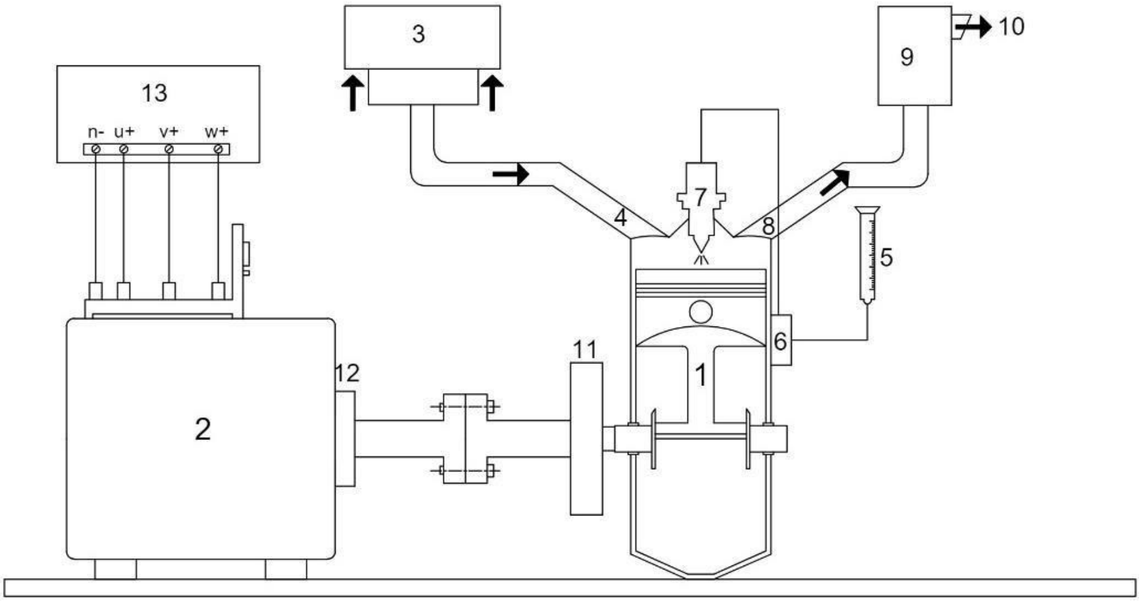
becomes less effective, which may reduce power output and increase brake specific fuel consumption. For this reason, optimization of injection parameters and combustion chamber configuration is an important approach in diesel engine performance improvement.

Combustion chamber geometry has a direct influence on the flow structure inside the cylinder. A piston chamber with an appropriate geometry can support air motion, improve fuel–air interaction, and promote more effective combustion. The Lateral Swirl Combustion System (LSCS) piston is one of the piston chamber concepts designed to generate lateral swirl motion during the combustion process[6]. This lateral motion is expected to intensify fuel–air mixing after fuel injection, thereby improving combustion quality and fuel utilization. In marine-related diesel engines, such improvement is important because the engine is often required to maintain performance under different load conditions[7]. For a four-stroke heavy-duty marine diesel, re-entrant and "−type" bowls increased cylinder power by up to 2.67%, cut specific fuel oil consumption by up to 1.60%, and reduced NO by up to 46% versus a U-type bowl, with little change in soot and CO_2[8]. Applying LSCS to opposed-piston two-stroke engines improves mixing uniformity, burn rate, power, and soot when the axial/radial use of space and convex-edge height are optimized for split-flow[9].



Description: 1. Jiangdong ZH1115N diesel engine; 2. generator; 3. air filter; 4. intake manifold; 5. measuring glass; 6. fuel pump; 7. injector; 8. exhaust manifold; 9. muffler; 10. exhaust gas outlet; 11. flywheel; 12. generator shaft; 13. load panel.
Figure. 1. Experimental setup of diesel engine–generator test rig

In addition to piston chamber design, injector pressure is also a key parameter affecting diesel engine performance. Different injector pressure settings can alter the spray pattern, droplet size, penetration behavior, and evaporation rate of the injected fuel. A suitable injector pressure may improve atomization and combustion stability, while an unsuitable setting may cause inefficient combustion or increased fuel consumption. Therefore, injector pressure variation needs to be evaluated experimentally to determine its effect on performance indicators such as power, torque, brake specific fuel consumption, and brake mean effective pressure.

Previous works have discussed diesel engine performance improvement through piston modification, fuel injection adjustment, and fuel consumption analysis. However, the combined evaluation of an LSCS piston chamber and injector pressure variation still requires further experimental investigation, particularly using a performance mapping approach. A performance map provides a broader interpretation of engine behavior because it relates operating speed, load, fuel consumption, and pressure characteristics in a single analysis framework. This approach is useful for identifying the most efficient operating region rather than only comparing individual performance values[10]. Based on this background, this study investigates the performance and fuel efficiency characteristics of a four-stroke single-cylinder diesel engine equipped with an LSCS piston under different injector pressure settings. The injector pressure was varied at 170, 180, and 190 bar, while the engine was tested at 1000, 1200, 1300, and 1400 rpm under electrical load variations of 2000, 3000, and 4000 W. The main parameters evaluated were power, torque, brake specific fuel consumption, and brake mean effective pressure, which are also used to construct and interpret the engine performance map. These variables follow the experimental design reported in the source material.

The contribution of this study lies in the experimental performance mapping of an LSCS piston diesel engine under injector pressure variation for marine application relevance. The study provides a practical comparison of injector pressure settings and identifies the operating condition that offers better fuel efficiency and engine performance. The results are expected to support further optimization of small diesel engines used in marine auxiliary systems, small vessel propulsion support, and generator-based maritime applications.

II. METHOD

A. Experimental Setup

The experimental work was conducted using a single-cylinder four-stroke diesel engine coupled with a three-phase generator and an electrical load bank. The test engine used in this study was a Jiangdong ZH1115N diesel engine, which represents a small diesel power unit suitable for laboratory-scale performance evaluation and relevant to small marine auxiliary power applications. The engine was selected because its operating characteristics allow controlled testing under different speed, load, and injector pressure conditions.

The diesel engine has a horizontal single-cylinder configuration with a direct injection combustion system. The main engine specifications include a 115 mm cylinder bore, 115 mm piston stroke, 17:1 compression ratio, and rated output of 14.7 kW at 2200 rpm. The standard injector pressure of the engine is approximately 18.13 ± 0.49 MPa, equivalent to about 185 ± 5 kgf/cm². The engine is equipped with a radiator cooling system and a combined pressure and splash lubrication system. These specifications provide the basis for evaluating the engine response after LSCS piston modification and injector pressure adjustment.

The engine was connected to a Mindong STC-5 three-phase generator to convert mechanical output into measurable electrical load. The generator has a rated capacity of 6.3 kVA, output power of 5 kW, voltage of 380/660 V, current of 5.5 A, power factor of 0.8, speed of 1500 rpm, frequency of 50 Hz, and four poles. During the experiment, the generator was connected to a lamp-based load bank to provide controlled electrical loading conditions.

TABLE 1.
MAIN SPECIFICATIONS OF THE TEST ENGINE AND GENERATOR.

