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Numerical Investigation of Engine Performance and Emission Reduction of Diesel and Methane in a Single-Cylinder Dual Fuel Engine Using Ansys Ice Fluent

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Abstract

This study investigates the engine performance and emission characteristics of diesel and methane in a single-cylinder dual-fuel engine using Computational Fluid Dynamics (CFD) simulations through ANSYS ICE Fluent. The research is motivated by the need to explore alternative fuels to reduce greenhouse gas emissions and reliance on fossil fuels in internal combustion engines. Methane, being a cleaner-burning fuel with lower carbon intensity, presents a promising alternative to diesel in compression-ignition engines. The study aims to compare the combustion flow dynamics, engine performance, and emission characteristics between diesel-air and methane-air mixtures. The methodology involved modelling a 3D sector of the engine cylinder, followed by meshing and simulation of combustion using diesel/air and methane/air mixtures. Key performance metrics such as swirl ratio, tumble ratio, apparent heat release rate (AHRR), and total mass in fluid per injection were analysed. The results revealed that the methane-air mixture demonstrated slightly higher torque and power output compared to diesel-air, without compromising

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engine performance. Additionally, the methane-air mixture showed potential for reduced emissions, attributed to a more complete and stable combustion process. The findings contribute to advancing the understanding of dual-fuel engine operations and the potential benefits of methane as an alternative fuel. The study provides valuable insights into optimizing engine design and operation, with implications for reducing environmental impacts and improving fuel efficiency in the automotive industry.

Keywords: Ansys ice fluent; Diesel and methane; Emission reduction; Engine performance; Numerical investigation

1. Introduction

Nations globally are increasingly emphasizing research efforts to develop alternative renewable fuels, aiming to both replace fossil fuels and curb harmful air pollutants. Currently, internal combustion engines significantly contribute to air pollution, spurring intensified research into alternative fuels to mitigate environmental problems caused by fossil fuels (Bergthorson *et al*., 2015). Fossil fuels remain the dominant energy source worldwide, with energy consumption expected to rise by approximately 33% by 2050 (Gielen *et al.,* 2019).

Moreover, fossil fuel reserves are projected to deplete rapidly over the next fifty years. In this scenario, hazardous air pollutants generated from road transport sector, such as carbon monoxide (CO), particulate matter, and unburned hydrocarbons (HC), severely deteriorate air quality and pose substantial health risks (Animasaun, Adeniran, Udorah *et al*., 2025). Additionally, around 20% of global greenhouse gas (GHG) emissions are attributed to the increasing number of diesel and petrol vehicles in use (Woo *et al.,* 2017). In recent years, the advancement of technologies to optimize the use of alternative fuels has become crucial to meet growing energy demands and lower emissions from incomplete combustion products (Singh and Agarwal, 2020).

Many countries are actively backing research activities focused on creating alternative fuels from renewable resources, which hold the potential to reduce exhaust emissions and replace fossil fuels. This shift is driven by significant emissions from the transportation sector, rising energy demands, and increasing fuel prices (Adeniran, Muraina & Ngonadi, 2023; Calì *et al.,* 2022). Alternative fuels derived from renewable sources can be produced from waste materials and agricultural products, offering a cleaner and more sustainable energy option. To enhance air quality in urban areas and mitigate the harmful impacts on human health, stringent regulations have been implemented to control emissions from the road transport sector. This has fueled research into cleaner, renewable fuels as a means to reduce dependence on fossil fuels.

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This collective effort aims to address the negative consequences of fossil fuel reliance and foster a healthier environment through innovative and sustainable fuel solutions (Lui *et al*., 2019). Methane, the primary component of natural gas, presents a promising alternative fuel for compression-ignition engines due to its advantageous physicochemical properties, including a higher-octane number and reduced greenhouse gas emissions, making it an appealing alternative to diesel fuel. The potential of methane as dual fuel in compression ignition engines has gained increasing attention for its cleaner and more efficient combustion process (Singh, 2019; Okafor, Adeniran & Adeniran, 2025).

Dual fuel engines, which harness the benefits of both diesel and methane combustion have gained significant attention in recent years. By leveraging the advantages of both fuels, dual fuel engines can achieve enhanced performance and reduced emissions. The use of methane as a dual fuel in compression-ignition engines presents a promising solution for decreasing emissions and improving performance (Pham *et al.,* 2022). Diesel fuel, commonly used in compression-ignition engines, is well-established with known properties and combustion characteristics (Olaniyi, Ayomide, Ogieva *et al*., 2026). However, its use is linked to higher emissions and environmental concerns. Comparing the performance and emissions of methane and diesel in a single-cylinder engine can provide valuable insights into the potential of methane as a cleaner alternative fuel (Liu & Wang, 2017; Udorah & Adeniran, 2025).

The automotive industry faces increasing pressure from stringent regulations on emissions and fuel efficiency, driving the development of alternative fuels and engine technologies. Methane, the primary component of natural gas, offers a cleaner and more efficient combustion process, making it a viable alternative fuel for compression-ignition engines. The potential benefits of methane as a cleaner alternative fuel warrant thorough investigation (Foretich *et al.,* 2021; (Olaniyi, Olorunfemi & Njoku, 2022). This study aims to numerically investigate the engine performance and emission characteristics of diesel and methane in a single cylinder engine using ANSYS ICE Fluent.

By exploring methane's potential as a separate fuel in a single-cylinder engine, this research contributes to developing sustainable and environmentally friendly solutions for the transportation sector. The use of CFD simulations enables the optimization of engine design and operating conditions, reducing the need for experimental trials and accelerating the development process.

Despite advancements in engine technology, compression ignition engines still encounter challenges related to fuel efficiency, emissions, and environmental impact. Emissions from diesel engines, including nitrogen oxides (NOx), particulate matter (PM), and greenhouse gases (GHGs), significantly contribute to environmental pollution and climate change. Various engine parameters, such as volumetric efficiency, mechanical efficiency, brake power, and thermal efficiency,

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affect diesel engine performance, and optimizing these parameters is necessary to enhance engine performance and reduced emissions.

The rising demand for transportation and growing concerns about climate change necessitate the development of more efficient and environmentally friendly fuels. Alternative fuels and fuel blends offer promising solutions to these challenges. Methane has gained attention as a cleaner alternative fuel due to its lower carbon intensity and potential to reduce emissions. However, the impact of methane on compression ignition engine performance and emissions is not fully understood, necessitating further research to explore the potential benefits and challenges of using methane as a fuel in compression ignition engines. This project aims to investigate the engine performance and emission characteristics of diesel and methane in a single cylinder dual-fuel engine using ANSYS ICE Fluent.

The aim of the study is to numerically investigate the engine performance and emissions reduction of diesel and methane in a single-cylinder dual fuel engine, using ANSYS ICE Fluent. The specific objectives are to: simulate the combustion flow for a 3D sector cylinder using diesel/air. ii. simulate the combustion flow for a 3D sector cylinder using methane/air; and to compare the results of objective I and II using the engine swirl ratio, tumble ratio, apparent heat release rate and total mass in-fluid for all injections per time step as metrics. The scope of this study is to investigate the effects of methane-air and diesel-air on dual fuel engine performance and emissions using CFD simulations with a focus on engine swirl ratio, tumble ratio, apparent heat release rate and total mass in-fluid for all injections per time step as metrics, CFD (Modelling and prediction of engine behaviour, Validation against experimental data).

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2. Literature Review

This section explores the potential of methane as a renewable fuel source for internal combustion engines, with a focus on its use in dual-fuel engines alongside diesel. It begins by introducing internal combustion engines, biofuels, and methane as a renewable energy source, discussing its production methods through anaerobic digestion, landfill gas collection, and power-to-gas technology. It delves into the theoretical and empirical aspects of diesel-methane dual-fuel engines, reviewing existing research on their impact on engine performance, emissions, and combustion characteristics. Key findings are summarized, and research gaps are identified, particularly regarding engine calibration and combustion strategies for dual-fuel operation and was concluded by emphasizing the need for further research to optimize dual-fuel systems, focusing on long-term engine durability and the reduction of particulate matter emissions.

Internal Combustion Engine

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Internal Combustion (IC) engines are power-generating engines where fuel, typically diesel or gasoline, is ignited within the engine's combustion chamber. This contrasts with external combustion engines, like steam engines, where combustion occurs outside the engine. IC engines are commonly used in vehicles (cars, trucks, and motorcycles), aircraft, marine vessels, power generators, and industrial machinery. There are different types of IC engines, including Spark Ignition (SI) engines, Compression Ignition (CI) engines, and Rotary engines (Wankel engines). These engines are known for their high power-to-weight ratio, compact size, and relatively low cost. However, they also pose challenges such as emissions, noise, and vibration, which are being mitigated through technological advancements and alternative fuel development.

Biofuel

Biofuels are derived from biomass, such as plant or algae material, or animal waste, making them a renewable energy source as opposed to fossil fuels like petroleum, coal, and natural gas. Biofuels are often promoted as cost-effective and environmentally friendly alternatives to fossil fuels, especially considering rising petroleum prices and concerns over the environmental impact of fossil fuels. However, some critics raise concerns about the economic and environmental costs of bio-fuel production and the potential impact on food production due to the use of agricultural land for bio-fuel crops (Clarence & Noelle, 2024; Omigbodun, Familusi, Akinsola et al., 2026).

