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Assessment of Engine Thermal Conditions on Combustion and Emissions: A Comprehensive Design-Oriented Experimental Investigation of Coolant and Lubricating Oil Temperature Variations in an Automotive Diesel Engine

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ABSTRACT

Engine thermal conditions play a decisive role in governing combustion behavior, efficiency, and pollutant formation in compression ignition engines, particularly under varying operating and warm-up conditions. While coolant temperature has traditionally been considered the primary thermal control parameter, the independent and combined influence of lubricating oil temperature on in-cylinder combustion and emissions remains insufficiently understood. This study presents a comprehensive, design-oriented experimental investigation into the effects of controlled coolant and lubricating oil temperature variations on combustion characteristics and exhaust emissions in an automotive diesel engine. Experiments were conducted on a four-stroke, direct-injection diesel engine equipped with independent thermal management systems for coolant and lubricating oil circuits, enabling precise regulation of their respective temperatures over a wide operational range. The engine was tested at selected steady-state operating conditions representative of typical automotive usage. High-resolution in-cylinder pressure measurements were employed to derive combustion metrics, including ignition delay, heat release rate, and combustion

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phasing parameters (CA10, CA50, and CA90). Concurrently, regulated gaseous emissions namely nitrogen oxides (NO_x), carbon monoxide (CO), unburned hydrocarbons (HC), and smoke opacity were measured using calibrated exhaust analyzers. The results demonstrate that both coolant and lubricating oil temperatures exert a significant and distinct influence on combustion dynamics and emission formation. Elevated coolant temperatures were found to increase in-cylinder wall temperatures, leading to reduced ignition delay, advanced combustion phasing, and enhanced thermal efficiency, albeit accompanied by increased NO_x emissions. In contrast, higher lubricating oil temperatures primarily affected mechanical and thermal boundary conditions by reducing lubricant viscosity and friction losses, which in turn improved combustion stability and reduced CO and HC emissions, particularly at lower loads. The coupled variation of coolant and oil temperatures revealed nonlinear interactions, highlighting the importance of coordinated thermal management strategies. The findings underline the critical role of integrated engine thermal control in balancing efficiency and emissions. From a design and control perspective, the study provides valuable insights into optimal thermal operating windows and supports the development of advanced coolant and oil temperature management strategies aimed at improving combustion performance and meeting increasingly stringent emission regulations.

Keywords: Diesel Engine; Thermal Management; Coolant Temperature; Lubricating Oil Temperature; Combustion Analysis; Exhaust Emissions.

Introduction:

Compression ignition (CI) diesel engines continue to occupy a critical position in the global transportation and industrial energy landscape due to their high thermal efficiency, robustness, and suitability for heavy-duty and long-haul applications. Despite rapid progress in electrification and hybrid powertrains, diesel engines remain indispensable in sectors such as freight transport, construction machinery, agricultural equipment, and power generation, where high energy density, operational reliability, and extended service life are essential. However, increasingly stringent emission regulations and growing environmental concerns have intensified the demand for advanced engine design and control strategies that simultaneously improve efficiency and reduce pollutant emissions. Engine combustion and emission characteristics are governed by a complex interplay of fuel properties, air–fuel mixing, injection strategy, in-cylinder flow dynamics, and thermal boundary conditions [1]. Among these, the thermal state of the engine plays a particularly decisive role. Engine thermal conditions influence ignition delay, combustion phasing, heat release rate, wall heat transfer, mechanical friction losses, and ultimately the formation of regulated exhaust emissions. In real-world driving, engines frequently operate under non-ideal thermal conditions, including cold start, warm-up, and transient load variations, during which deviations from optimal thermal equilibrium can significantly degrade combustion efficiency and increase emissions of nitrogen oxides (NO_x), carbon monoxide (CO), unburned hydrocarbons (HC), and particulate matter. Engine thermal management systems are therefore designed to regulate heat rejection and maintain components within safe and efficient temperature limits. Traditionally, coolant temperature has

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been treated as the primary indicator of engine thermal condition and has consequently been the focus of extensive experimental and numerical research. Variations in coolant temperature directly affect cylinder wall temperatures, in-cylinder gas temperature histories, and heat transfer rates, thereby influencing ignition delay, combustion duration, and combustion stability [2]. Numerous studies have demonstrated that elevated coolant temperatures generally shorten ignition delay and advance combustion phasing, resulting in improved thermal efficiency. However, these benefits are often accompanied by increased NO_x emissions due to higher peak combustion temperatures. Conversely, low coolant temperatures, particularly during cold-start operation, are associated with longer ignition delays, incomplete combustion, and increased CO and HC emissions. In contrast, lubricating oil temperature has received comparatively limited attention in combustion-focused studies, despite its fundamental role in engine mechanical and thermal behavior. Lubricating oil temperature strongly influences oil viscosity, friction losses, piston–liner lubrication regimes, and heat transfer between moving engine components [3]. At lower oil temperatures, increased viscosity leads to higher friction losses and poorer lubrication, which can adversely affect mechanical efficiency and combustion stability. At higher oil temperatures, reduced viscosity lowers friction losses but may also alter thermal boundary conditions and heat dissipation paths within the engine. Importantly, changes in oil temperature can indirectly influence combustion and emissions by modifying mechanical losses, component temperatures, and in-cylinder thermal environments. In practical engine operation, coolant and lubricating oil temperatures do not necessarily vary synchronously. During cold start and warm-up, coolant temperature typically rises more rapidly than oil temperature, while under sustained high-load operation, oil temperature may exceed coolant temperature. Despite this, many existing studies implicitly assume a coupled thermal behavior or treat oil temperature as a secondary parameter [4]. Furthermore, a significant portion of the literature investigates coolant or oil temperature effects in isolation, without systematically examining their combined and interacting influences on combustion and emissions. This limitation restricts the development of integrated thermal management strategies capable of optimizing efficiency, emissions, and durability simultaneously. To contextualize the current research and highlight existing gaps, Table 1 summarizes representative findings from previous studies investigating coolant and lubricating oil temperature effects in diesel engines.

Table 1: Summary of representative literature on coolant and lubricating oil temperature effects in diesel engines

Study focus	**Thermal parameter investigated**	**Key combustion effects**	**Emission trends**	**Major limitation**
Coolant temperature variation	Coolant temperature only	Reduced ignition delay; advanced combustion phasing	↑ NO_x, ↓ CO and HC at higher coolant temperatures	Oil temperature effects neglected

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Cold-start studies	Low coolant temperature	Delayed ignition; unstable combustion	↑ CO, HC, smoke	Limited steady-state relevance
Friction and efficiency analysis	Lubricating oil temperature only	Improved mechanical efficiency at higher oil temperatures	Indirect emission reduction	Limited combustion diagnostics
Combined thermal analysis (limited)	Coolant–oil coupled trends	General performance trends reported	Qualitative emission trends	Lack of independent control
Present study	Independent coolant and oil temperature control	Detailed combustion phasing and HRR analysis	Quantified NO_x, CO, HC, smoke	Focused on steady-state conditions

Beyond the limited scope of thermal parameter coupling, many prior investigations emphasize global performance indicators or exhaust emissions, while detailed combustion diagnostics remain scarce. High-resolution in-cylinder pressure analysis offers valuable insight into fundamental combustion phenomena, including ignition delay, heat release rate, and combustion phasing (CA10, CA50, CA90), which are directly influenced by engine thermal conditions. A comprehensive experimental framework combining controlled thermal boundary conditions with detailed combustion analysis is therefore essential to elucidate the underlying physical mechanisms governing observed performance and emission behavior. Motivated by these research gaps, the present study provides a comprehensive and design-oriented experimental assessment of the effects of coolant and lubricating oil temperature variations on combustion characteristics and exhaust emissions in an automotive diesel engine [5]. Independent thermal control of the coolant and lubricating oil circuits is employed to systematically isolate and analyze their individual and coupled influences under representative steady-state operating conditions. Detailed in-cylinder pressure measurements are used to derive combustion metrics, while regulated emissions are simultaneously quantified. The outcomes of this work aim to support the development of advanced, integrated engine thermal management strategies capable of balancing efficiency, emissions, and durability in modern diesel engines.