Component	Specification
Engine model	Jiangdong ZH1115N
Engine type	Single-cylinder, horizontal, four-stroke diesel engine
Combustion system	Direct injection
Bore × stroke	115 mm × 115 mm
Compression ratio	17.01
Rated power	14.7 kW at 2200 rpm
Standard injector pressure	18.13 ± 0.49 MPa / 185 ± 5 kgf/cm²
Cooling system	Radiator cooling
Generator model	Mindong STC-5, three-phase
Generator output	5 kW / 6.3 kVA
Generator voltage	380/660 V
Power factor	00.08
Generator speed	1500 rpm
Frequency	50 Hz

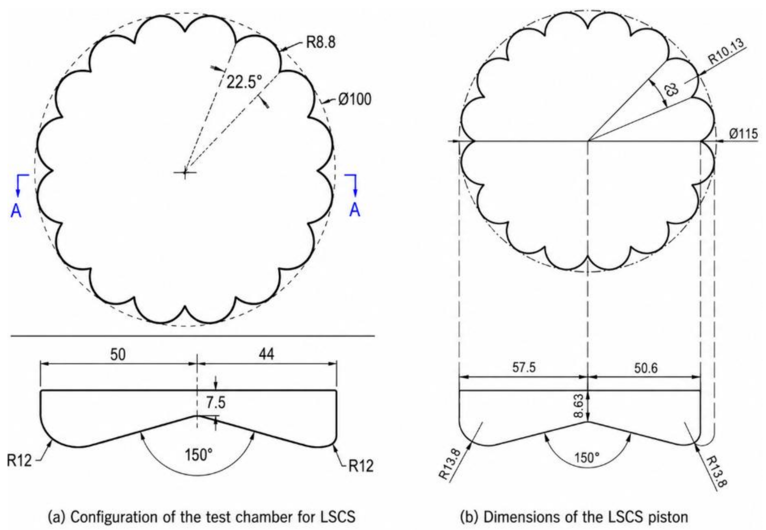


Figure 2. LSCS piston modification: (a) LSCS piston chamber concept and (b) modified piston chamber dimensions.

The experimental system consisted of the diesel engine, generator, air intake system, intake manifold, fuel pump, injector, measuring glass for fuel consumption measurement, exhaust manifold, muffler, flywheel, generator shaft, and load panel. This configuration was used to measure the operating response of the engine under different injector pressure settings. The primary measured variables included engine speed, fuel consumption time, output voltage, and output current. These measured values were then used to calculate engine performance parameters, including power, torque, brake specific fuel consumption, and brake mean effective pressure.

Before the performance test was carried out, the engine and loading system were inspected to ensure stable operation during data collection. The cooling system, generator load bank, electrical wiring, and measuring instruments were checked to minimize experimental error. The load bank was used to apply three load levels, namely 2000 W, 3000 W, and 4000 W, while the engine was operated at 1000, 1200, 1300, and 1400 rpm. The fuel consumption measurement was performed using a fixed fuel volume of 25 ml, and the time required to consume this volume was recorded for each test condition. The injector pressure was later varied at 170 bar, 180 bar, and 190 bar to evaluate its effect on engine performance and fuel efficiency.

The overall experimental setup was designed to simulate variable load operation of a small diesel engine under marine-related auxiliary power conditions. By using the generator-load bank arrangement, the study could evaluate how injector pressure and LSCS piston configuration influence performance output and fuel consumption across different operating points. This setup also supports the development of performance maps based on engine speed, load, BSFC, and BMEP.

TABLE 2.
EXPERIMENTAL TEST MATRIX.

Parameter	Variation / Value
Injector pressure	170, 180, 190 bar
Engine speed	1000, 1200, 1300, 1400 rpm
Electrical load	2000, 3000, 4000 W
Fuel volume for each test	25 ml
Measured variables	Voltage, current, fuel consumption time, engine speed
Calculated variables	Power, torque, BSFC, BMEP
Piston configuration	LSCS piston chamber

TABLE 3.
PERFORMANCE PARAMETERS EVALUATED IN THIS STUDY.

Parameter	Symbol	Unit	Purpose
Output power	P	kW	Engine output evaluation
Torque	T	N·m	Rotational performance evaluation
Brake specific fuel consumption	BSFC	g/kWh	Fuel efficiency indicator
Brake mean effective pressure	BMEP	bar	Effective pressure indicator

B. LSCS Piston Modification

The standard diesel piston was modified into a Lateral Swirl Combustion System (LSCS) piston to enhance the air–fuel mixing process inside the combustion chamber[11]. The LSCS chamber geometry was designed to generate lateral swirl motion when the injected fuel interacted with the piston bowl surface. [12]This flow behavior was expected to support more homogeneous combustion and improve fuel utilization[13].

The modification process consisted of three main stages. First, the LSCS piston chamber was designed using AutoCAD to obtain the required three-dimensional geometry. Second, the standard piston crown was prepared as the base component for chamber modification[14]. Third, the final LSCS chamber profile was produced using a CNC machining process. After machining, the modified piston was installed in the Jiangdong ZH1115N diesel engine for experimental testing under injector pressure variations of 170, 180, and 190 bar. The engine response was evaluated using power, torque, BSFC, and BMEP as the main performance parameters.

C. Injector Pressure Variation

Injector pressure was selected as the main experimental variable in this study because it directly affects the fuel spray characteristics, atomization quality, and combustion behavior of a direct injection diesel engine. In the experimental procedure, the injector pressure was adjusted into three levels, namely 170 bar, 180 bar, and 190 bar. These pressure levels were chosen to evaluate the engine response below, near, and slightly above the standard injector pressure range of the Jiangdong ZH1115N diesel engine.

The injector pressure adjustment was carried out before the engine performance test. A nozzle tester was used to check and set the injector opening pressure. The adjustment was performed gradually by modifying the injector spring compression through the adjusting mechanism until the pressure gauge indicated the required target pressure. After each adjustment, the injector was inspected to ensure stable fuel spray formation and to avoid leakage at the nozzle tip. This procedure was important to maintain consistency among the three injector pressure conditions.

After the target pressure was reached, the injector was installed on the test engine and the performance test was conducted under predetermined speed and load conditions. Each injector pressure setting was tested at 1000, 1200, 1300, and 1400 rpm, with electrical load variations of 2000, 3000, and 4000 W. For each test point, the output voltage, current, engine speed, and fuel consumption time were recorded. A fixed fuel volume of 25 ml was used to calculate the fuel consumption rate and brake specific fuel consumption.

The injector pressure variation was used to determine how changes in fuel injection pressure influence engine power, torque, brake specific fuel consumption, and brake mean effective pressure. The source material states that the injector pressure of the ZH1115N diesel engine was adjusted using a nozzle tester to obtain target pressures of 170, 180, and 190 bar, and the engine was then tested under different RPM and load conditions.

In this study, the LSCS piston was maintained as the fixed combustion chamber configuration, while injector pressure was varied as the control parameter. This arrangement allowed the effect of injection pressure on the LSCS piston diesel engine to be analyzed more clearly. The results from these variations were later used to construct the performance map and to identify the most efficient operating condition for marine-related diesel engine applications.

D. Testing Procedure

The experimental test was carried out after the LSCS piston installation and injector pressure adjustment. The injector pressure was varied at 170, 180, and 190 bar, while the engine was operated at 1000, 1200, 1300, and 1400 rpm under electrical loads of 2000, 3000, and 4000 W. These test conditions were applied using a generator connected to a lamp-based load bank.

Before data collection, the engine was operated until stable conditions were reached. At each test point, the output voltage, output current, engine speed, and the time required to consume 25 ml of fuel were recorded. The same procedure was repeated for each injector pressure setting and load condition. The measured voltage and current were used to calculate engine power, while the fuel consumption time was used to determine fuel consumption rate and BSFC. The calculated values were then used to analyze power, torque, BSFC, BMEP, and performance mapping characteristics.