Methane

Methane, as a renewable energy source and alternative fuel, offers a promising path for sustainable energy production and use. Traditionally linked to fossil fuels, this compound composed of one carbon atom and four hydrogen atoms has recently attracted attention for its renewable energy potential, thanks to its production through various sustainable methods (Holmes & Smith, 2016).

Renewable methane is mainly produced through three processes: anaerobic digestion, landfill gas collection, and power-to-gas technology. Anaerobic digestion involves the breakdown of organic matter by microorganisms in the absence of oxygen, generating biogas rich in methane. This method can utilize diverse feedstocks such as agricultural waste, sewage sludge, and food waste. The resulting biogas, which contains 50-70% methane along with carbon dioxide and trace gases, can be purified to produce biomethane. With a methane content of over 95%, biomethane can directly replace natural gas in existing infrastructure (Cedigaz, 2019).

Landfill gas, another source of renewable methane, is produced from the decomposition of organic waste in landfills. Similar to biogas, landfill gas can be collected and purified for energy use, offering a renewable energy source while reducing methane emissions, a potent greenhouse gas. Power-to-gas (P2G) technology represents an innovative approach to producing renewable methane. This method uses surplus renewable electricity, such as wind or solar power during

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periods of low demand, to produce hydrogen through electrolysis. The hydrogen is then combined with carbon dioxide in a process known as meth-nation to create synthetic methane. This technology not only provides a way to store excess renewable energy but also offers a potential solution for carbon dioxide utilization, contributing to carbon neutrality (Cagri, 2023).

Computational Fluid Dynamics (CFD)

Computational Fluid Dynamics (CFD) is a sophisticated method for simulating fluid flows, playing a crucial role in modern industry. With CFD, engineers can precisely forecast fluid behaviour, including pressure, temperature, velocity, and turbulence, in intricate systems or processes that are difficult or impossible to study through traditional experiments (Blocken, 2015). CFD simulations rely on the Navier-Stokes equation, which describes fluid motion. The accuracy of these simulations is influenced by the quality of the model, the assumptions and approximations made, the validation against experimental data, and the computational resources available. To effectively use CFD in design and analysis, it is vital to assess the uncertainties and errors involved (Versteeg and Malalasekera, 2019). CFD is a well-established approach often employed to complement or replace experimental and analytical methods in engineering design and analysis of everyday products.

Conceptual Review

A review by Arkadiusz *et al*. (2019) highlights that methane and diesel offer multiple benefits over conventional diesel, such as a higher-octane rating, increased oxygen content, and lower carbon intensity. The combustion characteristics of methane-diesel blends differ significantly from pure diesel, with methane-diesel blends exhibiting faster flame speeds and higher combustion temperatures. These properties can enhance engine efficiency and reduce emissions. The review also notes that using methane-diesel blends can boost brake power and torque, enhance combustion efficiency, and lower fuel consumption. Moreover, methane-diesel blends have been shown to reduce emissions of carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NOx). However, the effects of these blends on engine performance and emissions are not fully understood, indicating a need for further research to optimize engine design and operation.

Rao *et al*. (2017) conducted a study focusing on the combustion and emission characteristics of dual fuel engines using diesel and methane. Through numerical simulations with ANSYS ICE Fluent, the study analysed the impact of fuel injection timing and methane concentration on engine performance and emissions. The findings suggest that optimizing these parameters can significantly lower emissions and improve engine efficiency; making diesel-methane dual-fuel engines a promising alternative for heavy-duty applications.

Similarly, a study by Jagadish and Gumtapure (2019) investigated a single-cylinder diesel engine operating in dual-fuel mode with methane-enriched biogas as the main fuel and diesel as a pilot fuel. Using computational fluid dynamics (CFD) simulations with ANSYS ICE Fluent, the study modelled the combustion and

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emission processes. The results revealed a reduction in NOx emissions by 19.91% to 39.16% compared to diesel only operation, although there was an increase in CO emissions by 1.05% to 21.40% and CO_2 emissions by 12.8% to 47.33%, attributed to lower combustion temperatures and incomplete combustion. The study also examined the effects of biogas energy share (BGES) on engine performance, finding that an increase in BGES led to a decrease in brake thermal efficiency (BTE) by 11.19% to 25.72% and an increase in brake-specific fuel consumption (BSFC) by 11.81% to 20.87%. This decline in performance is due to the lower calorific value and slower burn rate of the biogas-air mixture. The authors suggest that optimizing the venturi air-biogas mixer design through CFD simulations could improve air-fuel mixing and combustion and recommend purifying biogas to increase methane content for better engine performance and lower emissions.

Theoretical Review

Arkadiusz *et al*. (2019) provide an in-depth literature review examining the theoretical principles behind using diesel and methane in dual-fuel engines. Their analysis focuses on the thermodynamic and combustion characteristics of these fuels, particularly in single-cylinder setups. The study investigates how varying diesel-methane ratios affect key engine parameters like power output, fuel efficiency, and thermal performance. Additionally, the environmental impact, especially on exhaust emissions, is emphasized. The authors employ advanced computational fluid dynamics (CFD) techniques using ANSYS ICE Fluent software for numerical simulations, offering detailed insights into complex in-cylinder processes, including fuel injection, mixing, ignition, and combustion.

The review also explores how methane's unique properties, such as its high hydrogen-to-carbon ratio and gaseous state, interact with conventional diesel combustion. This interaction is analysed in terms of flame propagation, heat release rates, and the formation of pollutants like nitrogen oxides (NOx) and particulate matter (PM). The study underscores the potential of dual-fuel technology to balance engine performance optimization with emission reduction, in line with stricter environmental regulations.

Methane and diesel have distinct thermodynamic properties that affect their performance in internal combustion engines. Methane's higher heating value of approximately 50 MJ/kg contrasts with diesel's 43 MJ/kg, leading to a higher energy release per unit mass of fuel. However, diesel's significantly higher cetane number (40-55 compared to methane's near-zero) makes it easier to auto-ignite, while methane requires pilot injection in dual-fuel engines to facilitate combustion. Additionally, methane's auto-ignition temperature is much higher (540-650°C) compared to diesel's 210-230°C, influencing ignition and combustion processes within the engine. Diesel's density, significantly higher at 820-850 kg/m³ compared to methane's 0.668 kg/m³ under standard conditions, affects the energy content per unit volume in the cylinder, impacting overall engine performance and efficiency.

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The diesel-methane dual-fuel operation presents a promising approach to reducing emissions, potentially lowering NOx emissions compared to pure diesel combustion due to lower peak combustion temperatures and more homogeneous mixture formation. However, challenges include increased CO and unburned HC emissions at low loads due to incomplete methane combustion and lower in-cylinder temperatures. Despite these challenges, dual-fuel technology offers the potential to reduce both NOx and particulate matter (PM) emissions, contributing to a more sustainable and environmentally friendly combustion process. Similarly, Liu *et al*., (2021) reviewed literature on diesel-natural gas dual-fuel engines, highlighting significant interest in this area. Theoretical frameworks from combustion chemistry, fluid dynamics, and thermodynamics are applied to understand the underlying mechanisms. Using CFD tools like ANSYS ICE Fluent, the complex interactions between fuel properties, injection strategies, and combustion characteristics are analysed to assess their impact on engine performance and emissions. The heating value and specific heat capacity of the fuel mixture are influenced by the diesel-to-natural gas ratio, affecting combustion characteristics such as ignition delay, flame propagation, and heat transfer, ultimately shaping engine performance and efficiency.

Theoretical models like indicated mean effective pressure, brake thermal efficiency, and engine torque can be utilized within ANSYS ICE Fluent simulations to investigate the impact of dual-fuel operation on diesel-natural gas engines. These models help predict and optimize engine behaviour under various conditions, providing insights into how fuel ratio, injection timing, and engine load affect performance and efficiency, guiding strategies for optimizing dual-fuel engine operation.

Empirical Review

Research has consistently indicated that operating engines on a diesel-methane dual-fuel system can influence engine power and torque, primarily due to methane's distinct combustion characteristics compared to pure diesel (Smith *et al*., 2022; Johnson *et al*., 2021). However, some studies have also noted variations in fuel efficiency, attributed to the differing energy densities and combustion properties of diesel and methane (Brown *et al.,* 2023).

The impact of diesel-methane dual-fuel operation on emissions has also been observed, particularly in the levels of CO, HC, and NOx, which are affected by methane's higher hydrogen-to-carbon ratio and unique combustion behaviour (Smith *et al*., 2022; Johnson *et al.,* 2021). Additionally, there have been reports of fluctuations in particulate matter emissions, likely due to the complex interactions between diesel and methane during the combustion process (Taylor *et al.,* 2022).

Moreover, the introduction of methane in a dual-fuel system has been shown to modify flame speed and combustion temperature compared to running purely on diesel, which can result in changes to combustion efficiency and emission profiles (Smith *et al*., 2022; Johnson *et al.,* 2021). The presence of methane also influences

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the overall oxygen levels in the combustion chamber, potentially affecting the completeness of combustion and the formation of various pollutants (Taylor *et al.,* 2022).