Influence of Engine Thermal Conditions on Diesel Combustion:

The thermal state of a diesel engine plays a governing role in compression ignition (CI) combustion by directly influencing in-cylinder thermodynamic conditions, fuel–air interaction, chemical reaction kinetics, and heat transfer mechanisms. Engine thermal conditions are primarily characterized by in-cylinder gas temperature, combustion chamber wall temperatures, and the associated heat transfer rates between the working gases and surrounding engine components. These parameters collectively

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determine the ignition delay period, the relative contribution of premixed and diffusion combustion phases, combustion stability, and overall combustion efficiency. During the compression process, higher in-cylinder gas temperatures enhance fuel evaporation and accelerate low-temperature chemical reactions preceding ignition. As a result, elevated engine thermal conditions typically reduce ignition delay and promote a more controlled and stable combustion process [6]. Shorter ignition delays limit excessive fuel accumulation prior to ignition, thereby moderating the intensity of the premixed combustion phase and reducing cycle-to-cycle variability. Several experimental studies have demonstrated that engines operating under higher thermal boundary conditions exhibit smoother pressure rise rates and improved combustion repeatability, particularly under low- and medium-load conditions. In contrast, low engine thermal conditions—commonly encountered during cold-start and warm-up phases significantly deteriorate combustion behavior. Lower wall and gas temperatures delay fuel evaporation and slow chemical reaction rates, leading to prolonged ignition delay and increased fuel accumulation before ignition. This often results in unstable combustion, higher cycle-to-cycle variations, and incomplete oxidation of fuel [7]. Additionally, increased heat losses to relatively cold combustion chamber walls further suppress in-cylinder temperatures, exacerbating combustion inefficiencies. These effects are particularly pronounced in modern diesel engines operating with advanced injection strategies and high exhaust gas recirculation (EGR) rates. Thermal boundary conditions also influence the relative contributions of premixed and diffusion combustion phases. Elevated engine temperatures tend to shift combustion toward a more diffusion-controlled regime by reducing the premixed fuel fraction, whereas lower temperatures increase the premixed burn fraction due to extended ignition delay. This shift has direct implications for pressure rise rates, combustion noise, and emission formation [8]. Furthermore, wall temperatures affect fuel impingement behavior and spray–wall interactions, which are critical for soot formation and late-cycle combustion processes. Beyond ignition and heat release characteristics, engine thermal conditions also affect heat transfer losses and indicated efficiency. Higher wall temperatures generally reduce temperature gradients between the combustion gases and engine components, lowering convective heat transfer losses and improving thermal efficiency. However, excessive thermal conditions may raise material durability concerns and increase nitrogen oxide (NO_x) emissions due to elevated peak combustion temperatures. Consequently, understanding the influence of engine thermal conditions on combustion requires a careful balance between efficiency, emissions, and component reliability. A summary of representative findings from previous studies investigating the influence of engine thermal conditions on diesel combustion is provided in **Table 2,** highlighting commonly reported trends and associated limitations.

Table 2: Reported effects of engine thermal conditions on diesel combustion characteristics

Thermal condition	**Dominant combustion effect**	**Observed combustion behavior**	**Implications**	**Key limitation in literature**

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High engine temperature	Accelerated ignition chemistry	Reduced ignition delay; stable combustion	Improved efficiency	Often neglects oil temperature
Moderate temperature	Balanced premixed/diffusion burn	Controlled heat release	Optimal performance window	Limited transient analysis
Low temperature (cold start)	Delayed fuel evaporation	Long ignition delay; unstable combustion	↑ CO, HC, smoke	Focused mainly on coolant effects
High wall temperature	Reduced heat loss	Higher indicated efficiency	Potential NO_x increase	Durability not always assessed
Low wall temperature	Increased heat transfer losses	Incomplete combustion	Efficiency penalties	Lack of detailed HRR analysis

To illustrate the mechanisms through which engine thermal conditions influence diesel combustion,

Figure 1 conceptually depicts the interaction between thermal boundary conditions, in-cylinder processes, and combustion outcomes.

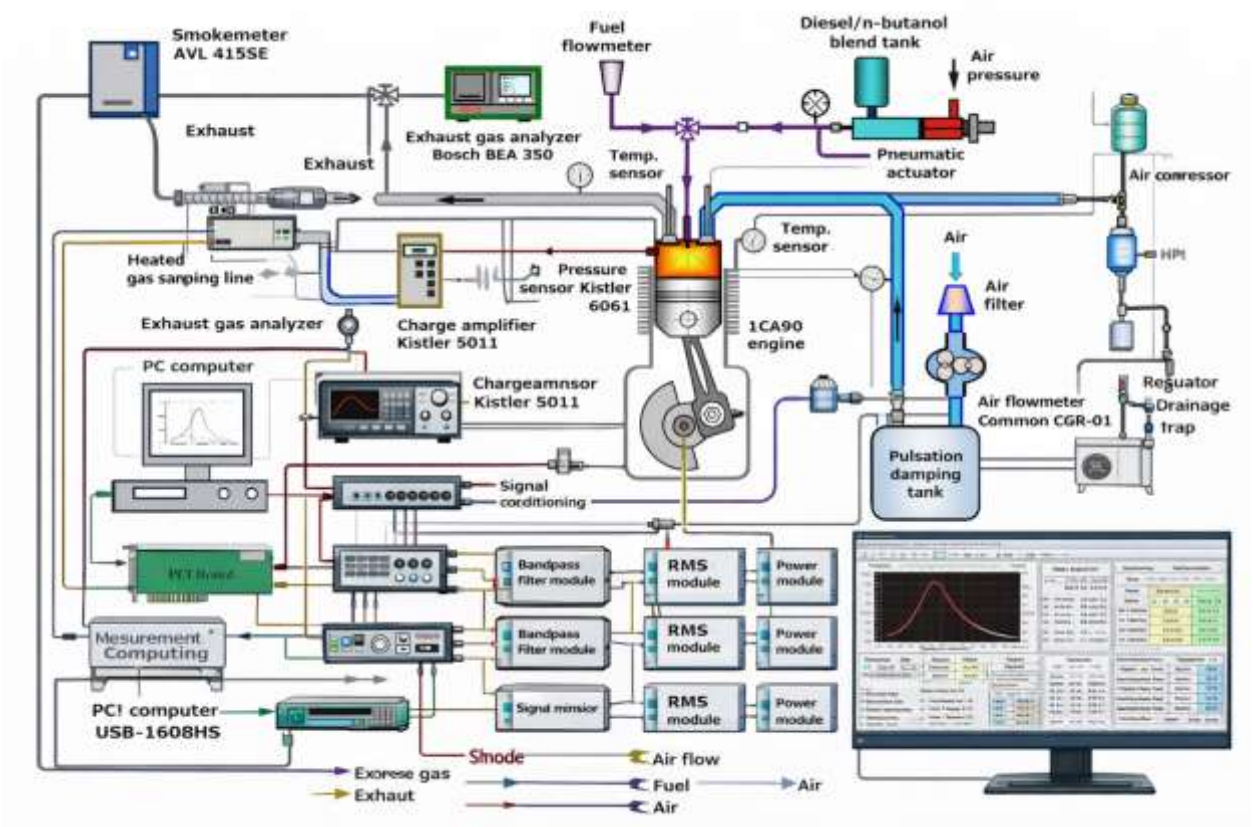


Figure 1: Conceptual illustration of the influence of engine thermal conditions on

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diesel combustion processes

Figure 1 illustrates the effect of engine thermal conditions on diesel combustion, highlighting the influence of coolant and lubricating oil temperatures on wall temperatures, in-cylinder gas temperature evolution, ignition delay, heat release rate, and combustion phasing. Elevated thermal conditions promote faster fuel evaporation and shorter ignition delay, leading to more stable combustion, whereas low thermal conditions result in delayed ignition, increased heat losses, and incomplete combustion. Overall, the reviewed studies clearly demonstrate that engine thermal conditions are a critical determinant of diesel combustion behavior. However, most existing investigations primarily focus on coolant temperature as a proxy for engine thermal state, while the role of lubricating oil temperature and its interaction with coolant temperature remain insufficiently explored [9]. Moreover, many studies emphasize global performance trends without integrating detailed combustion diagnostics such as heat release rate analysis and combustion phasing metrics. These limitations underline the need for comprehensive experimental investigations that systematically examine engine thermal conditions using independent thermal control and high-resolution combustion analysis, as undertaken in the present study.