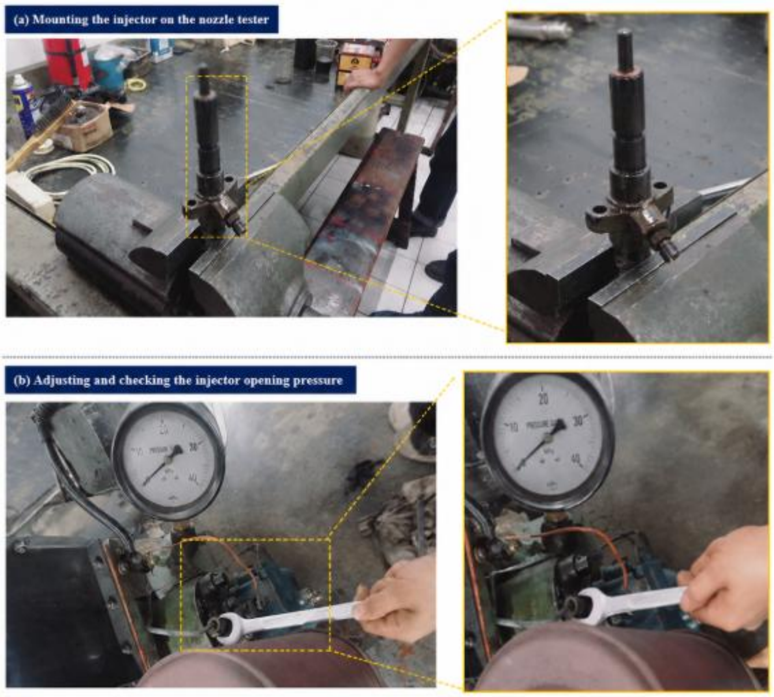


Figure 3. Injector pressure adjustment using a nozzle tester

E. Performance Parameters

The engine performance was evaluated using four main parameters: output power, torque, brake specific fuel consumption (BSFC), and brake mean effective pressure (BMEP). These parameters were selected because they represent the mechanical output, rotational response, fuel efficiency, and effective cylinder pressure characteristics of the LSCS piston diesel engine. The measured variables obtained during the experiment included engine speed, fuel consumption time, output voltage, and output current. These data were then processed to determine the performance characteristics of the engine under different injector pressure settings[15].

The electrical power generated by the engine–generator system was calculated from the measured voltage and current. Since the test system used a three-phase generator, the output power was determined using the following equation[16]:

$$P = \sqrt{3}\ x\ V x\ I\ x\ cos\varphi\ x\ \eta_{gen}\ x\ \eta_{tr} \quad (1)$$

Where:

P = is the output power (W),

V = is the generator output voltage (V),
I = is the output current (A),
Cosφ = is the power factor,
ηgen = is the generator efficiency, and
ηtr = is the transmission efficiency.

In this study, the power factor of the generator was 0.8, while the generator and transmission efficiencies were taken as 0.9 and 0.95, respectively[17]. The TA source also states that power calculation used voltage, current, power factor, generator efficiency, and transmission efficiency as the main variables.

The engine torque was calculated based on the relationship between output power and engine rotational speed. Torque was determined using the following equation[18]:

$$P = \frac{60 \ x \ P}{2\pi \ x \ N} \quad (2)$$

Where:
A

T = is torque (N·m),
P = is output power (W), and
N = is engine speed (rpm).

This parameter was used to evaluate the ability of the LSCS piston diesel engine to deliver rotational force under different load and injector pressure conditions[19].

Fuel consumption was determined from the time required by the engine to consume a fixed fuel volume of 25 ml. The fuel consumption rate was calculated using[20]:

$$mf = \frac{V_f x \ \rho f \ x \ 3600}{t} \quad (3)$$

Where:
m˙f =is the fuel mass flow rate (g/h),
Vf =is the fuel volume (ml),
ρf =is the fuel density (g/ml), and
t =is the fuel consumption time (s).

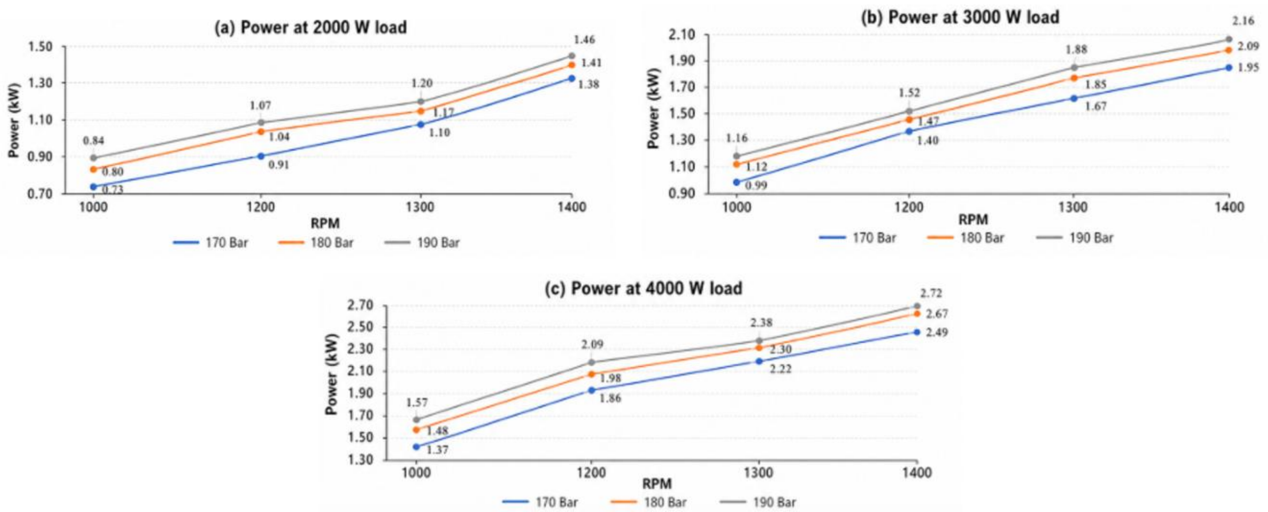


Figure 4. Engine power characteristics under injector pressure variation at different electrical loads: (a) 2000 W, (b) 3000 W, and (c) 4000 W.

This calculation was used to convert the measured fuel consumption time into the mass flow rate of fuel[21].

Brake specific fuel consumption was used as the main indicator of fuel efficiency. It shows the amount of fuel consumed to produce one unit of output power. BSFC was calculated as[22]:

$$BSFC = \frac{m_f}{P_b} \quad (4)$$

Where:
BSFC =is the brake specific fuel consumption (g/kWh),
m˙f = is the fuel mass flow rate (g/h), and
Pb =is the engine output power (kW).

A lower BSFC value indicates better fuel efficiency because less fuel is required to produce the same amount of power. In this study, BSFC was used as a key parameter for evaluating the effect of injector pressure variation on fuel efficiency[23].

Brake mean effective pressure was calculated to evaluate the average effective pressure acting on the piston during the power-producing process. BMEP was determined using[24]:

$$BMEP = \frac{P \ x \ z \ x \ 60}{V_d x \ N} \quad (5)$$

Where:
BMEP = is the brake mean effective pressure (Pa),
P =is output power (W),
Z =is the cycle factor for a four-stroke engine,
Vd = is the displacement volume (m³), and
N =is engine speed (rpm). Since the engine used in this study was a four-stroke engine, the cycle factor was adjusted according to the four-stroke operating cycle. The calculated BMEP values were used to interpret the effective pressure characteristics of the engine and to support the construction of the performance map.[25]

The calculated power, torque, BSFC, and BMEP values were then compared for each injector pressure condition. The experimental source confirms that the study evaluated these four parameters and used them to analyze the effect of injector pressure variations of 170, 180, and 190 bar on the LSCS piston diesel engine.

F. Performance Mapping

Performance mapping was used to evaluate the operating characteristics of the LSCS piston diesel engine under different injector pressure settings[26]. The map was developed from calculated performance parameters obtained at injector pressures of 170, 180, and 190 bar, engine speeds of 1000, 1200, 1300, and 1400 rpm, and electrical loads of 2000, 3000, and 4000 W. For each operating point, power, torque, BSFC, and BMEP were calculated from measured voltage, current, and fuel consumption time.

In this study, BSFC was used as the main fuel efficiency indicator, while BMEP was used to represent the effective pressure performance of the engine. The optimal operating region was identified from the condition that produced lower BSFC and higher BMEP. The performance maps were compared for each injector pressure setting to determine the most efficient configuration for marine-related diesel engine applications[27].

III. Results and Discussion

1. Effect of Injector Pressure on Engine Power

The variation of injector pressure produced a clear effect on the output power of the LSCS piston diesel engine. In general, the engine power increased as the injector pressure was raised from 170 bar to 190 bar. This trend indicates that a higher injector pressure improved the fuel delivery process, allowing better atomization and a more effective combustion process inside the LSCS piston chamber. The experimental results showed that the highest power was obtained at an injector pressure of 190 bar, with a maximum output of 2.72 kW. This value was higher than the power produced at lower injector pressure settings. The source data also reports that the 190 bar condition increased engine power by approximately 1.87% compared with the 180 bar injector pressure setting.