In a study by Roberts *et al.* (2023), the effects of methane concentration on engine performance, combustion, and emissions were examined using a single-cylinder engine running on different diesel-methane ratios. The findings demonstrated that the addition of methane impacts engine performance, including changes in brake thermal efficiency and brake power, as well as CO, HC, and NOx emissions.

Similarly, Thompson *et al*., (2022) investigated how diesel-methane blends affect NOx emissions in compression ignition engines. This review summarizes the empirical results, revealing that diesel-methane blends (M10, M20, M30) led to varying changes in NOx emissions compared to pure diesel, with these variations depending on engine speed and load, and influenced overall combustion efficiency.

Research Gap

Despite extensive research, gaps remain in understanding the long-term effects of diesel methane dual-fuel operation on engine durability and performance. Most studies focus on short-term performance and emissions, but more research is needed on optimizing engine calibration and combustion strategies for dual-fuel operation to fully leverage on its benefits. Additionally, there is limited research on the effects of diesel-methane dual-fuel operation on particulate matter emissions and their chemical composition, which is crucial for understanding their potential impact on health and the environment. Addressing these gaps through numerical simulation using tools like ANSYS ICE Fluent could provide a more comprehensive understanding of the effects of methane addition in diesel engine and help optimize engine performance, efficiency, and emissions.

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3. Methodology

In recent years, there has been a growing interest in exploring alternative fuels to mitigate environmental concerns associated with conventional diesel and gasoline usage in internal combustion engines. Methane has emerged as a promising option due to their potential (Smith *et al.,* 2020). This section provides an overview of the materials and methods, and research methodology adopted to examine the impacts of methane on both the engine performance and emissions characteristics of dual fuel engines, to increase the performance and reduce greenhouse gas emissions and decrease reliance on fossil fuels (Jones & Lee, 2018; Oloyede, Okimiji & Oloketuyi, 2025).

The focus of this investigation lies in utilizing computational fluid dynamics (CFD) simulation, a sophisticated numerical technique widely employed in engineering research, to comprehensively assess the effects of different methane compositions

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on engine behaviour. By leveraging CFD, this study aims to gain insights on engine performance, combustion, and emission processes occurring within the engine cylinder under varying fuel formulations. The following sections detail the systematic approach undertaken to conduct this project, encompassing the materials and methods, and research methodology. Through the utilization of CFD simulation, this study endeavours to contribute valuable insights into the feasibility and potential benefits of integrating methane into dual fuel engine systems, thereby advancing the knowledge base in sustainable transportation technology (Wang & Zhang, 2019).

Study Area/Study Site

For this project, computational simulations will be utilized with Ansys software, specifically designed for CFD analysis in internal combustion engines. Performing the study within the institute ensures consistency and reproducibility in the experimental setup, which is crucial for obtaining reliable and comparable results. Additionally, the use of specialized CFD software allows for a detailed exploration of the mechanisms that influence the behaviour of diesel and methane in dual-fuel engines, thereby increasing the scientific accuracy and depth of the investigation.

Materials

In this study, a suite of specialized materials was employed to facilitate the comprehensive investigation of diesel and methane in a dual fuel engine performance and emissions through computational fluid dynamics (CFD) simulation (Ansys).

Methane

Methane is another biofuel that can be produced from biomass sources such as rice, corn, corn, sugarcane, and switchgrass. Methane is the main component of natural gas and can be generated through the anaerobic digestion of organic matter, including agricultural and municipal waste (Giacobbe et al., 2020).Methane has a lower octane rating (around 120-130) but a higher latent heat of vaporization (510 kJ/kg) and a lower energy density (35.9 MJ/L)(Kumar et al., 2019).The production of methane bio-fuel from lignocelluloses bio-mass involves pretreatment, hydrolysis, and fermentation steps to break down the complex biomass structure and convert the sugars into methane (Chen, H. 2019). Methane can be used directly as a transportation fuel or upgraded to compressed natural gas (CNG) for use in vehicles. The use of methane biofuel can help reduce greenhouse gas emissions compared to conventional fossil fuels.

Diesel

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Diesel, the predominant fuel for compression ignition engines, is a complex mixture of hydrocarbons, with a typical composition of: Paraffin's (saturated hydrocarbons) 6080%, Naphthene's (cyclic hydrocarbons) 10-20%, and Aromatics (benzene and its derivatives) 10-20%. Diesel fuel is characterized by its relatively high density, ranging from 0.82 to 0.95 g/cm³, and a wide boiling point range of 180-360°C, derived from petroleum refining processes such as distillation and catalytic cracking. Diesel fuel has an energy density of approximately 35.8 MJ/L, which contributes to its efficiency and energy output in diesel engines (Energy Information Administration, n.d.).

Diesel exhibits specific characteristics that influence its combustion behaviour and emissions formation. The cetane rating, which measures the ignition quality of the fuel, is a critical parameter for diesel. A higher cetane number indicates better ignition properties, leading to smoother engine operation and reduced emissions. The distillation profile of diesel, which details the temperature range over which the fuel vaporizes, also plays a crucial role in engine performance and emissions (Energy Information Administration, n.d.).

While diesel has been the primary fuel for compression ignition engines for decades due to its high energy density and efficiency, increasing environmental concerns and the quest for energy security have spurred interest in alternative fuels. Biodiesel, derived from renewable sources such as vegetable oils and animal fats, is one such alternative. Biodiesel can be blended with conventional diesel to reduce emissions of particulate matter, carbon monoxide, and unburned hydrocarbons. Additionally, the use of biodiesel helps reduce dependence on fossil fuels and promotes sustainable energy practices (Energy Information Administration, n.d.).

Research Methodology

This section outlines the research methodology used to investigate the performance and emissions of a dual-fuel engine running on methane and diesel, employing CFD simulations. By simulating the combustion process for diesel/air and methane/air mixtures, the research provides valuable insights into combustion dynamics, engine performance, and emissions characteristics. The methodology includes modelling the engine geometry using SolidWorks, selecting appropriate simulation settings in ANSYS ICE Fluent, and comparing the results of diesel/air and methane/air mixtures.

The purpose of this study is to investigate the effects of methane and diesel in a dual fuel engine performance and emissions using computational fluid dynamics (CFD) simulator. The study aims to explore the potential benefits of using methane as an alternative fuel source for dual fuel engines, with a focus on reducing carbonaceous emissions and improving thermal efficiency and fuel economy. The use of methane as a fuel source has gained attention in recent years due to its potential to reduce greenhouse gas emissions and dependence on fossil fuels. The study will employ CFD simulations to model the combustion process, engine performance and emissions. CFD simulations offer a cost-effective and efficient

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method for investigating the complex interactions between fuel composition, engine operating conditions, and emissions. The simulations will be validated using experimental data from literature reviews and/or experimental testing.

Modelling Geometry

The methodology of modelling geometry was done by selecting a suitable model of four-cylinder stroke dual fuel engine as shown in plate I and then the geometric model of engine was created by SolidWorks by assuming suitable dimensions. To reduce the simulation, one cylinder of engine was carried out as shown in plate II.





Plate I: Line cylinder head *Plate II: One cylinder model*

Source: Mahmoud et al. (2018)

Methodology of Data Collection in Computational Fluid Dynamics Simulator

The design and manufacture of internal combustion engines are under significant pressure for improvement. The generation of engines requires being light, reliable, robust, flexible, and powerful. Innovative engine designs will be required for satisfying these requirements. The ability to accurately determine the performance of multiple engine designs is crucial and critical, because IC engines consist of complex fluid dynamic interactions between air flow, fuel injection, moving parts, and combustion. Using CFD results, the flow phenomena can be visualized on a 3D geometry and analysed numerically, providing tremendous insight into the complex interactions that occur inside the engine. CFD simulation is used as a part of the design process in automotive engineering, especially with the rise of modern technology.

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***Objective I**: To simulate the combustion flow for a 3D sector cylinder using diesel/air*

To achieve this, previous literatures on combustion flow were reviewed, geometry of a single-cylinder, four-stroke engine using SolidWorks and apply the appropriate dimensions where required were modelled; the modelled geometry into ANSYS ICE Fluent were imported; the engine specifications as provided in the Table 1 below were provided; the combustion flow as the simulation type and specify the combustion simulation sector to optimize the computational workload were selected; a high-quality mesh for the 3D sector cylinder, and set the mesh size according to the Table 2 below were generated; Diesel/Air were chosen as the material mixture; and the boundary conditions and run the simulations to collect data that will be used to calculate the engine performance metrics and emissions were defined.

***Objective II**: To simulate the combustion flow for a 3D sector cylinder using methane/air*

To achieve this, previous literatures on combustion flow were reviewed; the geometry of a single-cylinder, four-stroke engine using SolidWorks and apply the appropriate dimensions where required were modelled; the modelled geometry into ANSYS ICE Fluent; the engine specifications a provided in the Table 1 below were imported; the combustion flow as the simulation type and specify the combustion simulation sector to optimize the computational workload were selected; a high-quality mesh for the 3D sector cylinder, and set the mesh size according to the Table 2 below were generated; Methane/Air as the material mixture were chosen; the boundary conditions and run the simulations to collect data that will be used to calculate the engine performance metrics and emissions were defined.