Combined Effects of Coolant and Lubricating Oil Temperatures:

In practical diesel engine operation, coolant and lubricating oil temperatures evolve according to different thermal time constants and heat transfer pathways, resulting in asynchronous thermal behavior under most operating conditions. Coolant temperature is primarily governed by combustion heat rejection through the cylinder head and liner, whereas lubricating oil temperature is influenced by frictional heat generation, piston–liner interaction, bearing losses, and oil circuit heat exchange. As a consequence, the two thermal subsystems may differ substantially during cold start, warm-up, steady-state cruising, and high-load operation. Despite this inherent decoupling, many experimental and modeling studies implicitly assume a coupled thermal response, treating coolant temperature as a surrogate for overall engine thermal state [10]. The combined influence of coolant and lubricating oil temperatures on diesel combustion is inherently nonlinear due to their distinct yet interacting effects on in-cylinder thermal boundary conditions. Coolant temperature predominantly affects combustion chamber wall temperatures, heat transfer rates, and in-cylinder gas temperature evolution, thereby influencing ignition delay, combustion phasing, and thermal efficiency. Lubricating oil temperature, on the other hand, modifies mechanical friction losses, lubrication regimes, and component-level heat transfer, indirectly altering combustion stability and effective in-cylinder conditions [11]. When both parameters vary simultaneously, their combined impact on combustion cannot be described as a simple superposition of individual effects. Several studies have reported that during engine warm-up, rapid increases in coolant temperature accompanied by comparatively low oil temperatures can lead to mixed combustion behavior, characterized by reduced ignition delay but elevated friction losses and combustion instability. Conversely, under prolonged high-load operation, oil temperature may exceed coolant temperature, reducing mechanical losses but increasing heat transfer through oil-cooled components, thereby modifying in-cylinder thermal gradients. These contrasting scenarios highlight the importance of

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coordinated thermal control, particularly for engines employing advanced combustion strategies or operating under strict emission constraints. Existing literature that considers both coolant and oil temperatures often lacks independent thermal regulation, making it difficult to isolate their individual contributions. In many cases, oil temperature is allowed to follow coolant temperature passively, masking its specific influence on combustion and emissions. Studies that report combined effects frequently observe nonlinear trends in fuel consumption, combustion phasing, and emission formation, particularly for carbon monoxide (CO), unburned hydrocarbons (HC), and smoke. However, without independent control, the underlying interaction mechanisms such as friction–combustion coupling and wall heat loss modulation remain ambiguous [12]. The interaction between coolant and oil temperatures also plays a critical role in emission trade-offs. Elevated coolant temperatures tend to increase nitrogen oxides (NO_x) due to higher peak combustion temperatures, while higher oil temperatures often reduce CO and HC emissions by improving combustion stability and reducing quenching effects. When varied together, these competing mechanisms can either amplify or offset each other depending on operating conditions. Understanding these coupled effects is therefore essential for developing integrated thermal management strategies that balance efficiency, emissions, and durability. A summary of representative findings related to the combined effects of coolant and lubricating oil temperatures reported in the literature is provided in **Table 3,** highlighting key observations and existing limitations.

Table 3: Combined effects of coolant and lubricating oil temperatures on diesel engine behavior [13].

Thermal condition combination	**Observed combustion behavior**	**Emission trends**	**Reported interaction effect**	**Key limitation**
High coolant – low oil temperature	Advanced ignition with unstable combustion	↑ CO, HC	Friction–combustion mismatch	No independent oil control
Moderate coolant – moderate oil	Stable combustion	Balanced emissions	Near-optimal thermal window	Limited operating range
Low coolant – low oil (warm-up)	Long ignition delay; unstable HRR	↑ CO, HC, smoke	Strong nonlinear interaction	Mostly cold-start focused
High coolant – high oil	Short ignition delay; stable combustion	↑ NO_x, ↓ CO, HC	Synergistic thermal effects	Durability not addressed
Present study	Independently controlled coolant and oil	Quantified trends	Isolated interaction mechanisms	Steady-state focus

To conceptually illustrate the coupled influence of coolant and lubricating oil temperatures on diesel combustion and emissions, **Figure 2** presents a schematic

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representation of the interaction pathways between thermal subsystems and in-cylinder processes.

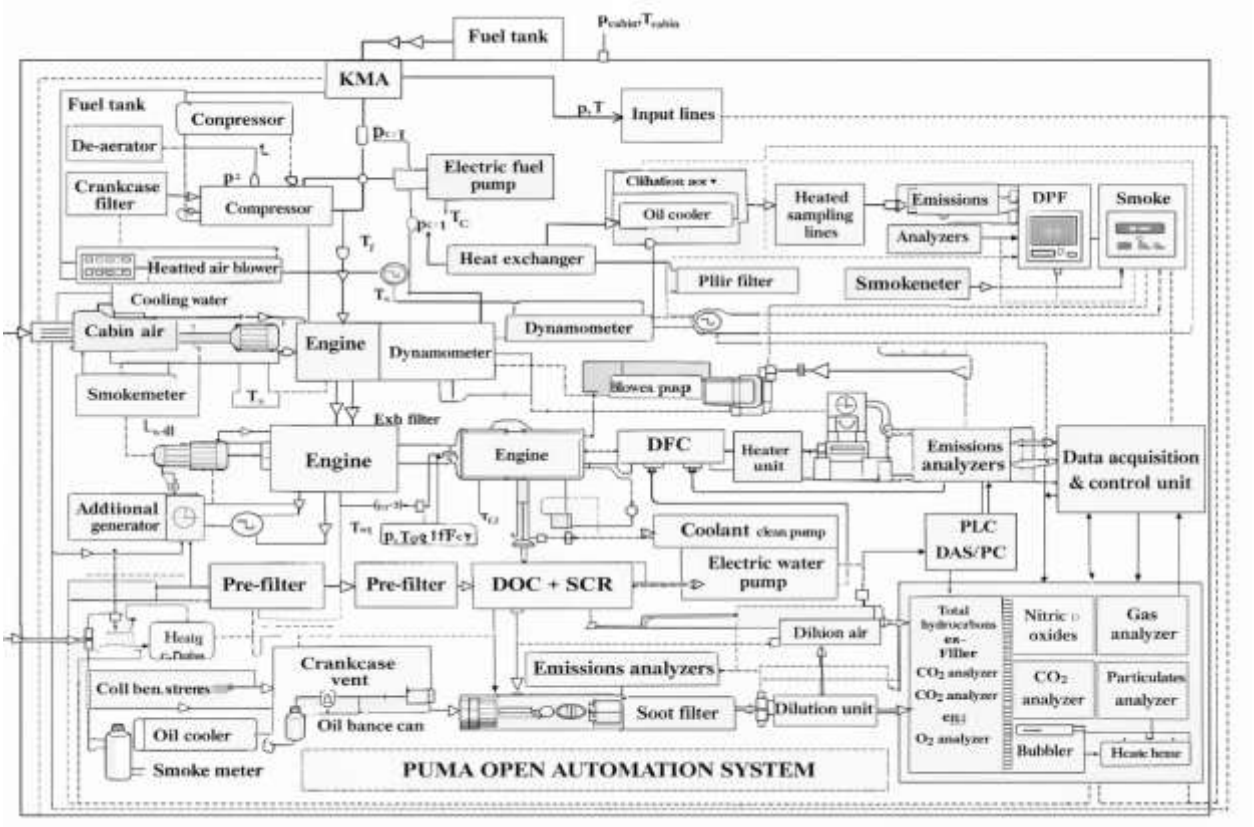


Figure 2: Combined coolant and lubricating oil temperature effects on diesel combustion and emissions

Figure 2 illustrates the coupled influence of coolant and lubricating oil temperatures on diesel engine combustion. Coolant temperature affects combustion chamber wall temperatures, in-cylinder gas temperature evolution, ignition delay, and NO_x formation, while lubricating oil temperature influences friction losses, lubrication regimes, component heat transfer, and combustion stability. Their interaction governs heat release rate characteristics, combustion phasing, and emission trade-offs, highlighting the need for coordinated thermal management strategies. Although previous studies acknowledge that coolant and lubricating oil temperatures jointly influence diesel engine behavior, the lack of independent thermal regulation has limited mechanistic understanding of their combined effects. Nonlinear interactions observed in combustion efficiency and emission formation underscore the inadequacy of treating either parameter in isolation [14]. A comprehensive experimental framework with independent control of coolant and oil temperatures, coupled with detailed combustion diagnostics, is therefore essential to elucidate the underlying interaction mechanisms and to support the development of advanced, integrated engine thermal management systems. The present study directly addresses these gaps through a systematic and design-oriented experimental investigation.