The increase in power at higher injector pressure can be associated with improved spray atomization. When the injector pressure is increased, the fuel tends to be broken into finer droplets. Smaller droplets have a larger surface area for evaporation and mixing with compressed air. In the LSCS piston chamber, this condition is beneficial because the lateral swirl motion can further support the distribution of fuel–air mixture inside the combustion chamber. As a result, the combustion process becomes more effective, producing higher pressure development and greater power output.

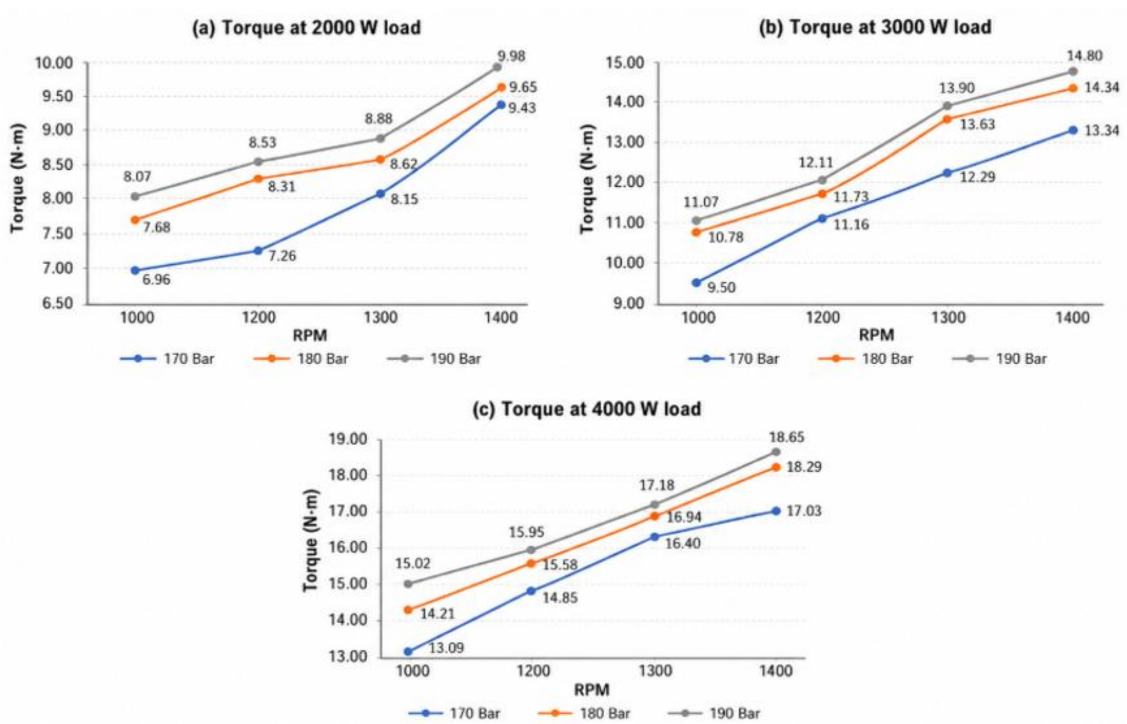


Figure 5. Torque characteristics of the LSCS piston diesel engine under injector pressure variation at different electrical loads: (a) 2000 W, (b) 3000 W, and (c) 4000 W.

The results also show that engine speed and load affected the power produced by the engine. At higher rotational speeds, the generator output generally increased because more combustion cycles occurred per unit time. Similarly, higher electrical load required greater engine response, which resulted in higher calculated output power. The best power performance was observed in the higher speed and load region, particularly at the 190 bar injector pressure setting. This confirms that the combination of LSCS piston geometry and higher injector pressure can improve engine performance under variable operating conditions.

Compared with the 170 bar and 180 bar settings, the 190 bar injector pressure provided the most favorable power characteristics across the tested operating range. At lower injector pressure, fuel atomization may be less effective, causing a slower mixing process and less complete combustion. This condition can limit the conversion of fuel energy into useful output power. In contrast, the 190 bar setting produced a stronger combustion response, which contributed to higher power generation.

From a marine application perspective, the improvement in power output is important for small diesel engines used in auxiliary power systems, generator sets, or small vessel applications. Marine diesel engines often operate under changing load conditions, and stable power delivery is required to maintain operational reliability. The result suggests that injector pressure optimization can support better power availability while maintaining the potential for improved fuel efficiency. However, the use of higher injector pressure should still consider the mechanical limits of the injector and engine components to avoid excessive wear or premature failure. The TA source also notes that although higher injector pressure improves performance, the mechanical capability of the injector and main engine components must be considered.

Overall, the experimental results indicate that increasing injector pressure up to 190 bar improved the power characteristics of the LSCS piston diesel engine. This finding supports the role of injector pressure as an important operating parameter in performance optimization. The 190 bar condition can therefore be considered the most effective injector pressure setting for improving engine power within the tested range.

2. Effect of Injector Pressure on Torque

Torque is an important indicator of the engine's ability to generate rotational force under different operating conditions. In this study, the torque characteristics of the LSCS piston diesel engine were affected by injector pressure, engine speed, and applied electrical load. The experimental results showed that increasing injector pressure from 170 bar to 190 bar generally improved the torque output. The highest torque was obtained at 190 bar, reaching 18.65 N·m, which was approximately 1.96% higher than the torque produced at the 180 bar injector pressure setting. This result indicates that the 190 bar injector pressure provided better combustion effectiveness in the tested LSCS piston diesel engine.

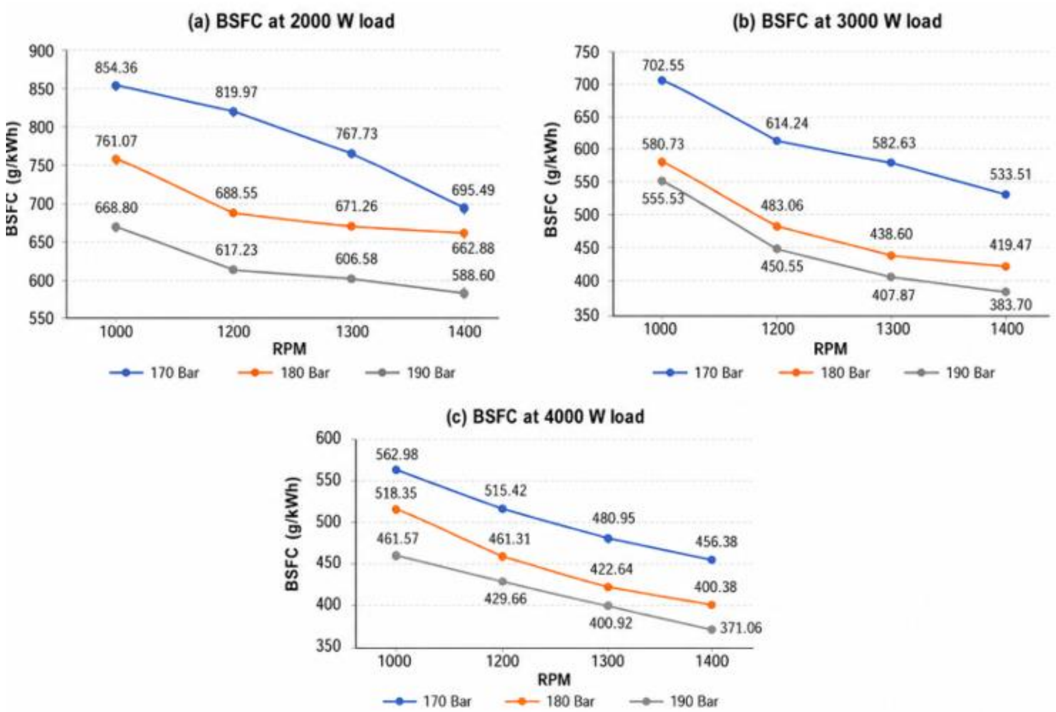


Figure 6. Brake specific fuel consumption characteristics under injector pressure variation at different electrical loads: (a) 2000 W, (b) 3000 W, and (c) 4000 W.