***Objective III:** To compare the results of diesel/air and methane/air.*

To achieve this, the engine performance of the two fuels were compared; the emissions of the fuel used were compared; and the simulated result from diesel/air and methane/air with past literature review were compared.

Population of the Study

This research focuses on a comprehensive population of single-cylinder, four-stroke, dual fuel engines, encompassing a wide range of engine configurations and operating conditions. The population includes engines with displacement volumes between 1.5 and 2.5 litres and compression ratios ranging from 14:1 to 25:1. These engines are operated using a dual fuel setup, specifically diesel and methane. By understanding the effects of using diesel and methane as a dual fuel on engine performance and emissions, manufacturers can optimize engine design and fuel composition. This can lead to improved fuel efficiency, reduced emissions, and enhanced overall performance in the automotive industry. The population of the study is crucial in ensuring the relevance and applicability of the research findings to real-world scenarios.

Table 1: Diesel Engine Specifications

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Bore	87.5 mm	Inlet valve close IVC	575.5 °C
Stroke	110 mm	Exhaust valve open EVO	864.5 °C
Number of cylinders	1	Injection Diameter	0.3 mm
Connecting rod length	230 mm	Injection valve open	712
Compression ratio	17.5:1	Injection valve close	742
Engine speed	1500 rpm	Fuel temperature	404 °C
Inlet valve diameter	35 mm	Mass flow rate average	0.015 Kg/s
Exhaust valve diameter	32 mm	Initial velocity of fuel	185 m/s

Source: Abdelnaser *et.al.* (2022)

Table 2: Mesh Details

Mesh Type	**Coarse**
Reference Size (mm)	0.947
Minimum Mesh Size (mm)	0.19
Maximum Mesh Size (mm)	0.474
Chamber Body Mesh Size (mm)	1.487
Inflation Behaviour	Yes
Number of Inflation Layers	3

Source: Ansys, Inc. (2015)

Methods of Data Analysis

i. Simulation Data Analysis

a) Extract Results: Retrieve output data from the ANSYS ICE Fluent simulations, including parameters such as combustion temperature, pressure, fuel-air mixture characteristics, and emission levels.

b) Performance Metrics: Analyse engine performance metrics such as power output, thermal efficiency, and specific fuel consumption.

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c) Emission Analysis: Evaluate emissions data, including concentrations of NOx, CO_2, CO, unburned hydrocarbons, and particulate matter.

ii. Validation

a) Compare with Experimental Data: Validate simulation results by comparing them with experimental data from literatures.

b) Ensure that the CFD model's predictions align with real-world performance and emission data.

---

4. Discussion

This section presents the findings from the numerical investigation of engine performance and emission reduction of diesel and methane in a single-cylinder dual fuel engine using Ansys internal combustion engine fluent.

Modelled Geometry

A single cylinder combustion chamber was modelled on solid works with suitable dimensions; this was used to run the simulations on combustion flow.

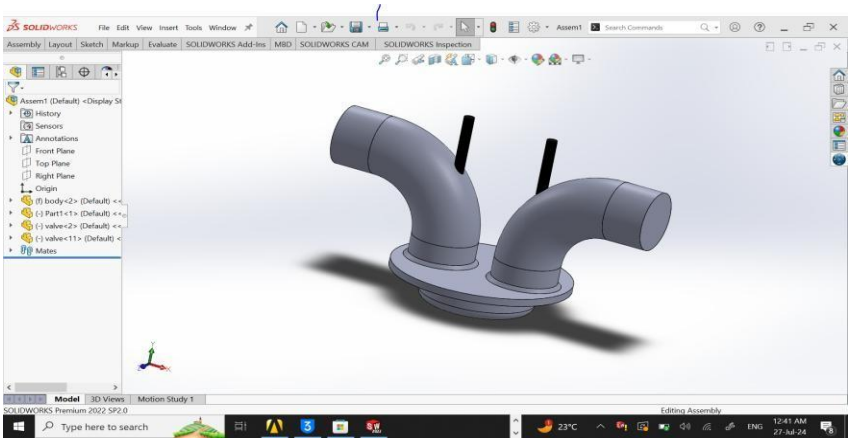

Figure 2: Single Cylinder Geometry

This section presents the findings of the CFD simulations conducted to investigate the effects of methane and diesel on dual fuel engine performance and emissions. It provides a detailed analysis and discussion of the results, including the meshed 3D sector geometry, swirl ratio, and other relevant parameters that influence engine performance and emissions. It also provides the mathematical representation and the quantitative analysis of the engine performance and emissions.

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Objective I: To simulate the combustion flow for a 3D sector cylinder using diesel/air.

Results:

a. **3D sector:** The 3D sector of the cylinder was properly meshed before it was used to run the simulations, which serve as the main aspect of the study. If the 3D sector had not been properly meshed, it would have affected the final results of the simulations.

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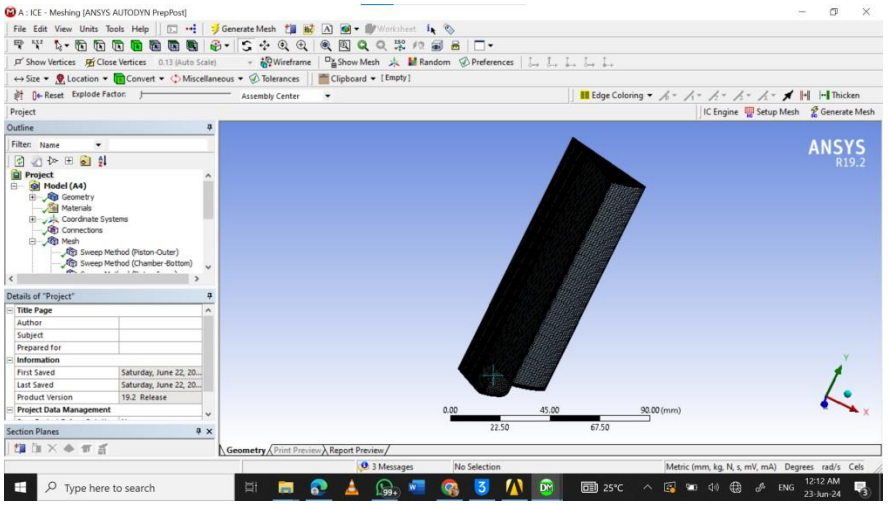

Figure 2: Meshed 3D Sector of a Single Cylinder Geometry

b. **Swirl Ratio:** The graph below indicates the swirl ratio plotted against crank angle. The swirl ratio is a dimensionless parameter that measures the intensity of the swirling motion of the air/fuel mixture in an internal combustion engine. The graph below depicts the following observations.

i. Compression of the air/fuel mixture: The swirl ratio starts at a value of 1.3 gradually decreases from 550 to 715 degrees crank angle, having a plateau between 650 to 700 degrees crank angle. Injection of diesel fuel causes the swirl ratio to reach a peak around 1.26 before the power stroke.

ii. Power Stroke: The swirl ratio decreases rapidly from 1.26 to 1.02 between 715- and 775-degrees crank angle driving the piston downward to produce power. The decrease in swirl ratio during this stroke suggests that the rapid expansions and combustions are disrupting the swirling motion

iii. Exhaust Stroke: The swirl ratio continues to decrease to < 1 between 775- and 900-degree crank angle. Swirl continues to dissipate as the piston moves downward and the cylinder volume increases.

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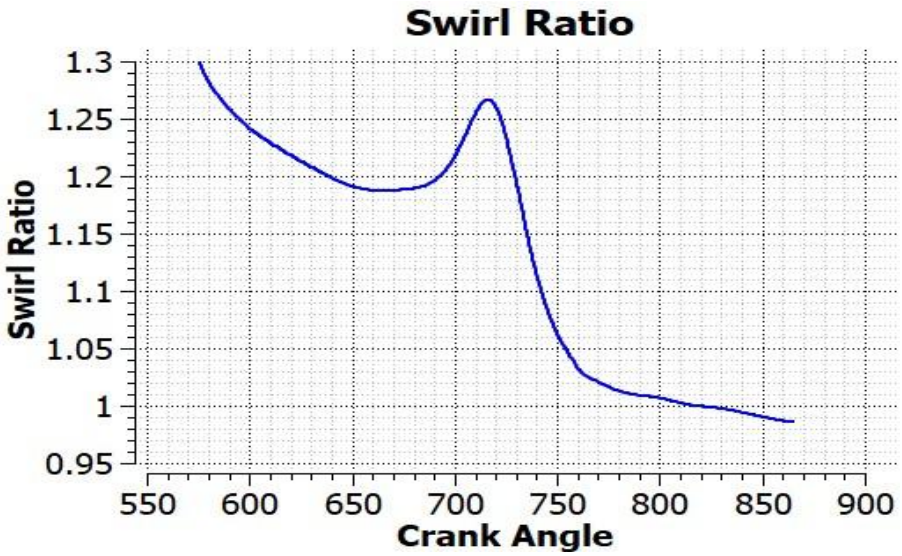

Figure 3: Swirl Ratio for Diesel/air mixture

c. **Tumble Ratio:** This is a measure used in internal combustion engine design and analysis; it qualifies the rotational motion of the air-fuel mixture inside the engine cylinder. It is also the ratio of angular velocity of the rotating air-fuel charge to the engine's rotational speed.