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Methodology:

This study employs a systematic and design-oriented experimental methodology to comprehensively investigate the individual and coupled effects of coolant and lubricating oil temperature variations on combustion behavior and exhaust emission characteristics in an automotive diesel engine. The experimental approach is founded on the implementation of independent thermal management systems for the coolant and lubricating oil circuits, enabling precise and stable regulation of thermal boundary conditions over a wide operating range. This independent control strategy overcomes the limitations of conventional engine configurations, in which oil temperature passively follows coolant temperature, and allows the distinct contributions of each thermal parameter to be isolated and analyzed. Throughout the experimental campaign, engine operating conditions including speed, load, fuel injection timing, and injection pressure are held constant to ensure that observed variations in combustion and emissions can be attributed solely to changes in thermal conditions. High-resolution in-cylinder pressure measurements are acquired using a piezoelectric pressure transducer synchronized with a high-precision crank angle encoder, providing detailed insight into cycle-resolved combustion processes. These pressure data are used to derive key combustion metrics such as ignition delay, apparent heat release rate, combustion duration, and combustion phasing parameters (CA10, CA50, and CA90), which collectively characterize the influence of thermal boundary conditions on combustion dynamics. In parallel, regulated exhaust emissions including nitrogen oxides, carbon monoxide, unburned hydrocarbons, and smoke opacity are measured using calibrated exhaust gas analyzers, enabling a comprehensive assessment of emission formation mechanisms under varying thermal states. All experiments are conducted under steady-state operating conditions, with sufficient stabilization time allowed to ensure thermal equilibrium of the engine, coolant, and lubricating oil systems prior to data acquisition [15]. This approach minimizes the influence of transient effects and enhances measurement repeatability and data reliability. The overall methodology integrates rigorous instrumentation, a structured and repeatable test matrix, and systematic data processing and uncertainty analysis to provide robust and physically interpretable insights into the coupled influence of engine thermal conditions on diesel combustion performance and emission behavior.

Experimental Engine and Test Facility:

The experimental investigation was conducted on a four-stroke, water-cooled, direct-injection automotive diesel engine installed on a fully instrumented engine test bench specifically configured for combustion and emission studies. The engine represents a conventional automotive diesel architecture and was selected to ensure relevance to real-world operating conditions while allowing accurate control and measurement of key parameters. The test bench was designed to provide a stable and controlled experimental environment, enabling systematic investigation of engine thermal effects with high repeatability. Engine speed and load were precisely regulated using an eddy-current dynamometer, which allowed smooth and continuous control across the selected operating points. The dynamometer was equipped with a torque measurement system of high accuracy, enabling reliable determination of brake power and

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facilitating consistent load control throughout the experimental campaign. During all tests, engine speed and load were maintained at fixed values to isolate the influence of thermal boundary conditions from other operating variables [16]. The test facility incorporated dedicated subsystems for fuel supply, air intake conditioning, exhaust handling, and thermal management. The fuel system ensured a constant fuel supply pressure and stable fuel temperature to eliminate variations in injection behavior unrelated to thermal effects. Intake air was drawn through an air conditioning unit that stabilized intake air temperature and pressure, thereby minimizing the influence of ambient fluctuations on combustion behavior. The exhaust system was designed with sufficient length and insulation to allow accurate emission sampling while preventing condensation and heat loss effects that could compromise measurement accuracy. Thermal management was a central feature of the experimental setup. The engine cooling system was integrated with an external coolant conditioning unit capable of precisely regulating coolant inlet temperature. Similarly, the lubricating oil circuit was modified to allow controlled heating and cooling of the oil independently of the coolant system [17]. This configuration ensured stable and repeatable thermal boundary conditions at the engine block, cylinder head, and moving components, forming the basis for investigating the coupled thermal effects addressed in this study. All experiments were performed under steady-state operating conditions. Prior to data acquisition, the engine was allowed to operate for a sufficient stabilization period to ensure thermal equilibrium of the coolant, lubricating oil, and engine structure. Steady-state operation minimized the influence of transient phenomena such as thermal inertia and warm-up effects, thereby improving data consistency and enabling direct comparison between different thermal test conditions. To provide a clear overview of the experimental arrangement,

Figure 3 presents a schematic representation of the engine test facility and associated subsystems.

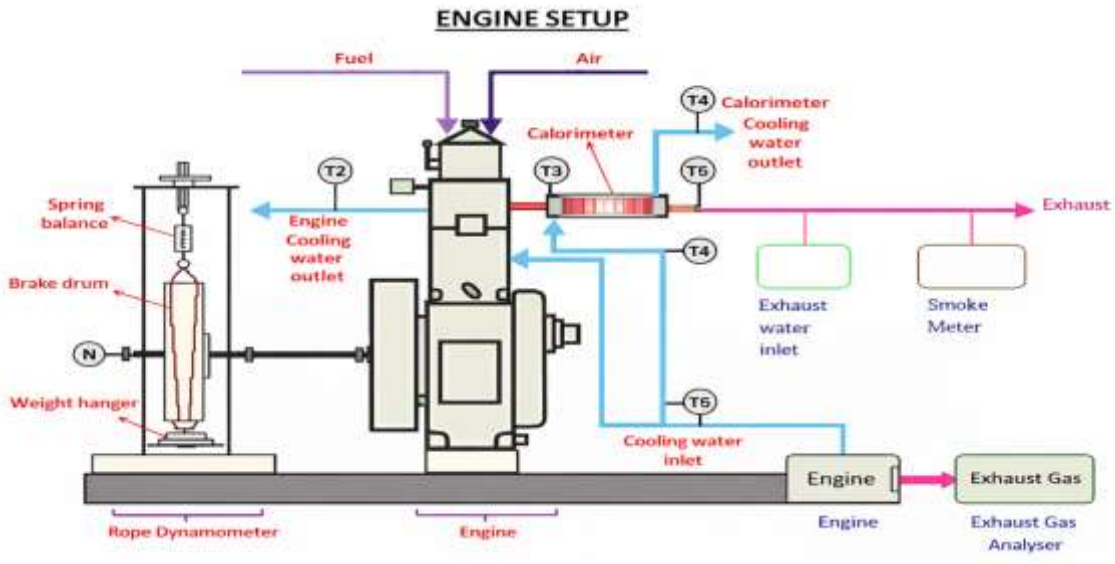


Figure 3: Schematic layout of the experimental engine and test facility

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Figure 3 illustrates the layout of the experimental engine test bench, including the diesel engine, eddy-current dynamometer, fuel supply system, intake air conditioning unit, exhaust handling and emission measurement system, and independent thermal management units for coolant and lubricating oil. The schematic highlights the key measurement locations and control interfaces used to regulate operating and thermal conditions during the experiments. Overall, the experimental engine and test facility were designed to provide a robust and repeatable platform for investigating the influence of engine thermal conditions on combustion and emissions. The combination of precise speed and load control, stabilized boundary conditions, and independently regulated thermal subsystems ensured that the observed combustion and emission trends could be confidently attributed to variations in coolant and lubricating oil temperatures rather than external disturbances or transient effects.

Independent Thermal Management of Coolant and Lubricating Oil:

To systematically investigate the individual and coupled effects of coolant and lubricating oil temperatures on diesel combustion and emissions, independent thermal management systems were implemented for both circuits. This approach was adopted to decouple the thermal behavior of the coolant and lubricating oil subsystems, which are inherently interlinked in conventional engine configurations. By enabling precise and independent control of each thermal circuit, the experimental setup allows the direct attribution of observed combustion and emission trends to specific thermal boundary conditions. The coolant circuit was modified to incorporate an external thermal conditioning unit consisting of a plate-type heat exchanger, an electric heating element, and a proportional control valve [18]. This configuration enabled accurate regulation of coolant inlet temperature supplied to the engine block and cylinder head. The proportional valve dynamically adjusted coolant flow rate based on feedback from temperature sensors, ensuring stable coolant temperature control under varying engine operating conditions. By regulating the coolant inlet temperature rather than relying solely on thermostat-based control, the system provided a wide and flexible temperature operating range, representative of cold, nominal, and elevated thermal conditions. In parallel, the lubricating oil circuit was independently modified to include an oil heating unit and a dedicated temperature control module. The oil heater was installed downstream of the oil pump, allowing controlled heating of the oil prior to circulation through critical engine components such as the crankshaft bearings, piston cooling jets, and valve train. Temperature sensors placed at the oil inlet and outlet ensured accurate monitoring and feedback control. This configuration enabled independent adjustment of oil temperature without passive thermal coupling to the coolant circuit, thereby overcoming a key limitation of conventional engine layouts in which oil temperature closely follows coolant temperature [19]. Independent regulation of coolant and oil temperatures allowed both parameters to be varied over predefined ranges, either individually or simultaneously, while all other engine operating variables were held constant. For each test point, sufficient stabilization time was provided to ensure that the target coolant and oil temperatures were achieved and maintained. Temperature stability within ±1 °C was consistently achieved prior to data acquisition, ensuring repeatability and minimizing thermal drift effects. This high level of thermal control was essential for isolating nonlinear

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interaction effects between the two thermal subsystems. The independent thermal management strategy also enabled investigation of realistic operating scenarios encountered in real-world driving [20]. For example, conditions corresponding to high coolant temperature with relatively low oil temperature, typical during early warm-up, as well as high oil temperature exceeding coolant temperature during sustained high-load operation, could be reproduced under controlled laboratory conditions. Such scenarios are difficult to isolate in conventional experimental setups but are critical for understanding the coupled influence of thermal boundary conditions on combustion stability and emission formation. Thermal control ranges and regulation characteristics employed in the present study is provided in **Table 4.**

Table 4: Thermal management parameters for coolant and lubricating oil circuits

Parameter	**Coolant circuit**	**Lubricating oil circuit**
Temperature control method	External heater + heat exchanger	Dedicated oil heater
Control strategy	Proportional feedback control	Closed-loop temperature control
Temperature measurement location	Coolant inlet to engine	Oil inlet to engine
Adjustable temperature range	Low–medium–high levels	Low–medium–high levels
Temperature stability	±1 °C	±1 °C
Passive coupling to other circuit	No	No

To clarify the configuration and interaction of the independent thermal control systems, **Figure 4** presents a schematic illustration of the coolant and lubricating oil circuits integrated with the engine test bench.