The improvement in torque can be related to the enhancement of fuel atomization at higher injector pressure. When the injector pressure increases, the fuel spray becomes finer and more widely distributed in the combustion chamber. This condition supports faster fuel evaporation and better interaction between fuel and compressed air. In the LSCS piston chamber, the lateral swirl motion can help distribute the fuel–air mixture more effectively, allowing combustion pressure to act more uniformly on the piston surface. As a result, the engine is able to produce greater rotational force at the crankshaft.

The torque response also varied with engine speed. In general, torque is influenced by the balance between output power and rotational speed. At lower-to-medium speed ranges, the engine tends to produce stronger torque because the combustion process has sufficient time to develop pressure during the power stroke. However, as engine speed increases, the available time for air–fuel mixing and combustion becomes shorter. Therefore, the injector pressure setting becomes important because better atomization can help maintain combustion quality even when the engine operates at higher speed.

The comparison among injector pressure settings shows that the 190 bar condition produced the most favorable torque characteristic. At 170 bar, the lower injection pressure may have resulted in less effective atomization, causing slower mixture formation and reduced combustion intensity. At 180 bar, the engine performance improved, but the torque output was still lower than that obtained at 190 bar. The 190 bar setting appears to provide a better balance between spray penetration, fuel atomization, and mixture formation inside the LSCS piston chamber.

From the perspective of marine applications, torque improvement is important because small marine diesel engines often operate under variable load demands. Auxiliary engines, generator sets, and small vessel propulsion support systems require sufficient torque to maintain stable operation when load changes occur. The increase in torque at 190 bar suggests that injector pressure optimization can improve the load response of an LSCS piston diesel engine. However, as with power performance, the practical use of higher injector pressure should still consider injector durability, fuel system capability, and long-term engine reliability.

Overall, the torque analysis confirms that injector pressure variation has a measurable influence on the rotational performance of the LSCS piston diesel engine. Among the tested pressure settings, 190 bar provided the best torque output and can be considered the most suitable injector pressure for improving engine torque within the tested operating range.

3. Fuel Efficiency and BSFC Analysis

Brake specific fuel consumption (BSFC) was used as the main indicator to evaluate the fuel efficiency of the LSCS piston diesel engine. BSFC represents the amount of fuel required to produce one unit of output power. Therefore, a lower BSFC value indicates better fuel utilization and higher fuel efficiency. In this study, injector pressure variation affected the BSFC characteristics of the engine under different speed and load conditions.

The experimental results showed that increasing injector pressure generally reduced BSFC. The lowest BSFC value was obtained at the 190 bar injector pressure setting, with a minimum value of 371.06 g/kWh. This value was approximately 7.32% lower than the BSFC obtained at the 180 bar injector pressure setting. This result indicates that the 190 bar injector pressure provided more efficient fuel utilization compared with the lower injector pressure settings. The source data also reports that the 190 bar condition produced the best overall fuel consumption performance among the tested injector pressures.

The reduction in BSFC at higher injector pressure can be explained by the improvement in fuel atomization. At lower injector pressure, the fuel droplets tend to be larger, which may slow down evaporation and reduce the uniformity of air–fuel mixing. As a result, part of the fuel may not burn effectively, leading to higher fuel consumption for the same power output. In contrast, the 190 bar injector pressure produces finer fuel droplets and improves spray distribution. This condition allows the fuel to evaporate and mix more effectively with compressed air before and during combustion.

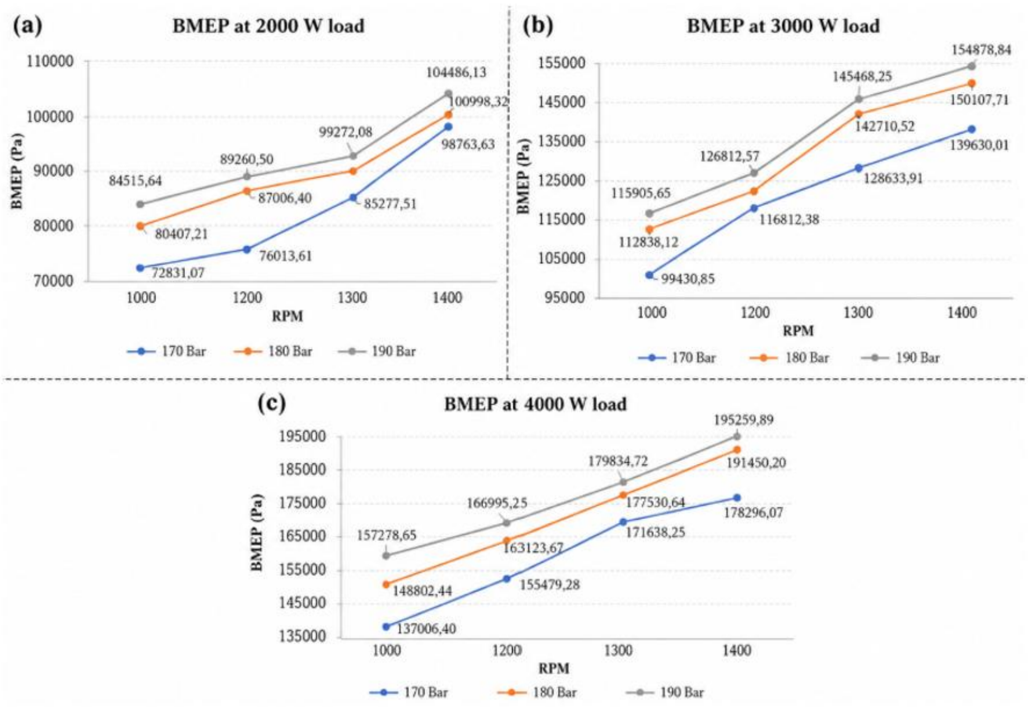


Figure 7. BMEP characteristics under injector pressure variation at different electrical loads: (a) 2000 W, (b) 3000 W, and (c) 4000 W

The LSCS piston chamber also contributes to the improvement of fuel efficiency. The lateral swirl motion generated by the modified chamber geometry supports the distribution of the fuel–air mixture inside the combustion chamber. When combined with higher injector pressure, the swirl effect can help improve combustion completeness and reduce unnecessary fuel consumption. This explains why the 190 bar setting produced lower BSFC while also improving power and torque.

The BSFC characteristics were also influenced by engine speed and applied load. At certain operating points, higher load operation can improve fuel efficiency because the engine output increases more significantly than the fuel consumption rate. However, if the engine operates outside its efficient region, BSFC may increase due to incomplete combustion, excessive fuel delivery, or insufficient time for mixture formation. Therefore, the BSFC trend should not be interpreted only from a single operating point, but should be evaluated together with engine speed, load, and BMEP through performance mapping.

For marine applications, the reduction of BSFC is highly relevant because fuel cost is one of the largest operational expenses in diesel-powered vessels and auxiliary systems. A lower BSFC indicates that less fuel is required to generate the same amount of power, which can improve operational economy in small marine diesel engines, generator sets, and auxiliary power units. The result suggests that adjusting injector pressure to 190 bar can improve the fuel efficiency of an LSCS piston diesel engine within the tested operating range.

Overall, the BSFC analysis confirms that injector pressure variation has a significant effect on fuel efficiency. Among the tested conditions, the 190 bar injector pressure provided the most efficient fuel consumption performance, as indicated by the lowest BSFC value. This finding supports the use of injector pressure optimization as a practical approach to improve fuel economy in LSCS piston diesel engines for marine-related applications.