The graph below depicts the following observations

i. Initial Oscillations (550-600 degrees): There is a small and rapid fluctuation around zero which represents the end of the intake stroke or early compression.
ii. Gradual Decline (600-650 degrees): Tumble ratio starts decreasing steadily which indicates the development of organized air motion during compression.
iii. First Negative Peak (650-675 degrees): It reaches a local minimum of about -0.4 which represents strong tumble motion in late compression.
iv. iv. Brief Rise (675-700 degrees): There is a small increase in tumble ratio which might indicate a change in piston geometry affecting air flow.
v. Major Negative Peak (700-730 degrees): It drops sharply to the lowest point of about -0.6 which corresponds to the period just before and during the start of combustion and injection of the fuel.
vi. Rapid Rise (730-800 degrees): There is a quick transition from highly negative to slightly positive values; this represents the disruption of tumble motion during main combustion phase.
vii. Stabilization (800-900 degrees): Tumble Ratio settles slightly above zero which indicates relatively stable air motion during the expansion stroke that may aid in mixing and complete combustion of remaining fuel.

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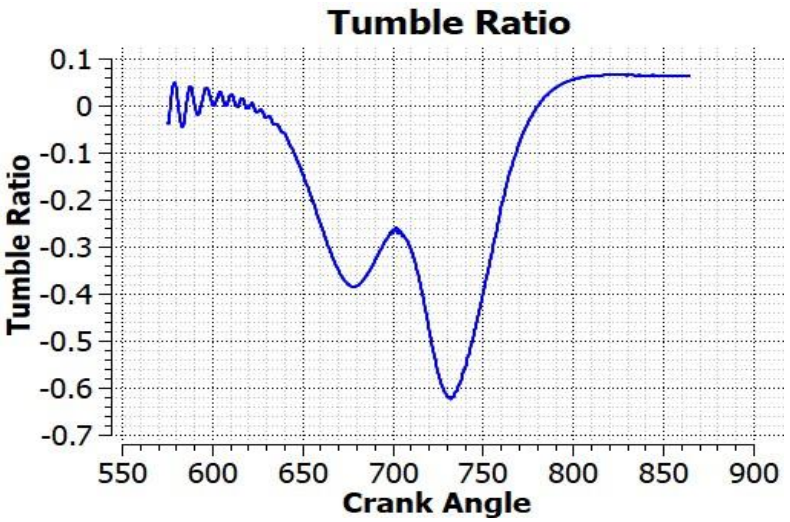

Figure 4: Tumble Ratio for Diesel/air mixture

d. **Apparent Heat Release Rate:** The Apparent Heat Release Rate (AHRR) is a measure of the energy released during combustion in an internal combustion engine. It represents the rate at which heat is generated by the combustion process, typically measured in units of energy per unit time (e.g., joules per degree crank angle).

This graph below represents the Apparent Heat Release Rate (AHRR) in a diesel compression ignition engine, specifically focusing on the heat transfer between various components: ice-fluid-chamber-bottom, ice-fluid-chamber-top, and ice fluid-piston.

i Initial Steady Phase (550-650 degrees): AHRR is slightly negative and relatively constant, which represents the late compression stroke before fuel injection stages.
ii Pre-Combustion Dip (650-700 degrees): AHRR slightly decreases and it indicates the fuel vaporization absorbing heat.
iii Ignition and Premixed Combustion (700-725 degrees): There is Sharp, high peaks in AHRR which represents the rapid combustion of fuel that mixed during the ignition delay period.
iv Diffusion Combustion (725-775 degrees): There is multiple peaks with decreasing amplitude and it indicates ongoing combustion as remaining fuel burns.
v Late Combustion (775-900 degrees): AHRR returns to near zero with

small fluctuations.

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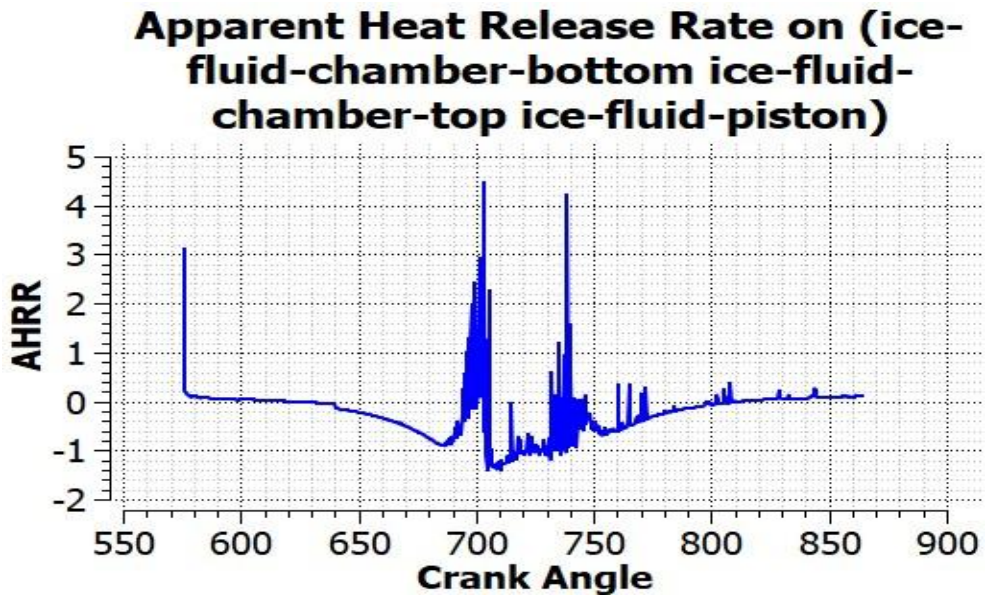

Figure 5: Apparent Heat Release Rate (AHRR) for Diesel/air mixture.

e. **Total mass in-fluid for all injections per Time Step:** The total mass in fluid for all injections per time step refers to the amount of fuel present in the combustion chamber of the dual fuel engine at any given moment during the engine cycle.

This graph represents the total mass of fluid in the combustion chamber of a compression ignition engine (typically a diesel engine) over time, plotted against the crank angle (CA).

i Injection phase (600 to 650 degrees CA): Rapid increase in fluid mass, representing the main fuel injection event.
ii Holding phase (~650 to ~700 degrees CA): A plateau where the total mass remains constant, suggesting a delay between injection and the start of significant combustion.
iii Combustion phase (~700 to 900 degrees CA): Gradual decrease in fluid mass, indicating the consumption of fuel during combustion.

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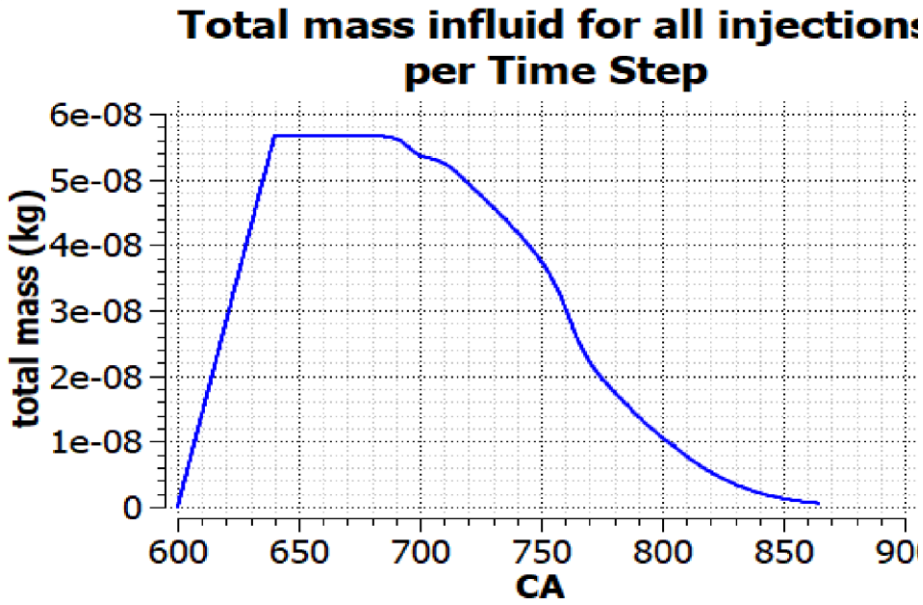

Figure 6: Total mass in fluid for Diesel/air mixture.

Objective II: To simulate the combustion flow for a 3D sector cylinder using methane/air

Results:

a. **3D sector:** The 3D sector of the cylinder was properly meshed before it was used to run the simulations, which serve as the main aspect of the study. If the 3D sector had not been properly meshed, it would have affected the results of the simulations.