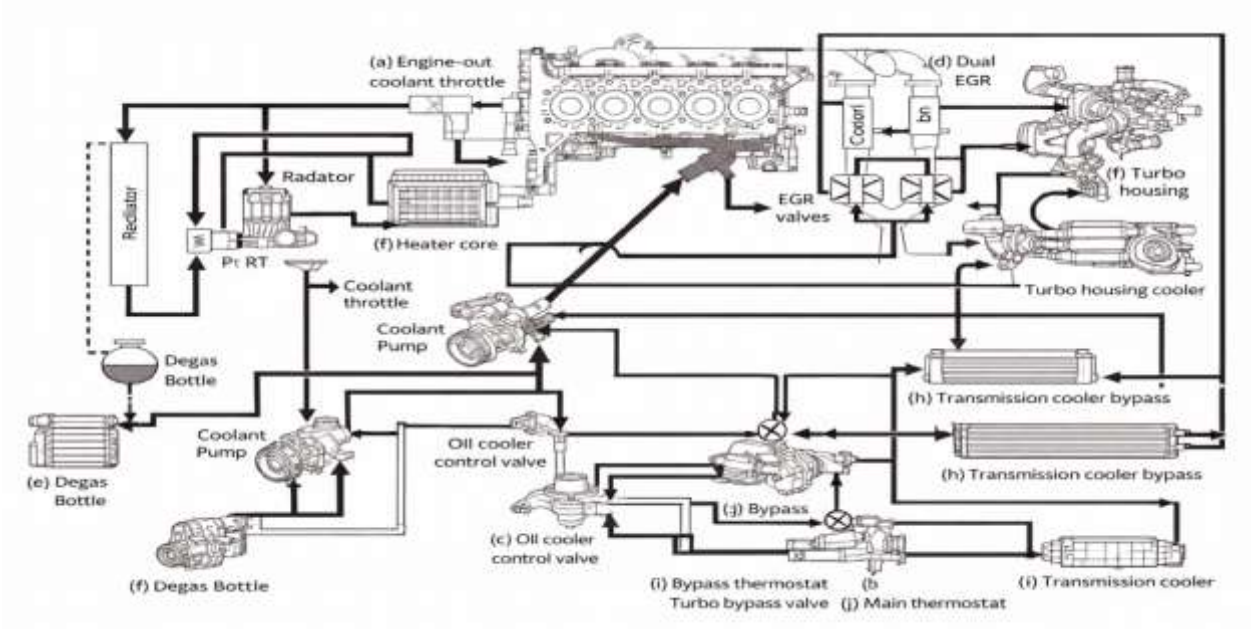


Figure 4: Independent coolant and lubricating oil thermal management systems

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Figure 4 illustrates the independent thermal management configuration employed in the present study. The coolant circuit includes an external heat exchanger, electric heater, proportional control valve, and temperature sensors regulating coolant inlet temperature to the engine. The lubricating oil circuit comprises an oil heater, temperature control unit, and sensor feedback loop, enabling independent regulation of oil temperature. The schematic highlights the decoupled nature of the two thermal circuits and their respective influence on engine thermal boundary conditions. Overall, the independent thermal management of the coolant and lubricating oil circuits constitutes a key methodological contribution of this study [21]. By enabling precise and stable control of both thermal parameters, the experimental setup provides a robust platform for isolating and analyzing their individual and combined effects on diesel combustion and emissions. This approach addresses key limitations in existing literature and supports the development of integrated engine thermal management strategies based on physically grounded experimental evidence.

Instrumentation and Data Acquisition:

Accurate and synchronized measurement of combustion, thermal, and performance parameters is essential for quantifying the influence of coolant and lubricating oil temperature variations on diesel engine behavior. In the present study, a comprehensive instrumentation and data acquisition system was employed to capture high-resolution in-cylinder combustion data alongside key thermal and operating parameters, ensuring reliable and repeatable experimental results. In-cylinder pressure was measured using a water-cooled piezoelectric pressure transducer mounted flush with the combustion chamber to minimize disturbance of the combustion process and avoid resonance effects [22]. The pressure transducer provided high temporal resolution and was selected for its suitability in high-temperature and high-pressure diesel combustion environments. Pressure measurements were synchronized with crank angle position using an optical crank angle encoder with high angular resolution, enabling precise correlation between pressure signals and engine cycle events. Pressure data were recorded over a large number of consecutive engine cycles at each test point and subsequently ensemble-averaged to reduce cycle-to-cycle variability and improve signal-to-noise ratio. Temperature measurements formed a critical component of the instrumentation system. Coolant and lubricating oil temperatures were measured at both the inlet and outlet of their respective circuits using calibrated K-type thermocouples. These measurements ensured accurate characterization of thermal boundary conditions and verification of temperature stability during each test condition. Intake air temperature was monitored upstream of the intake manifold, while exhaust gas temperature was measured downstream of the exhaust manifold to provide additional insight into combustion and heat rejection behavior. Engine performance parameters, including fuel flow rate and engine torque, were continuously monitored throughout the experiments [23]. Fuel consumption was measured using a precision fuel flow measurement system, while torque was measured directly through the dynamometer load cell. These measurements enabled accurate determination of engine operating consistency during thermal parameter variation and supported subsequent performance and efficiency analysis. All sensor signals were recorded using a high-speed, multi-channel data acquisition system

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capable of simultaneous sampling at appropriate frequencies for both fast-varying and steady-state signals. The data acquisition system ensured synchronized recording of pressure, temperature, and performance signals, allowing direct correlation between combustion events and thermal conditions. Prior to testing, all sensors were calibrated according to manufacturer specifications to ensure measurement accuracy and repeatability [24]. Key instrumentation and measurement characteristics employed in the present study is provided in **Table 5**.

Table 5: Instrumentation and measurement characteristics

Parameter measured	**Sensor type**	**Measurement location**	**Resolution / accuracy**
In-cylinder pressure	Piezoelectric pressure transducer	Combustion chamber	High temporal resolution
Crank angle position	Optical encoder	Crankshaft	High angular resolution
Coolant temperature	K-type thermocouple	Inlet and outlet	±1 °C
Lubricating oil temperature	K-type thermocouple	Inlet and outlet	±1 °C
Intake air temperature	Thermocouple	Intake manifold	±1 °C
Exhaust gas temperature	Thermocouple	Exhaust manifold	±1 °C
Fuel flow rate	Precision flow meter	Fuel supply line	Manufacturer-specified
Engine torque	Dynamometer load cell	Dynamometer shaft	±1% FS

Overall, the instrumentation and data acquisition framework provided a robust and synchronized measurement platform capable of capturing detailed combustion dynamics and thermal boundary conditions. The combination of high-resolution pressure measurement, precise thermal monitoring, and synchronized data acquisition ensured that the observed trends in combustion characteristics and emissions could be confidently attributed to variations in coolant and lubricating oil temperatures.