4. BMEP Characteristics

Brake mean effective pressure (BMEP) was analyzed to evaluate the effective pressure generated during the engine power-producing process. Unlike power, which is strongly influenced by engine speed, BMEP provides a useful indication of the engine's ability to convert combustion pressure into useful work within the cylinder. Therefore, BMEP is an important parameter for comparing the combustion effectiveness of the LSCS piston diesel engine under different injector pressure settings.

The experimental results showed that injector pressure variation affected the BMEP characteristics of the engine. The highest BMEP was obtained at the 190 bar injector pressure setting, reaching 1.95 bar. This value was approximately 2.09% higher than the BMEP obtained at the 180 bar injector pressure setting. This result indicates that increasing injector pressure up to 190 bar improved the effective pressure development in the combustion chamber. The source material reports that the 190 bar injector pressure produced the highest BMEP, along with the best power, torque, and BSFC performance among the tested pressure conditions.

The increase in BMEP at 190 bar can be attributed to improved combustion intensity. Higher injector pressure promotes better fuel atomization, allowing the fuel to evaporate and mix more effectively with compressed air. In the LSCS piston chamber, the lateral swirl motion supports this mixing process by distributing the fuel–air mixture more evenly inside the combustion chamber. As a result, combustion pressure can develop more effectively and act on the piston during the power stroke, leading to higher BMEP.

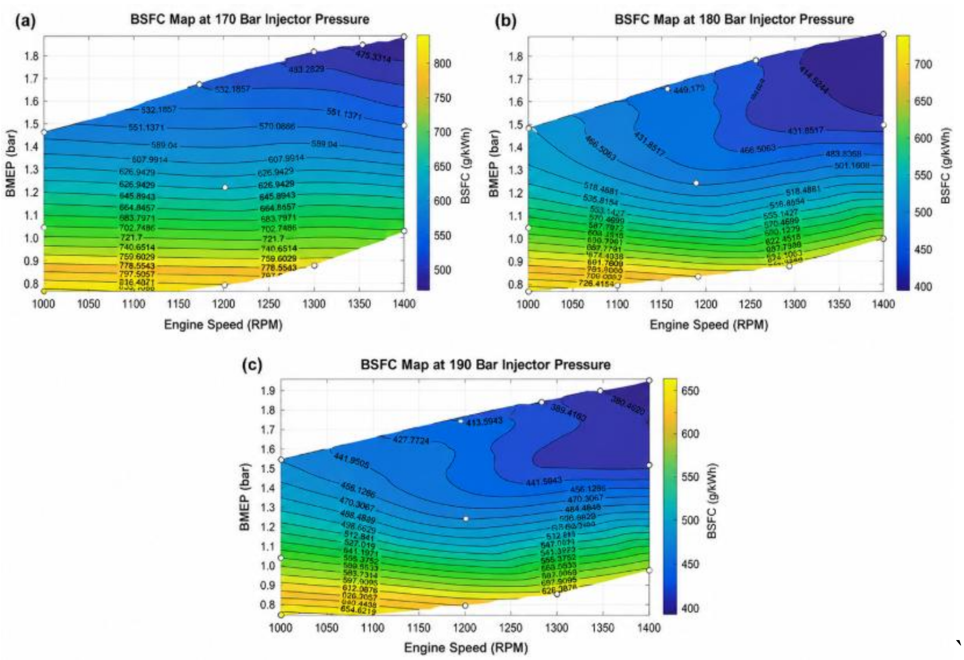


Figure 8. Performance maps of the LSCS piston diesel engine under injector pressure variation: (a) 170 bar, (b) 180 bar, and (c) 190 bar.

The BMEP trend also confirms the relationship between injector pressure, combustion quality, and engine load response. A higher BMEP value indicates that the engine can generate greater effective pressure for a given displacement volume. This is beneficial for small diesel engines used in marine-related applications, where the engine may be required to maintain stable operation under changing load conditions. In this study, the 190 bar injector pressure provided the most favorable BMEP characteristic, suggesting that this setting improved the load-carrying capability of the LSCS piston diesel engine.

Compared with the lower injector pressure settings, the 170 bar condition produced a weaker effective pressure response. This may be caused by less effective fuel atomization, which can limit the rate and completeness of combustion. The 180 bar setting improved BMEP, but the value was still lower than that of the 190 bar condition. Therefore, the experimental data suggest that the 190 bar injector pressure provided a better balance between spray atomization, mixture formation, and combustion pressure development within the tested range[28].

From a marine engineering perspective, BMEP is important because it reflects the engine's ability to produce useful work under load[29]. For auxiliary engines, generator sets, or small marine diesel systems, higher and more stable BMEP can support better operational reliability. The improvement in BMEP at 190 bar indicates that injector pressure optimization can contribute not only to higher output power, but also to more effective in-cylinder pressure utilization.

Overall, the BMEP analysis supports the previous findings on power, torque, and BSFC. The 190 bar injector pressure produced the most effective combustion response, as indicated by the highest BMEP value of 1.95 bar. This confirms that the LSCS piston diesel engine achieved better performance when operated with the 190 bar injector pressure setting within the tested operating range.

5. Performance Map Interpretation

Performance mapping was used to interpret the operating characteristics of the LSCS piston diesel engine under different injector pressure settings. Unlike single-parameter analysis, the performance map provides a broader view of the relationship between engine speed, load, fuel consumption, and effective pressure. In this study, the map was interpreted mainly through BSFC and BMEP, where lower BSFC indicates better fuel efficiency and higher BMEP indicates stronger effective pressure development during combustion.

The performance maps showed that injector pressure influenced the distribution of efficient operating regions. At lower injector pressure, particularly 170 bar, the engine showed less favorable performance because fuel atomization was relatively weaker. This condition may reduce the quality of fuel–air mixing and limit the effective combustion pressure generated in the cylinder. As a result, the engine required more fuel to produce the same amount of useful output, which was reflected in higher BSFC and lower BMEP trends.

At 180 bar, the performance map indicated an improvement compared with 170 bar. The fuel spray characteristics became more favorable, resulting in better combustion response and improved effective pressure. However, the engine had not yet reached its best operating condition. The BSFC and BMEP distribution still showed that the 180 bar condition was less efficient than the 190 bar condition, especially when the engine operated under higher load conditions.

The most favorable performance map was obtained at the 190 bar injector pressure setting. This condition produced the best combination of lower BSFC and higher BMEP. The experimental result showed that the optimal operating condition occurred at 190 bar, with BSFC around 385.2381 g/kWh and BMEP in the range of 1.8–1.9 bar. This indicates that the 190 bar injector pressure provided a more balanced combustion process, where fuel atomization, lateral swirl mixing, and pressure development occurred more effectively. The TA source also reports that the diesel engine fuel map showed the most optimal performance at 190 bar, with BSFC of 385.2381 g/kWh and BMEP around 1.8–1.9 bar.

The interpretation of the performance map supports the findings from the previous power, torque, BSFC, and BMEP analyses. The 190 bar injector pressure produced the highest power, highest torque, lowest BSFC, and highest BMEP within the tested range. Therefore, the map confirms that the improvement was not limited to a single performance indicator, but occurred consistently across several important parameters. This strengthens the conclusion that 190 bar is the most suitable injector pressure setting for the LSCS piston diesel engine in this experimental configuration.

From a combustion perspective, the better performance at 190 bar can be linked to improved spray atomization and mixture preparation. Higher injector pressure helps produce finer fuel droplets, while the LSCS piston chamber promotes lateral swirl motion that supports fuel–air interaction. The combination of these two effects improves combustion quality and allows the engine to produce higher effective pressure with lower specific fuel consumption.

For marine-related applications, performance map interpretation is useful because marine diesel engines often operate under varying speed and load conditions. A performance map helps identify the operating region where fuel consumption can be minimized without reducing engine capability. In this study, the map suggests that the LSCS piston diesel engine operated more efficiently at 190 bar, making this injector pressure setting more suitable for small marine auxiliary engines, generator systems, or small vessel diesel power units.