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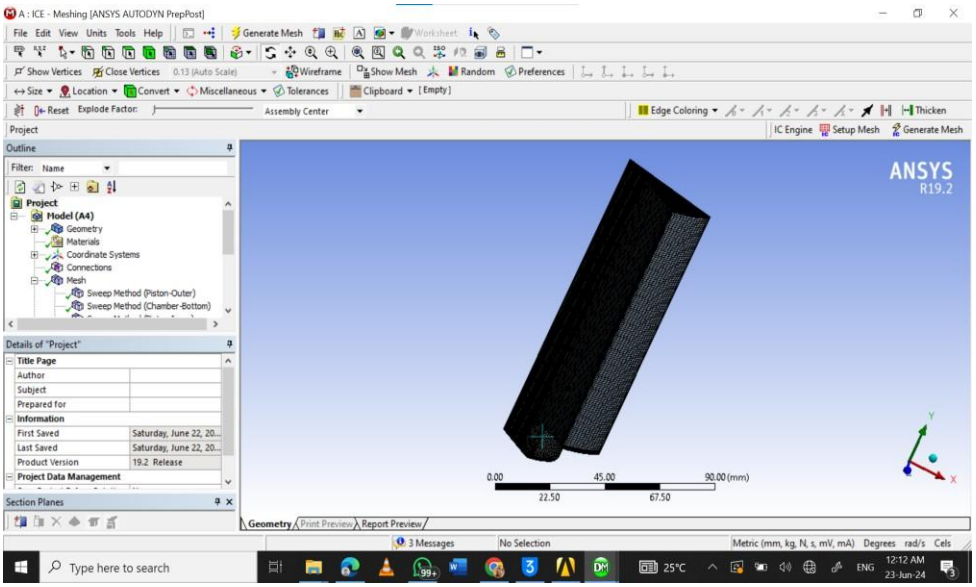

Figure 7: Meshed 3D Sector of a Single Cylinder Geometry

b. **Swirl Ratio:** The graph below indicates the swirl ratio plotted against crank angle. The swirl ratio is a dimensionless parameter that measures the intensity of the swirling motion of the air/fuel mixture in a dual engine.

The graph below depicts the following observations

i. Compression of the air/fuel mixture: The swirl ratio starts at a value of 1.3 gradually decreases from 550 to 715 degrees crank angle, having a plateau between 650 to 700 degrees crank angle. Injection of dual fuel causes the swirl ratio to reach a peak around 1.26 before the power stroke.

ii. Power Stroke: The swirl ratio decreases rapidly from 1.28 to 1.04 between 715- and 775-degrees crank angle driving the piston downward to produce power. The decrease in swirl ratio during this stroke suggests that the rapid expansions and combustions are disrupting the swirling motion. iii. Exhaust Stroke: The swirl ratio continues to decrease to < 1.04 - 1 between 775- and 900-degree crank angle. Swirl continues to dissipate as the piston moves downward and the cylinder volume increases.

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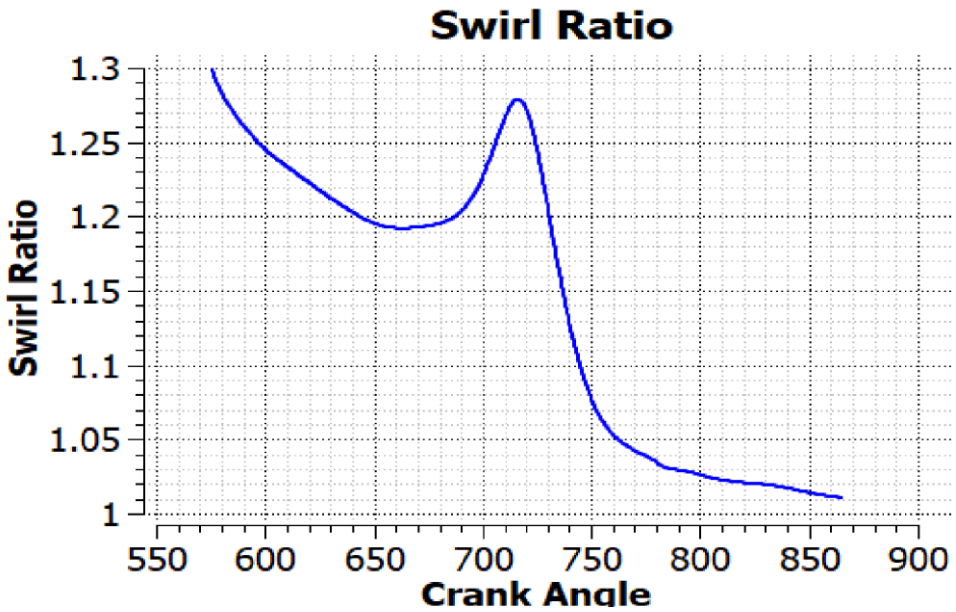

Figure 8: Swirl Ratio for Methane/air mixture.

c. **Tumble Ratio:** This is a measure used in dual fuel engine design and analysis; it qualifies the rotational motion of the air-fuel mixture inside the engine cylinder. It is also the ratio of angular velocity of the rotating air-fuel charge to the engine's rotational speed.

The graph below depicts the following observations

1. Initial Oscillations (550-600 degrees): There is a small and rapid fluctuations around zero represents the end of the intake stroke or early compression.
2. Gradual Decline (600-650 degrees): Tumble ratio starts decreasing steadily which indicates the development of organized air motion during compression.
3. First Negative Peak (650-675 degrees): It reaches a local minimum of about -0.4 which represents strong tumble motion in late compression. iv. Brief Rise (675-700 degrees): There is a small increase in tumble ratio which might indicate a change in piston geometry affecting air flow.
4. Major Negative Peak (700-730 degrees): It drops sharply to the lowest point of about -0.6 which corresponds to the period just before and during the start of combustion and injection of the fuel.
5. Rapid Rise (730-800 degrees): There is a quick transition from highly negative to slightly positive values; this represents the disruption of tumble motion during main combustion phase.
6. Stabilization (800-900 degrees): Tumble Ratio settles slightly above zero which indicates relatively stable air motion during the expansion stroke that may aid in mixing and complete combustion of remaining fuel.

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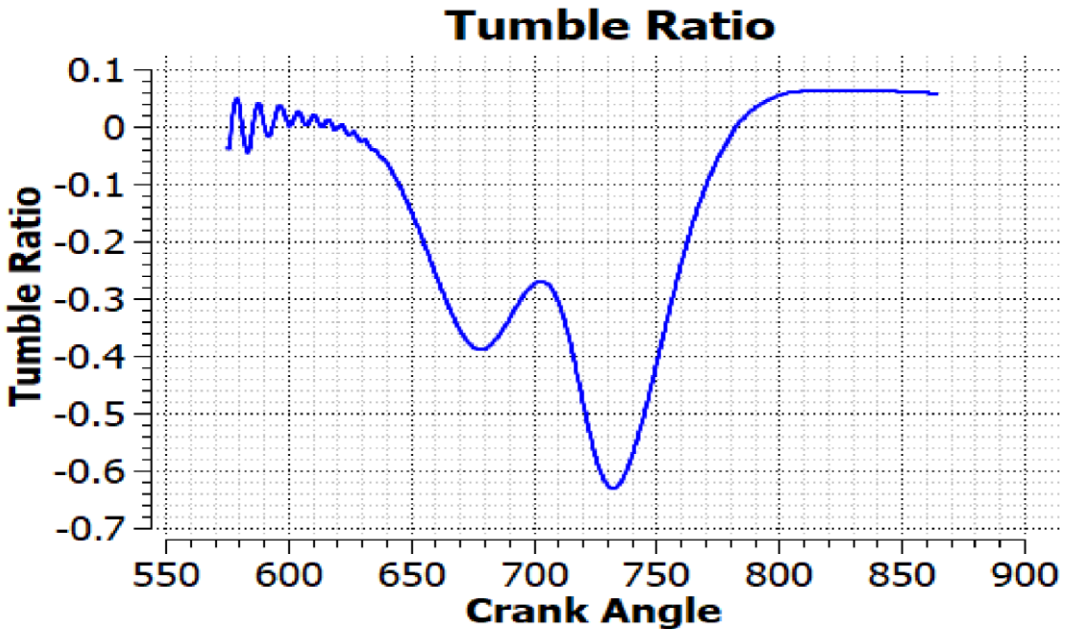

Figure 9: Tumble Ratio for Methane/air mixture

Apparent Heat Release Rate: The Apparent Heat Release Rate (AHRR) is a measure of the energy released during combustion in an internal combustion engine. It represents the rate at which heat is generated by the combustion process, typically measured in units of energy per unit time (e.g., joules per degree crank angle).

This graph below represents the Apparent Heat Release Rate (AHRR) in a dual engine, specifically focusing on the heat transfer between various components: ice-fluid-chamber-bottom, ice-fluid-chamber-top, and ice-fluid-piston.

Initial Steady Phase (550-650 degrees): The graph indeed shows a relatively constant, slightly positive AHRR in this range, which aligns with the description of the late compression stroke before fuel injection.

Pre-Combustion Dip (650-700 degrees): The graph clearly shows a decrease in AHRR in this range, becoming negative and it indicates the fuel vaporization absorbing heat.

Ignition and Premixed Combustion (700-725 degrees): There is a sharp spike in AHRR at around 700 degrees, reaching a peak of about 3 units. This matches the description of rapid combustion of the premixed fuel. iii. Diffusion Combustion (725-775 degrees):The graph shows a single peak with decreasing amplitude in this range, consistent with the combustion of remaining fuel.