Combustion Analysis and Heat Release Calculation:

Detailed combustion analysis was conducted using ensemble-averaged in-cylinder pressure data to characterize the influence of coolant and lubricating oil temperature variations on diesel combustion dynamics. High-resolution pressure signals were acquired over multiple consecutive engine cycles at each test point and ensemble-averaged to minimize cycle-to-cycle variability and improve signal fidelity. The averaged pressure traces served as the basis for subsequent thermodynamic analysis, enabling robust estimation of heat release characteristics and combustion phasing metrics. The apparent heat release rate (HRR) was calculated from the averaged in-cylinder pressure data using a single-zone thermodynamic model based on the first law of thermodynamics. The working gas inside the cylinder was assumed to behave

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as an ideal gas with temperature-dependent specific heats, while spatial variations in temperature and composition were neglected. The apparent HRR was obtained by accounting for pressure–volume work and internal energy changes of the gas during the engine cycle. This widely adopted approach provides reliable insight into the timing and intensity of combustion while maintaining computational simplicity suitable for large experimental datasets. The crank-angle-resolved heat release rate profiles were used to identify key combustion phases and quantify fundamental combustion parameters. Ignition delay was defined as the crank angle interval between the start of fuel injection (SOI) and the onset of detectable heat release, which corresponds to the point at which the apparent HRR becomes consistently positive. This parameter characterizes the duration of the physical and chemical ignition processes and is highly sensitive to in-cylinder temperature and thermal boundary conditions. Combustion phasing was quantified using the cumulative heat release method, whereby the crank angles corresponding to 10%, 50%, and 90% of total heat release (CA10, CA50, and CA90) were extracted. CA10 represents the onset of the main combustion event, CA50 corresponds to the location of peak heat release and is commonly used as a key indicator of combustion timing, while CA90 denotes the near-completion of combustion [25]. The interval between CA10 and CA90 was defined as the combustion duration, providing a measure of combustion rate and completeness. These metrics enable direct comparison of combustion behavior under different thermal conditions and are particularly useful for assessing the effects of coolant and oil temperature variations on combustion stability and efficiency. In addition to combustion phasing, peak cylinder pressure, maximum pressure rise rate, and total released energy were also extracted from the pressure data to provide further insight into combustion intensity and dynamic loading. These parameters are critical for evaluating combustion noise, mechanical stress, and thermal efficiency trends under varying thermal boundary conditions. To illustrate the combustion analysis methodology, **Figure 5** presents a representative in-cylinder pressure trace and corresponding heat release rate profile, highlighting the extraction of key combustion metrics.

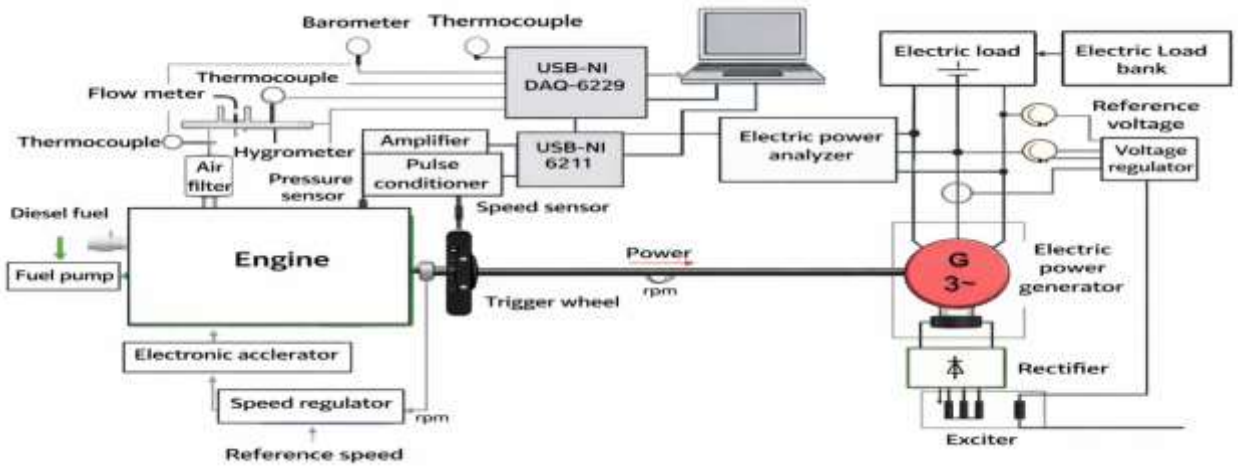


Figure 5: Representative in-cylinder pressure and heat release rate profiles with

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combustion parameter extraction

Figure 5 illustrates a typical ensemble-averaged in-cylinder pressure trace and the corresponding apparent heat release rate profile. The figure highlights the definition of ignition delay, as well as the determination of combustion phasing metrics CA10, CA50, and CA90 based on cumulative heat release. These parameters are used to quantify the influence of coolant and lubricating oil temperature variations on diesel combustion dynamics. Overall, the applied combustion analysis framework provides a comprehensive and physically grounded characterization of in-cylinder combustion behavior under varying thermal boundary conditions [26]. The use of high-resolution pressure measurements, coupled with systematic heat release analysis and standardized combustion metrics, ensures reliable assessment of how coolant and lubricating oil temperatures influence ignition processes, heat release characteristics, and combustion stability. This approach establishes a robust foundation for subsequent analysis of emission formation mechanisms and thermal efficiency trends.

Data Processing and Uncertainty Analysis:

All experimental data acquired during the test campaign were post-processed using standardized and repeatable procedures to ensure data consistency, accuracy, and reliability. Raw signals obtained from the data acquisition system were first screened for anomalies such as signal dropouts, spikes, or drift. Steady-state data segments were selected only after verifying that engine speed, load, coolant temperature, and lubricating oil temperature remained within predefined tolerance limits for a sufficient stabilization period. This approach ensured that the analyzed data accurately represented the intended thermal and operating conditions. In-cylinder pressure data were processed with particular care due to their critical role in combustion analysis [27]. Pressure signals were recorded over multiple consecutive engine cycles at each test point and ensemble-averaged to reduce the influence of random noise and cycle-to-cycle combustion variability. Prior to averaging, pressure traces were aligned with crank angle position using the encoder reference signal. Low-pass filtering was applied where necessary to suppress high-frequency noise without distorting combustion-related pressure features. The resulting ensemble-averaged pressure traces provided a robust basis for heat release analysis and combustion phasing calculations. Temperature, fuel flow, torque, and emission signals were processed using time-averaging techniques over steady-state intervals to minimize short-term fluctuations. All measured quantities were cross-checked to confirm consistency with expected physical trends, and data points exhibiting abnormal deviations were excluded from further analysis. Derived parameters, such as heat release rate and cumulative heat release, were calculated using consistent thermodynamic assumptions and numerical differentiation and integration schemes to ensure comparability across all test conditions. Measurement uncertainties associated with each sensor and measurement system were quantified based on manufacturer specifications, calibration certificates, and repeatability tests conducted prior to experimentation. Primary sources of uncertainty included in-cylinder pressure measurement, crank angle resolution, temperature sensing, fuel flow measurement, torque measurement, and emission analyzer accuracy. These uncertainties were treated as independent and combined using standard uncertainty propagation techniques to estimate the overall

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uncertainty of derived combustion parameters. Uncertainty propagation analysis was applied to key combustion metrics, including ignition delay, heat release rate, combustion duration, and combustion phasing parameters (CA10, CA50, and CA90). Partial derivative methods were used to assess the sensitivity of derived quantities to uncertainties in measured variables such as pressure, crank angle, and volume. This analysis ensured that reported differences between test conditions exceeded the associated uncertainty bounds and could therefore be attributed with confidence to variations in coolant and lubricating oil temperatures rather than measurement error. Main sources of measurement uncertainty and their estimated magnitudes is provided in **Table 6**.

Table 6: Measurement uncertainties and propagated errors

Parameter	**Measurement device**	**Typical uncertainty**
In-cylinder pressure	Piezoelectric transducer	±1% of full scale
Crank angle position	Optical encoder	±0.1° CA
Coolant temperature	Thermocouple	±1 °C
Lubricating oil temperature	Thermocouple	±1 °C
Fuel flow rate	Precision flow meter	±1–2%
Engine torque	Dynamometer load cell	±1% of full scale
Emission concentrations	Gas analyzers	Manufacturer-specified
Derived combustion phasing (CA50)	Calculated	±0.3–0.5° CA

The adopted data processing and uncertainty analysis methodology ensures a high level of confidence in the experimental findings. By combining rigorous signal conditioning, ensemble averaging, and systematic uncertainty propagation, the methodology provides a robust foundation for interpreting the effects of coolant and lubricating oil temperature variations on combustion characteristics and emissions. This approach strengthens the credibility of the reported trends and supports meaningful comparison with existing literature.

Results and Discussion:

The experimental results clearly demonstrate that engine thermal boundary conditions play a decisive and interconnected role in governing diesel combustion behavior and exhaust emission formation. Systematic variation of coolant and lubricating oil temperatures under steady-state operating conditions resulted in pronounced changes in ignition delay, heat release characteristics, combustion phasing, and regulated emissions, even though engine speed, load, and injection parameters were held constant. These observations confirm that thermal effects alone can significantly alter in-cylinder processes and underline the importance of coordinated thermal management strategies in modern diesel engines. Figure 6 presents representative ensemble-averaged in-cylinder pressure traces and corresponding apparent heat

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release rate profiles obtained at different coolant temperatures while maintaining a constant lubricating oil temperature. An increase in coolant temperature led to an earlier onset of combustion, as indicated by the advancement of both pressure rise and heat release initiation. This trend is primarily attributed to elevated combustion chamber wall temperatures, which reduce heat losses during the compression stroke and increase the in-cylinder gas temperature at the time of fuel injection. As a result, ignition delay decreased progressively with increasing coolant temperature, reflecting faster fuel vaporization and enhanced low-temperature oxidation kinetics. The shorter ignition delay limited excessive premixed fuel accumulation prior to ignition, producing a more controlled premixed combustion phase and reducing cycle-to-cycle combustion variability.