Overall, the performance map confirms that 190 bar was the optimal injector pressure among the tested variations. This pressure setting provided the most efficient operating region, characterized by relatively low BSFC and high BMEP. Therefore, performance mapping is effective for identifying not only maximum output, but also the most favorable fuel efficiency region of the LSCS piston diesel engine.

6. Relevance for Marine Applications

The results of this study are relevant to small marine diesel engines, auxiliary power units, and generator-based vessel systems that often operate under variable speed and load conditions. The experimental setup, which used different engine speeds and electrical loads, reflects the operating characteristics commonly found in small marine power applications. Therefore, the findings can provide practical insight into injector pressure optimization for improving engine response and fuel efficiency.

The 190 bar injector pressure produced the best overall performance, as indicated by higher power, higher torque, lower BSFC, and higher BMEP. This improvement suggests that better fuel atomization, when combined with the LSCS piston chamber, can enhance air–fuel mixing and combustion effectiveness. For marine applications, lower BSFC is particularly important because fuel consumption directly affects operating cost. In addition, improved torque and BMEP can support better load response in auxiliary generator systems and small vessel diesel engines.

However, the application of higher injector pressure should consider mechanical reliability and long-term durability of the injector, fuel pump, and combustion chamber components. Further studies involving emission measurement, long-duration testing, and real marine operating conditions are recommended to validate the applicability of this finding. Overall, the study supports the potential of LSCS piston modification and injector pressure optimization as practical approaches to improve the performance and fuel efficiency of small diesel engines for marine-related applications.

7. Discussion

The results show that injector pressure strongly influenced the performance and fuel efficiency of the LSCS piston diesel engine. The 190 bar injector pressure produced the best overall performance, with maximum power of 2.72 kW, torque of 18.65 N·m, BSFC of 371.06 g/kWh, and BMEP of 1.95 bar. This result indicates that increasing injector pressure within the tested range improved fuel atomization and combustion effectiveness.

TABLE 4.
SUMMARY OF BEST ENGINE PERFORMANCE UNDER INJECTOR PRESSURE VARIATION.

Injector pressure	Maximum power	Maximum torque	Lowest BSFC	Maximum BMEP	General performance
170 bar	2.49 kW	17.03 N·m	456.38 g/kWh	1.78 bar	Lower performance
180 bar	2.67 kW	18.29 N·m	400.38 g/kWh	1.91 bar	Moderate performance
190 bar	2.72 kW	18.65 N·m	371.06 g/kWh	1.95 bar	Best performance

TABLE 5.
PERFORMANCE IMPROVEMENT AT 190 BAR COMPARED WITH 180 BAR.

Parameter	Value at 190 bar	Improvement compared with 180 bar
Power	2.72 kW	+1.87%
Torque	18.65 N·m	+1.96%
BSFC	371.06 g/kWh	−7.32%
BMEP	1.95 bar	+2.09%

The improvement at 190 bar can be attributed to finer fuel droplets, faster evaporation, and better air–fuel mixing. The LSCS piston chamber also supported the combustion process by generating lateral swirl motion, which helped distribute the fuel–air mixture more effectively. As a result, the engine produced higher power and torque, while requiring less fuel per unit of output power.

The performance map confirmed that the 190 bar condition provided the most efficient operating region, with BSFC around 385.2381 g/kWh and BMEP in the range of 1.8–1.9 bar. This confirms that the 190 bar injector pressure improved not only individual performance parameters, but also the overall operating characteristics of the engine.

For marine applications, these findings are relevant because small diesel engines and auxiliary generator systems often operate under variable load conditions. Lower BSFC can reduce fuel consumption, while higher torque and BMEP can improve load response. However, the results are limited to a laboratory-scale single-cylinder diesel engine and should be further validated through emission testing, durability evaluation, and real marine operating conditions[30].

The novelty of this study is the experimental performance mapping of an LSCS piston diesel engine under injector pressure variation. Unlike previous studies that mainly evaluate diesel engine performance through separate indicators, this study integrates power, torque, BSFC, BMEP, and performance map interpretation to determine the most efficient operating region. The results show that the 190 bar injector pressure provided the best overall performance, with higher power, higher torque, lower BSFC, and higher BMEP compared with lower pressure settings.

This study contributes to the literature by demonstrating the combined role of LSCS piston geometry and injector pressure optimization in improving combustion effectiveness and fuel efficiency. The performance mapping approach also makes the results more actionable for real operational constraints, particularly in marine-related diesel engine applications where engines operate under variable speed and load conditions.

IV. CONCLUSION

This study investigated the effect of injector pressure variation on the performance and fuel efficiency of a four-stroke single-cylinder diesel engine equipped with an LSCS piston for marine-related applications. The injector pressure was varied at 170, 180, and 190 bar, while the engine was tested at different speed and load conditions. The engine performance was evaluated based on power, torque, brake specific fuel consumption, brake mean effective pressure, and performance map interpretation.

The experimental results showed that injector pressure variation affected the overall performance of the LSCS piston diesel engine. Among the tested pressure settings, the 190 bar injector pressure produced the best performance. This condition generated the highest power of 2.72 kW, the highest torque of 18.65 N·m, the lowest BSFC of 371.06 g/kWh, and the highest BMEP of 1.95 bar. Compared with the 180 bar setting, the 190 bar injector pressure increased power by 1.87%, increased torque by 1.96%, reduced BSFC by 7.32%, and increased BMEP by 2.09%.

The performance map also confirmed that the 190 bar condition provided the most favorable operating region, characterized by relatively low BSFC and higher BMEP. This result indicates that the combination of LSCS piston geometry and suitable injector pressure can improve fuel atomization, air–fuel mixing, combustion effectiveness, and fuel utilization. Therefore, injector pressure optimization can be considered a practical approach to improve the performance and fuel efficiency of small diesel engines for marine auxiliary systems, generator sets, and small vessel-related applications.

However, this study was limited to a laboratory-scale single-cylinder diesel engine and a specific injector pressure range. Further research should include exhaust emission analysis, in-cylinder pressure measurement, long-duration durability testing, and validation under real marine operating conditions to strengthen the practical applicability of the findings.

REFERENCES

[1] Y. Ding, M. Farrugia, Y. Peng, L. Xiang, and K. Scerri, 'Combustion performance optimization of marine diesel-natural gas dual-fuel engines under low operation loads', *J. Phys. Conf. Ser.*, vol. 2823, no. 1, p. 012013, Aug. 2024, doi: 10.1088/1742-6596/2823/1/012013.

[2] L. Liu, X. Wang, D. Liu, W. Mao, and F. Xiong, 'Research on combustion process optimization of marine diesel engines based on dual-injector system', *J. Phys. Conf. Ser.*, vol. 2683, no. 1, p. 012019, Jan. 2024, doi: 10.1088/1742-6596/2683/1/012019.

[3] Q. Wu, X. Liang, Z. Zhu, L. Cui, and T. Liu, 'Numerical Simulation Research on Combustion and Emission Characteristics of Diesel/Ammonia Dual-Fuel Low-Speed Marine Engine', *Energies (Basel).*, vol. 17, no. 12, p. 2960, Jun. 2024, doi: 10.3390/en17122960.

[4] T. D. Hountalas, M. Founti, and T. C. Zannis, 'Experimental Investigation to Assess the Performance Characteristics of a Marine Two-Stroke Dual Fuel Engine under Diesel and Natural Gas Mode', *Energies (Basel).*, vol. 16, no. 8, p. 3551, Apr. 2023, doi: 10.3390/en16083551.

[5] Z. Wang, J. Zhu, X. Liu, J. Zhong, and X. Jiang, 'Study on Combustion Characteristics of Compression Ignition Marine Methanol/Diesel Dual-Fuel Engine', *J. Mar. Sci. Eng.*, vol. 13, no. 11, p. 2213, Nov. 2025, doi: 10.3390/jmse13112213.

[6] H. Topkaya, M. Z. Işık, Y. Çelebi, and H. Aydın, 'Numerical analysis of various combustion chamber bowl geometries on combustion, performance, and emissions parameters in a diesel engine', *International Journal of Automotive Engineering and Technologies*, vol. 13, no. 2, pp. 63–72, Jun. 2024, doi: 10.18245/ijaet.1351644.