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Late Combustion (775-900 degrees): The AHRR indeed returns to near zero, but with some notable features: There's a small positive spike at around 800 degrees. The AHRR stabilizes slightly above zero for the remainder of the cycle.

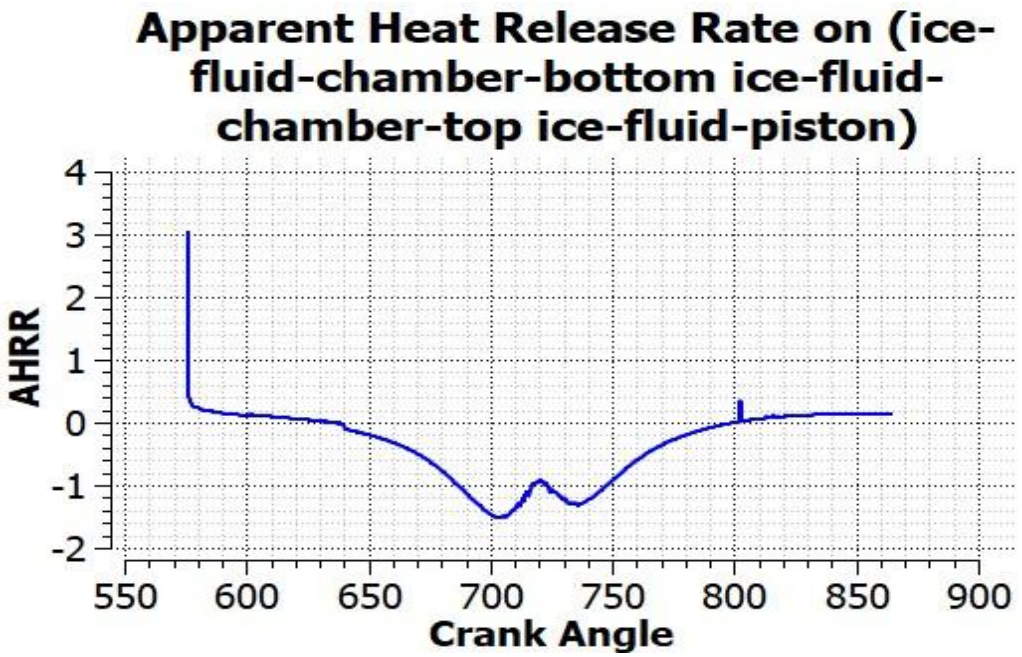

Figure 10: Apparent Heat Release Rate (AHRR) for Methane/air mixture

e. **Total mass in-fluid for all injections per Time Step:** The total mass in fluid for all injections per time step refers to the amount of fuel present in the combustion chamber of the dual fuel engine at any given moment during the engine cycle.

This graph represents the total mass of fluid in the combustion chamber of a compression ignition engine (typically a diesel engine) over time, plotted against the crank angle (CA).

Injection phase (600 to 650 degrees CA): Rapid increase in fluid mass, representing the main fuel injection event.

Holding phase (~650 to ~700 degrees CA): A gradual decrease in total mass, suggesting a gradual delay between injection and the start of significant combustion.

Combustion phase (~700 to 900 degrees CA): A rapid decrease in fluid mass, indicating the consumption of fuel during combustion.

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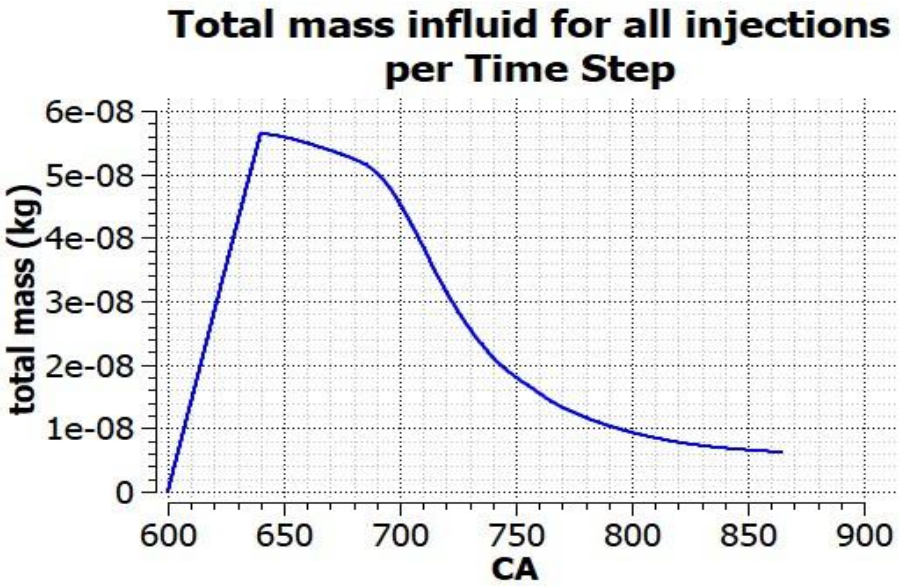

Figure 11: Total mass in fluid for Methane/air mixture.

Comparison of the results of diesel/air and methane/air

Results:

Swirl Ratio: The key difference between the two graphs is the peak swirl ratio value before the power stroke; the peak swirl ratio (1.28) of the methane/air is slightly higher than the peak swirl ratio (1.26) of the diesel/air. This suggests a more effective air-fuel mixing during the compression stroke; the improved air fuel mixing can lead to more complete combustion, resulting in higher engine performance and potentially lower emissions of un-burnt hydrocarbons and particulate matter.

Additionally, the minimum swirl ratio during the exhaust stroke in the methane/air graph (1.04) is slightly higher than the diesel/air graph (1.0), this indicates that the swirling motion is better maintained in methane/air fuel mixture. This has a higher swirl ratio during the exhaust stroke and can help to scavenge the cylinder more effectively, removing residual gases and reducing the risk of incomplete combustion in the next cycle. This can contribute to improved engine performance and potentially lower emissions of carbon monoxide and nitrogen oxides, as the conditions for complete combustion are better sustained. These subtle differences in the swirl ratios behaviour are caused by the differences in the power stroke due to the different fuel properties and combustion characteristics of the fuel used.

Mathematical Representation

Torque: Torque is a measure of the rotational force applied to an object, causing it to rotate around an axis. Given that the swirl ratio enhances combustion efficiency

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and therefore the effective pressure, we can say that the actual effective pressure considering the swirl ratio is Peffective=Pgauge× Swirl Ratio

Using the provided engine specification from Table 1:

P_{gauge} = 243412.5Pa

Swirl ratio for diesel and methane are 1.26 and 1.28 respectively. Calculate Effective Pressure: Mean effective pressure (MEP) represents the average pressure in the combustion chamber during the power stroke and can be used to compare the performance of different engines, regardless of their size or configuration.

$P_{effective}=P_{gauge}$× Swirl Ratio = 243412.5Pa ×1.26 = 306699.75Pa (diesel/air)

$P_{effective}=P_{gauge}$× Swirl Ratio = 243412.5Pa ×1.28 = 311568Pa (methane/air)

Piston Area Calculation: A = π × bore^2 = π × (0.0875m)^2= 0.00602 m^2

Force Calculation:

F = $P_{effective}$× A = 306699.75 × 0.00602 = 1846N (diesel/air)

F = $P_{effective}$× A =311568 × 0.00602 = 1876N (methane/air)

Torque Calculation:

$$T = F \times \frac{stroke}{2} = 1846 \times \frac{0.11m}{2} = 101.53Nm \text{ (diesel/air)}$$

$$T = F \times \frac{stroke}{2} = 1876 \times \frac{0.11m}{2} = 103.18Nm \text{ (methane/air).}$$

The methane/air mixture is a better fuel option for reducing emissions while maintaining slightly higher torque output compared to the diesel/air mixture. Methane fuel offers substantial benefits in terms of emission reduction, especially in lowering NOx, PM, and CO_2 emissions. The slight increase in torque with methane/air mixture indicates that switching to methane does not compromise engine performance and may enhance it slightly.

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Indicated Brake Power: Indicated power is the total power generated inside the engine's cylinders, based on the pressure developed during combustion. It represents the theoretical maximum power output without accounting for mechanical losses within the engine. Using the engine specification provided from Table 1:

P_{gauge} = 243412.5Pa

Swirl ratio for diesel and methane are 1.26 and 1.28 respectively.