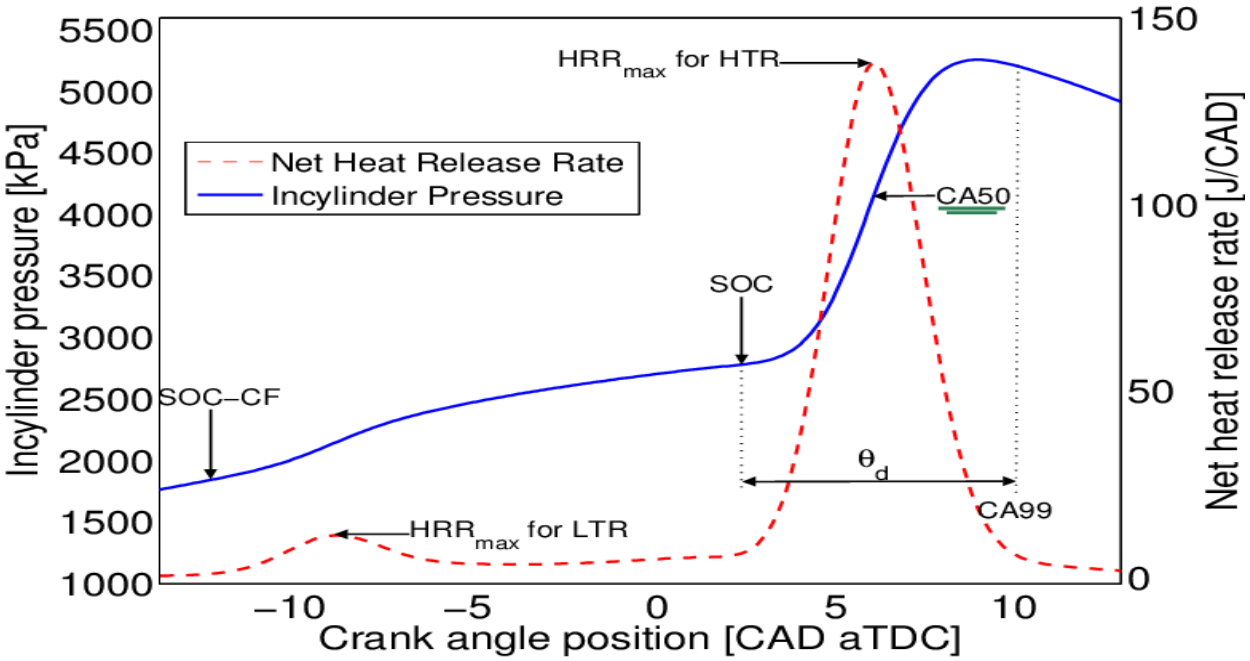


Figure 6: Effect of coolant temperature on in-cylinder pressure and heat release characteristics

The advancement of combustion phasing with increasing coolant temperature was further confirmed by shifts in cumulative heat release metrics, particularly CA10 and CA50, toward earlier crank angles. Peak cylinder pressure increased moderately at elevated coolant temperatures, indicating improved combustion efficiency and higher effective in-cylinder temperatures [28]. However, excessive advancement of combustion phasing may increase mechanical and thermal loading, highlighting that coolant temperature optimization should target a balanced operating window rather than the highest possible temperature. The dominant combustion trends associated with coolant temperature variation are summarized in Table 7, which highlights the consistent relationship between coolant temperature, ignition delay, combustion phasing, and thermal efficiency indicators.

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Table 7: Influence of coolant temperature on key combustion parameters

Coolant temperature level	Ignition delay	CA50 location	Peak pressure	Combustion stability
Low	Long	Retarded	Low	Poor
Medium	Moderate	Near-optimal	Moderate	Good
High	Short	Advanced	Higher	Very good

The influence of lubricating oil temperature on combustion behavior is illustrated in Figure 7, where combustion characteristics are compared at varying oil temperatures under a fixed coolant temperature. Although oil temperature exerted a weaker direct influence on ignition delay than coolant temperature, its effect on combustion stability and heat release uniformity was clearly observable. Higher oil temperatures reduced lubricant viscosity, leading to lower friction losses and improved lubrication conditions at the piston–liner and bearing interfaces. These effects contributed to smoother in-cylinder pressure traces, reduced cycle-to-cycle variability, and a slight reduction in combustion duration. Heat release rate profiles at higher oil temperatures exhibited a more compact and consistent combustion event, indicating improved combustion completeness and thermal uniformity.

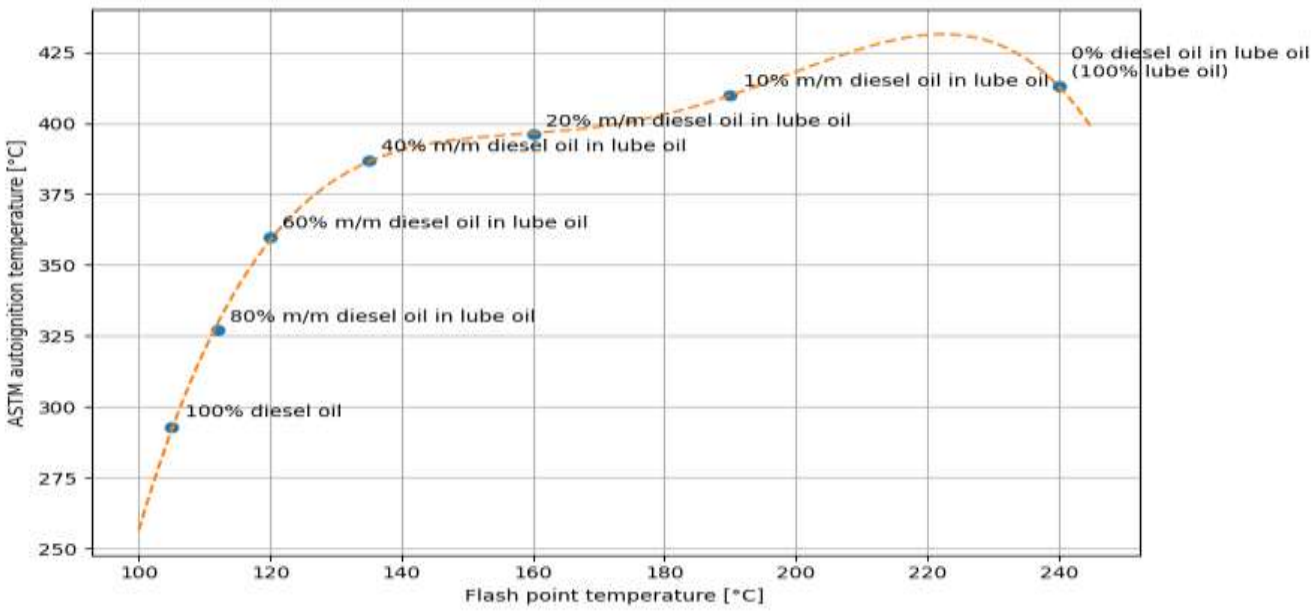


Figure 7: Influence of lubricating oil temperature on combustion stability and heat release behavior

The indirect influence of oil temperature on combustion can be explained by its impact on mechanical efficiency and component-level heat transfer. Reduced friction losses at higher oil temperatures limit parasitic energy dissipation and contribute to more stable in-cylinder conditions, particularly during the late combustion and expansion phases. These findings demonstrate that lubricating oil temperature, although often treated as a secondary parameter, plays a meaningful role in shaping combustion behavior and should be considered in integrated thermal management strategies. When coolant and lubricating oil temperatures were varied simultaneously,