[7] D. Liu, X. Li, H. Shang, L. Xie, Y. Chen, and J. Chang, 'Combustion performance and fuel injection timing adaptability of a lateral swirl combustion system for direct injection diesel engines', *Fuel*, vol. 296, p. 120663, Jul. 2021, doi: 10.1016/j.fuel.2021.120663.

[8] V. C. Pham, J. K. Kim, W.-J. Lee, S.-J. Choe, V. V. Le, and J.-H. Choi, 'Effects of Piston Bowl Geometry on Combustion and Emissions of a Four-Stroke Heavy-Duty Diesel Marine Engine', *Applied Sciences*, vol. 12, no. 24, p. 13012, Dec. 2022, doi: 10.3390/app122413012.

[9] W. Yang, F. Li, F. Ma, and J. Xu, 'Numerical analysis of mixing and combustion characteristics of a lateral swirl combustion system in OP2S diesel engines', *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, vol. 238, no. 1, pp. 147–158, Jan. 2024, doi: 10.1177/09544070221121874.

[10] S. Milicevic and I. Blagojevic, 'Managing fuel consumption and emissions for hybrid electric vehicles through optimization of engine operation', *Thermal Science*, vol. 29, no. 5 Part A, pp. 3545–3560, 2025, doi: 10.2298/TSCI241124025M.

[11] J. Chang *et al.*, 'A method of matching the combustion chamber diameter based on spray characteristics for lateral swirl combustion system', *Fuel*, vol. 348, p. 128575, Sep. 2023, doi: 10.1016/j.fuel.2023.128575.

[12] D. Liu, X. Li, Z. Zhang, W. Zhao, and G. Yi, 'Visualization and analysis of the impinging spray and combustion characteristics in a lateral swirl combustion system (LSCS)', *Fuel*, vol. 351, p. 129003, Nov. 2023, doi: 10.1016/j.fuel.2023.129003.

[13] W. Yang, F. Li, F. Ma, and J. Xu, 'Numerical analysis of mixing and combustion characteristics of a lateral swirl combustion system in OP2S diesel engines', *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, vol. 238, no. 1, pp. 147–158, Jan. 2024, doi: 10.1177/09544070221121874.

[14] R. N. Garad, S. R. K. Hudgikar, and K. Maniyar, 'An Extensive Study on the Optimized Piston Bowl with Spiral Grooves for the CI Engine', *Journal of Mines, Metals and Fuels*, pp. 1389–1394, May 2025, doi: 10.18311/jmmf/2025/48016.

[15] M. N. Ayob, Ku Muhammad Muslih Bin Ku Ahmad Bistamam, Hassrizal Hassan Basri, Muhamad Safwan Muhamad Azmi, Siti Marhainis Othman, and Mohd Sani Mohamad Hashim, 'Development of 3-Phase Power Measurement Instrument', *International Journal of Autonomous Robotics and Intelligent Systems (IJARIS)*, vol. 1, no. 1, pp. 117–128, Aug. 2025, doi: 10.58915/ijaris.v1i1.2366.

[16] I. E. Yuliyanto, T. Tjendro, B. W. Harini, and M. Martanto, 'Input Power Measurement System For Driving Motor In Testing Low-Speed Generator', *International Journal of Applied Sciences and Smart Technologies*, vol. 5, no. 1, pp. 113–132, Jun. 2023, doi: 10.24071/ijasst.v5i1.6339.

[17] M. Li, J. Matas, J. El Mariachet, C. G. C. Branco, and J. M. Guerrero, 'A Fast Power Calculation Algorithm for Three-Phase Droop-Controlled-Inverters Using Combined SOGI Filters and Considering Nonlinear Loads', *Energies (Basel).*, vol. 15, no. 19, p. 7360, Oct. 2022, doi: 10.3390/en15197360.

[18] O. Bialobrzheskyi, A. Postil, and S. Yakimets, 'Accounting for a positive, negative and zero sequences power in a three-

phase unbalanced electrical system', *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, no. 6, pp. 93–99, Dec. 2023, doi: 10.33271/nvngu/2023-6/093.

[19] H. Dave, D. Solanki, and P. Naik, 'Effect of pilot fuel quantity and fuel injection pressure on combustion, performance and emission characteristics of an automotive diesel engine', *International Journal of Thermofluids*, vol. 21, p. 100570, Feb. 2024, doi: 10.1016/j.ijft.2024.100570.

[20] T. D. Hong, B. T. T. Hoang, T. Q. M. Ho, P. T. Truong, and M. Q. Pham, 'An experimental investigation on the performance of a single cylinder diesel engine at various partial loads', *Transportation Engineering*, vol. 18, p. 100288, Dec. 2024, doi: 10.1016/j.treng.2024.100288.

[21] M. K. Balki, 'Determination of Optimum Operating Parameters in a Non-Road Diesel Engine Fueled with 1-Heptanol/Biodiesel at Different Injection Pressures and Advances', *Energies (Basel).*, vol. 17, no. 7, p. 1588, Mar. 2024, doi: 10.3390/en17071588.

[22] Z. Aldarwish, M. H. Aghkhani, H. Sadrnia, and J. Zareei, 'Investigation of the optimal timing and amount of fuel injection on the efficiency and emissions of a diesel engine through experimentation and numerical analysis', *Heliyon*, vol. 10, no. 19, p. e38790, Oct. 2024, doi: 10.1016/j.heliyon.2024.e38790.

[23] C. Kalangi *et al.*, 'Performance optimization of ethanol blends in diesel model using Taguchi and grey relational approach', *Sci. Rep.*, vol. 15, no. 1, p. 36048, Oct. 2025, doi: 10.1038/s41598-025-20009-6.

[24] N. X. Khoa and O. Lim, 'Influence of Combustion Duration on the Performance and Emission Characteristics of a Spark-Ignition Engine Fueled with Pure Methanol and Ethanol', *ACS Omega*, vol. 7, no. 17, pp. 14505–14515, May 2022, doi: 10.1021/acsomega.1c05759.

[25] E. E. Onojowho, E. Betiku, and A. A. Asere, 'Performance and CO2 emission of a single cylinder compression ignition engine powered by Khaya senegalensis non-edible seeds fuel blends', *Heliyon*, vol. 10, no. 7, p. e28380, Apr. 2024, doi: 10.1016/j.heliyon.2024.e28380.

[26] R. Finesso, F. Guidotti, and S. d'Ambrosio, 'Estimation of Heat Release and In-Cylinder Pressure in Diesel Engines from Basic Testbed Data', *Energies (Basel).*, vol. 18, no. 22, p. 5912, Nov. 2025, doi: 10.3390/en18225912.

[27] S. Subramania, P. D. Kumar, R. Govindasamy, and M. S. Iyamperumal, 'Comparative Analysis of Cylinder-to-Cylinder Variation of Parameters of an Automotive CRDI Engine', *Archives of Thermodynamics*, pp. 105–115, Dec. 2025, doi: 10.24425/ather.2025.156841.

[28] D. K. Singh and J. V. Tirkey, 'Performance optimization through response surface methodology of an integrated coal gasification and CI engine fuelled with diesel and low-grade coal-based producer gas', *Energy*, vol. 238, p. 121982, Jan. 2022, doi: 10.1016/j.energy.2021.121982.

[29] O. N. Volintiru, D. Mărășescu, D. Coșofreț, and A. Popa, 'Aspects Regarding the CO2 Footprint Developed by Marine Diesel Engines', *Fire*, vol. 8, no. 6, p. 240, Jun. 2025, doi: 10.3390/fire8060240.

[30] S. As'ad *et al.*, 'Performance Comparison of Four-Stroke Diesel Engine Fuelled by Various Biodiesel Blends and Diesel', *Advances in Science and Technology Research Journal*, vol. 17, no. 4, pp. 46–52, Aug. 2023, doi: 10.12913/22998624/168257.