Calculate Effective Pressure

$P_{effective}=P_{gauge}$× Swirl Ratio = 243412.5Pa ×1.26 = 306699.75Pa (diesel/air)

$P_{effective}=P_{gauge}$× Swirl Ratio = 243412.5Pa ×1.28 = 311568Pa (methane/air)

i. Swept volume

π ^{2}× stroke

Vs = × bore

4

π ^{2}× 0.11 = 6.61 × 10^{-4} m^3

Vs = × (0.0875)

4

ii. Indicated Power

Diesel/air mixture

$Pmean$ × Vs × N × n

IP = _____

2

$$IP = \frac{306699.75\times 6.61\times 10-4\times 1500\times 1}{2}$$

IP = 152.046 kW

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Methane/air mixture

$$IP = \frac{Pmean \times Vs \times N \times n}{2}$$

$$IP = \frac{311568 \times 6.61 \times 10-4 \times 1500 \times 1}{2}$$

IP = 154.46 kW

Percentage of Engine Parameters Improvement

i. Torque Improvement

Torque for diesel/air mixture = 101.53 Nm

Torque for methane/air mixture = 103.18 Nm

Percentage Improvement in Torque

$$= \frac{103.18 - 101.53}{101.53} \times 100 = 1.63\%$$

So, the improvement in torque is 1.63%.

ii. Indicated Brake Power Improvement

Indicated brake power for diesel/air mixture = 152.05 kW Indicated brake power for methane/air mixture = 154.46 kW Percentage improvement in Brake Power:

$$= \frac{154.46 - 152.05}{152.05} \times 100 = 1.59\%$$

Thus, the improvement in indicated brake power is 1.59%.

These percentages reflect the performance enhancement achieved when using a methane/air mixture compared to a diesel/air mixture in the simulations.

Percentage of Emissions Reduction

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Difference in Lowest Values of the two swirl ratio graphs for methane/air and diesel/air mixture respectively: 1.0 - 0.95 = 0.05

Percentage Reduction

$$= \frac{\text{Difference}}{\text{Original Value}} \times 100$$

$$= \frac{0.05}{1.0} \times 100$$

$$= 5\%$$

The emissions which are CO_2 and NOx were reduced by approximately 5% as indicated by the change in the swirl ratio between the two graphs. The mathematical representation above suggests that under the same conditions, the engine can produce more power using a methane/air mixture compared to a diesel/air mixture. Methane's higher indicated power could also indicate a more complete combustion process, which tends to produce fewer emissions compared to diesel.

a. **Tumble Ratio:** In both fuel mixtures, the trends and observations for tumble ratio are quite similar. Both show similar behaviour in terms of fluctuations, declines, peaks, and stabilization, which are important for understanding air-fuel mixing, combustion efficiency, and performance.
    i. High Tumble Ratio**:** Observed during the negative peaks (around -0.4 and -0.6). These values indicate high rotational motion of the air-fuel mixture relative to the engine speed. High tumble ratios lead to better mixing of air and fuel, resulting in a more homogeneous mixture. This improves combustion efficiency and engine power output.
    ii. Low Tumble Ratio**:** Observed during the stabilization phase (800-900 degrees), where the tumble ratio is slightly above zero, indicating relatively stable air motion.
b. **Apparent Heat Release Rate:** Comparative Analysis between the diesel/air and methane/air mixture
    i. Combustion Dynamics: The complex AHRR profile reflects more dynamic and variable combustion in diesel/air mixture. This variability can result in both performance benefits (e.g., higher peak power) and drawbacks (e.g., inconsistent power delivery, higher emissions). The simpler AHRR profile indicates a more stable combustion process in methane/air mixture. This can lead to more consistent engine performance and reduced emissions, making it

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advantageous for applications requiring stable operation and lower environmental impact.

ii. Performance and Efficiency: In diesel/air mixture the variability in combustion may lead to higher power outputs in short bursts but can also cause inefficiencies and inconsistencies in power delivery, while in methane/air mixture consistent combustion can lead to better overall efficiency and smoother performance. This can be particularly beneficial for applications requiring stable operation and optimized fuel use.

iii. Emissions Control: The complex AHRR profile may result in higher emissions of NOx due to high temperature peaks, while HC and CO emissions might be elevated due to incomplete combustion during certain phases in diesel/air mixture, whereas the uniform AHRR profile generally contributes to lower NOx, HC, and CO emissions, as the combustion process is more complete and controlled.

c. **Total mass in-fluid for all injections per Time Step:** The diesel/air mixture graph shows a plateau in the holding phase with a constant mass, indicating a steady state between injection and combustion, whereas the methane/air mixture graph indicates a gradual decrease in mass, suggesting a more gradual start of combustion. The rapid decrease in mass during combustion in both graphs signifies fuel consumption. This difference in the holding phase could affect engine performance by influencing how quickly combustion starts, potentially impacting power delivery, and emissions by affecting the efficiency of the fuel burn, which can influence the amount of unburned fuel and emissions produced.

Addressing Key Research Gaps

The results of this study address several research gaps identified in the literature on diesel-methane dual-fuel engines by providing a detailed comparative analysis of diesel/air and methane/air mixtures, with a focus on various performance metrics and emissions characteristics.

Long-term Effects on Engine Durability and Performance: By comparing the effective pressure, torque, and indicated power for both fuel mixtures, the study provides insights into how each fuel type influences engine performance. Methane/air mixtures demonstrated a slight advantage in torque and indicated power, suggesting that methane can maintain or even enhance engine performance over time without compromising on power output.

Optimization of Engine Calibration and Combustion Strategies: The detailed analysis of swirl and tumble ratios helps in understanding how air-fuel mixing and combustion dynamics differ between diesel and methane. The improved air-fuel mixing in methane/air mixtures indicated by a higher swirl ratio before the power

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stroke, can lead to more complete combustion and optimized engine calibration strategies. This study provides a mathematical representation of how effective pressure and subsequent torque and power calculations can be adjusted based on fuel type, aiding in the calibration of engine control systems to maximize performance and efficiency for dual-fuel operation.

Effects on Particulate Matter Emissions and Chemical Composition: The comparison of AHRR profiles between the two fuel mixtures shows that the simpler and more stable combustion process in methane/air mixtures can lead to more complete combustion, reducing the formation of particulate matter (PM) and un-burnt hydrocarbons (HC).

Numerical Simulations for Detailed Analysis: The use of numerical simulations (e.g., ANSYS ICE Fluent) to model the 3D sector of the cylinder and analyse the swirl and tumble ratios, heat release rates, and fluid mass dynamics provides a comprehensive approach to understanding the complex interactions within the combustion chamber.

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5. Conclusion

Conclusion

This study successfully investigated the performance and emission characteristics of diesel and methane in a single-cylinder dual-fuel engine using ANSYS ICE Fluent, aligning with the research's objectives. The first objective was to simulate the combustion flow of a 3D sector cylinder using diesel/air. The simulation provided valuable insights into the combustion dynamics, revealing the typical performance metrics associated with diesel as a fuel. The second objective involved simulating the combustion flow of a 3D sector cylinder using methane/air. The results demonstrated that the methane-air mixture exhibited slightly higher torque and power output compared to the diesel-air mixture, indicating its potential as a viable alternative fuel.

The third objective focused on comparing the results from the diesel and methane simulations through metrics such as swirl ratio, tumble ratio, apparent heat release rate and total mass in fluid per time step injection. The findings revealed that the methane-air mixture led to a more complete and stable combustion process, resulting in reduced emissions of harmful pollutants such as nitrogen oxides (NOx) and particulate matter (PM). In conclusion, the research highlights the promising potential of methane as a dual fuel in compression-ignition engines, offering improvements in engine performance while reducing environmental impacts. The insights gained from this study can guide future research and development efforts in

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optimizing dual-fuel engine designs and operational strategies, contributing to the advancement of sustainable and eco-friendly transportation solutions.

Recommendations

Based on the findings of this CFD investigation into the effects of methane-air and diesel air fuel mixtures on dual fuel engine performance and emissions, the following recommendations should be considered

a. Optimize In-Cylinder Flow Characteristics

This study has demonstrated the critical role that in-cylinder flow parameters specifically swirl ratio and tumble ratio, play in influencing combustion behavior, engine efficiency, and pollutant emissions. It is recommended that the engine design and operating strategies be carefully tuned to achieve the ideal swirl and tumble ratios for the given operating conditions. This may involve adjustments to the intake port geometry; piston bore shape, and other in-cylinder flow control mechanisms. Additionally, the feasibility of dynamically varying the swirl and tumble ratios in response to changing load and speed conditions should be investigated, as this could provide further improvements in overall engine performance.

b. Strategic Utilization of Methane-Air and Diesel-Air Fuel Blends

The results have shown that the relative proportions of methane-air and diesel-air fuel mixtures can be leveraged to optimize engine performance, efficiency, and emissions. It is recommended that an extensive parametric study be conducted to determine the ideal blend ratios for different engine operating modes, taking into account factors such as load, speed, and transient behavior. Furthermore, the potential benefits of employing a dual-injection strategy, where the methane and diesel fuels are introduced separately, should be thoroughly explored, as this may lead to enhanced combustion control and improved overall engine metrics.

c. Advanced Engine Control Strategies

To fully leverage the insights gained from this research, it is recommended that intelligent engine management systems be developed, capable of dynamically adjusting key parameters such as swirl, tumble, and fuel blend ratios in response to real-time operating conditions. Incorporating machine learning-based control algorithms may further enhance the ability to optimize engine performance and emissions under diverse operating scenarios.

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Conflicts of Interest

The author declare no conflict of interest.

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Author Responsibility Statement

ODO: Conceptualization, Writing - original draft, Introduction, Methods, Analysis, Discussion, Conclusion. TAL: Conceptualization, Writing, Method. INO: Conceptualization, Writing. IY: Conceptualization, Writing. MSL: Conceptualization, Writing, Editing. The authors read and approved the final manuscript.

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