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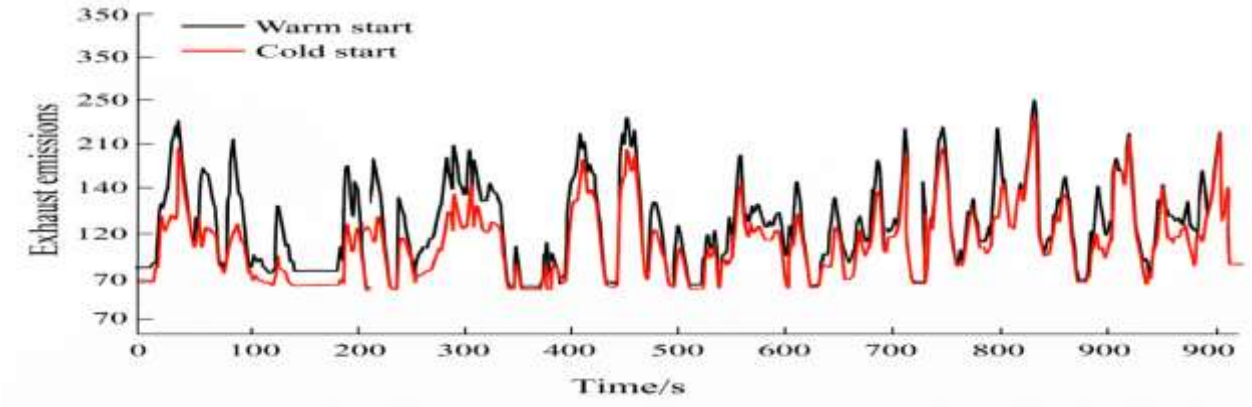
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strong nonlinear interaction effects emerged, as illustrated in Figure 15 and summarized quantitatively in Table 8. The combination of high coolant and high oil temperatures resulted in the shortest ignition delays, the most favorable combustion phasing, and the most stable heat release characteristics [29]. In contrast, operating conditions characterized by high coolant temperature but relatively low oil temperature produced advanced ignition accompanied by increased combustion variability, likely due to elevated friction losses and non-uniform component temperatures. Conversely, high oil temperature combined with low coolant temperature improved mechanical efficiency but could not fully compensate for the longer ignition delays caused by lower combustion chamber wall temperatures. These results confirm that the effects of coolant and oil temperatures are governed by distinct physical mechanisms and that their combined influence on combustion behavior is inherently nonlinear.

Table 8: Combined effects of coolant and lubricating oil temperatures on combustion behavior

Coolant temperature	**Oil temperature**	**Ignition delay**	**Combustion duration**	**Combustion stability**
Low	Low	Long	Long	Poor
High	Low	Short	Moderate	Moderate
Low	High	Moderate	Moderate	Good
High	High	Shortest	Short	Best

The impact of engine thermal conditions on exhaust emissions is illustrated in Figure 8, which shows the variation of nitrogen oxides (NO_x), carbon monoxide (CO), unburned hydrocarbons (HC), and smoke opacity with coolant and lubricating oil temperatures. Increasing coolant temperature resulted in a consistent increase in NO_x emissions due to higher peak combustion temperatures and enhanced thermal NO_x formation through the extended Zeldovich mechanism. Simultaneously, CO and HC emissions decreased with increasing coolant temperature, reflecting improved combustion completeness and reduced quenching effects at warmer combustion chamber walls. Smoke opacity also exhibited a declining trend under elevated coolant temperatures, particularly when combustion stability was enhanced.



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Figure 8: Variation of regulated exhaust emissions with engine thermal conditions

Lubricating oil temperature had a more pronounced effect on incomplete combustion emissions than on NO_x formation. Higher oil temperatures reduced CO and HC emissions by improving combustion stability, minimizing fuel-rich zones associated with wall wetting, and promoting more uniform in-cylinder temperature distribution. The combined condition of high coolant and high oil temperatures produced the lowest CO, HC, and smoke emissions, although this condition also resulted in the highest NO_x levels, highlighting the inherent efficiency–emission trade-off driven by thermal boundary conditions. Overall, the results demonstrate that coolant temperature predominantly controls ignition delay, combustion phasing, and NO_x formation by directly influencing in-cylinder thermal conditions, whereas lubricating oil temperature affects combustion indirectly through mechanical and thermal boundary effects. The strong nonlinear interaction between these two parameters explains why conventional single-parameter thermal control approaches are insufficient for achieving optimal performance across all operating conditions. From an engine design and control perspective, the findings highlight the need for advanced thermal management systems capable of independently and dynamically regulating coolant and lubricating oil temperatures. Such systems offer significant potential to improve combustion stability, reduce incomplete combustion emissions, and manage NO_x trade-offs, particularly during warm-up and sustained high-load operation. The experimental evidence presented in this study provides a robust foundation for the development of coordinated thermal management strategies in next-generation diesel engines.

Future Work:

The present investigation provides a comprehensive experimental assessment of the individual and combined effects of coolant and lubricating oil temperature variations on diesel combustion characteristics and exhaust emissions under steady-state operating conditions. While the findings offer valuable insights into the role of engine thermal boundary conditions, several avenues remain for further research to extend and enhance the applicability of the proposed framework [30]. Future work should focus on extending the experimental analysis to transient operating conditions, particularly during cold start, warm-up, and rapid load or speed changes. These operating regimes are highly relevant to real-world driving and are characterized by pronounced thermal gradients and time-dependent interactions between coolant and lubricating oil temperatures. Investigating combustion and emission behavior during such transient phases would provide deeper understanding of thermal inertia effects and enable the development of more effective warm-up and thermal control strategies [31]. Further studies could also examine the interaction between engine thermal conditions and advanced combustion modes, such as low-temperature combustion, partially premixed combustion, and high exhaust gas recirculation strategies. The influence of independently controlled coolant and oil temperatures on ignition behavior, heat release characteristics, and emission trade-offs in these regimes remains largely unexplored and could yield significant benefits in terms of efficiency and emission reduction. Integration of the experimental findings with detailed numerical modeling and simulation represents another important direction for future

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work. Coupling high-fidelity computational fluid dynamics models with experimentally validated thermal boundary conditions would allow detailed analysis of spatial temperature distributions, spray–wall interactions, and localized emission formation mechanisms that cannot be directly measured experimentally. Such models could also support the development of predictive control-oriented thermal management frameworks. In addition, future research may explore the application of adaptive and intelligent thermal management strategies, including model-based control, machine learning–assisted optimization, and real-time coordination of coolant and oil temperature regulation [32]. These approaches could exploit the nonlinear interactions identified in this study to dynamically balance combustion efficiency, emission constraints, and component durability across a wide range of operating conditions. Finally, extending the experimental methodology to multi-cylinder engines and incorporating aftertreatment system interactions would further enhance the industrial relevance of the findings. Understanding how coordinated engine thermal management influences catalyst light-off, aftertreatment efficiency, and overall vehicle emissions will be essential for translating laboratory-scale insights into practical automotive applications.

Conclusion:

This study presented a comprehensive, design-oriented experimental investigation into the influence of engine thermal boundary conditions on combustion characteristics and exhaust emissions in an automotive diesel engine. By independently controlling coolant and lubricating oil temperatures under steady-state operating conditions, the individual and coupled effects of these two critical thermal parameters were systematically isolated and analyzed using high-resolution in-cylinder pressure measurements and regulated emission data. The results demonstrated that coolant temperature plays a dominant role in governing in-cylinder thermal history, ignition delay, and combustion phasing. Elevated coolant temperatures consistently reduced ignition delay and advanced combustion timing by increasing combustion chamber wall temperatures and in-cylinder gas temperatures, leading to improved combustion efficiency and stability. However, these benefits were accompanied by increased nitrogen oxides emissions due to higher peak combustion temperatures, highlighting an inherent trade-off between efficiency-driven thermal conditions and NO_x control. Lubricating oil temperature was found to influence combustion behavior primarily through indirect mechanisms associated with mechanical and thermal boundary conditions. Higher oil temperatures reduced lubricant viscosity and friction losses, resulting in smoother heat release behavior, improved combustion stability, and lower emissions of carbon monoxide and unburned hydrocarbons. Although the direct effect of oil temperature on ignition delay was less pronounced than that of coolant temperature, its contribution to combustion completeness and emission reduction was significant, particularly under conditions of stable operation. A key outcome of this work is the identification of strong nonlinear interactions between coolant and lubricating oil temperatures. The most favorable combustion characteristics were achieved when both thermal parameters were simultaneously optimized, whereas mismatched thermal conditions led to increased combustion variability and suboptimal emission behavior. These

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findings demonstrate that coolant and oil temperatures cannot be treated independently and that coordinated thermal management is essential for achieving optimal combustion performance. From an engine design and control perspective, the results underline the potential benefits of integrated thermal management systems capable of independently regulating coolant and lubricating oil temperatures. Such systems can be leveraged to improve combustion stability, reduce incomplete combustion emissions, and manage NO_x trade-offs across a wide range of operating conditions. The experimental evidence provided in this study offers valuable guidance for the development of advanced thermal management strategies in modern diesel engines and contributes to a deeper understanding of the role of engine thermal conditions in combustion and emission control.

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