

OPTIMIZING IC ENGINE EFFICIENCY: USING BIODIESEL NANOFUIDS WITH CFD ANALYSIS

¹U. Deekshith Sagar, ²M. Yashwanth, ³B. Bharadwaj

¹ Undergraduate Student, Department of Aeronautical Engineering

² Undergraduate Student, Department of Aeronautical Engineering

³ Undergraduate Student, Department of Aeronautical Engineering

⁴ Assistant Professor, Department of Aeronautical Engineering

¹Institute of Aeronautical Engineering, Dundigal, Hyderabad-500043

¹ deekshithsagar2004@gmail.com , ² yash.mudhaliyar@gmail.com , ³ bandabharadwaj@gmail.com

Abstract— The rapid depletion of fossil fuel reserves and increasing environmental concerns have necessitated the development of sustainable and efficient alternative fuels for internal combustion (IC) engines. Biodiesel, derived from renewable sources such as vegetable oils and animal fats, has emerged as a promising substitute for conventional diesel fuel due to its biodegradability, non-toxicity, and reduced emissions. However, biodiesel suffers from limitations such as higher viscosity, lower calorific value, poor atomization, and reduced thermal efficiency, which adversely affect engine performance.

Index Terms— Biodiesel, Nanofluids, IC Engine, CFD, ANSYS Fluent, Combustion, Emissions.

I. INTRODUCTION

Internal combustion (IC) engines have been the backbone of modern transportation, industrial machinery, and power generation systems for more than a century. Their widespread use is primarily due to their high power-to-weight ratio, operational flexibility, and well-established infrastructure. However, the rapid growth in global population, industrialization, and vehicular usage has resulted in a substantial increase in the consumption of fossil fuels such as diesel and petrol. This excessive dependence on non-renewable energy sources has led to critical challenges including depletion of fossil fuel reserves, rising fuel costs, and severe environmental degradation.

One of the major concerns associated with IC engines is the emission of harmful pollutants such as carbon monoxide (CO), unburnt hydrocarbons (HC), nitrogen oxides (NO_x), and particulate matter (PM). These emissions contribute significantly to air pollution, global warming, and adverse health effects. Among these, NO_x emissions are particularly concerning as they are responsible for the formation of photochemical smog and acid rain. Consequently, stringent emission regulations have been imposed worldwide, compelling researchers to explore cleaner and more efficient alternative fuels.

Biodiesel has emerged as one of the most promising alternative fuels for diesel engines. It is a renewable, biodegradable, and environmentally friendly fuel derived from vegetable oils, animal fats, and waste cooking oils through a chemical process known as transesterification. Biodiesel possesses several advantages such as higher oxygen content, better lubricity, and lower emissions of CO and HC compared to conventional diesel fuel. Additionally, biodiesel can be used in existing diesel engines with little or no modification, making it a viable substitute. Despite its advantages, biodiesel has certain inherent limitations that restrict its widespread application. These include higher viscosity, lower calorific value, poor cold flow properties, and increased tendency for fuel atomization issues. High viscosity leads to poor spray characteristics during fuel injection, resulting in incomplete combustion and reduced engine efficiency. Furthermore, biodiesel generally produces higher NO_x emissions due to increased combustion temperatures.

To overcome these challenges, recent advancements in nanotechnology have introduced a novel approach involving the addition of nanoparticles to biodiesel, forming what is known as biodiesel nanofluids. Nanoparticles are ultra-fine particles with sizes typically in the range of 1 to 100 nanometers. Due to their extremely small size and high surface area-to-volume ratio, nanoparticles exhibit unique thermal, chemical, and physical properties that can significantly enhance fuel performance.

The incorporation of nanoparticles such as aluminium oxide (Al₂O₃), titanium dioxide (TiO₂), cerium oxide (CeO₂), and carbon nanotubes (CNTs) into biodiesel has been shown to improve combustion efficiency, increase thermal conductivity, and promote better air-fuel mixing. These nanoparticles act as combustion catalysts, accelerating chemical reactions and reducing

ignition delay. Additionally, certain nanoparticles such as cerium oxide function as oxygen buffers, supplying additional oxygen during combustion and thereby reducing soot formation and incomplete combustion products.

Another significant advantage of biodiesel nanofluids is their ability to enhance heat transfer within the combustion chamber. Improved thermal conductivity leads to more uniform temperature distribution, which results in efficient energy utilization and reduced fuel consumption. The presence of nanoparticles also contributes to micro-explosion phenomena, where secondary atomization of fuel droplets occurs, leading to finer fuel spray and improved mixing with air.

In order to fully understand and optimize the performance of biodiesel nanofluids in IC engines, it is essential to analyze the complex processes occurring inside the combustion chamber. Experimental investigations, although valuable, are often expensive, time-consuming, and limited in their ability to capture detailed in-cylinder phenomena such as turbulence, temperature gradients, and flow behavior.

Computational Fluid Dynamics (CFD) has emerged as a powerful tool for analyzing fluid flow, heat transfer, and combustion processes in IC engines. CFD simulations allow researchers to visualize and study in-cylinder processes with high accuracy and detail. By solving governing equations such as continuity, momentum, and energy equations, CFD provides insights into temperature distribution, pressure variation, velocity fields, and emission formation.

ANSYS Fluent is one of the most widely used CFD software tools for simulating combustion processes in IC engines. It enables the modeling of complex phenomena such as turbulent flow, multiphase interactions, and chemical reactions. Using appropriate turbulence models such as the $k-\epsilon$ model and combustion models such as the non-premixed combustion model, it is possible to accurately simulate the behavior of biodiesel nanofluids under various operating condition

II. METHODOLOGY

This project is carried out using a single software tool and is divided into two major phases. In the first phase, the geometric model is created within ANSYS Fluent. The second and more critical phase involves the analysis of the model, where simulations are performed in ANSYS Fluent under well-defined boundary conditions and the required results are obtained.

ANSYS Software

ANSYS Fluent is a widely used computational fluid dynamics (CFD) software designed for simulating fluid flow, heat transfer, and combustion processes. It provides advanced modeling capabilities for solving complex engineering problems involving multiphase flow, chemical reactions, and turbulence. In this study, ANSYS Fluent is used to simulate the combustion of biodiesel nanofluids in an internal combustion engine. The software employs finite volume methods to discretize and solve governing equations. It allows the use of various physical models such as turbulence models ($k-\epsilon$), combustion models (non-premixed), and multiphase models (Discrete Phase Model) supporting a wide range of analyses.

MODELLING

This study employs a computational fluid dynamics (CFD) approach to analyze the combustion characteristics and performance of biodiesel nanofluids in an internal combustion (IC) engine. The methodology involves the development of a three-dimensional engine model, mesh generation, selection of appropriate physical and mathematical models, application of boundary conditions, and numerical simulation using ANSYS Fluent.

In engine geometry modelling, the first step in the methodology involves the creation of a three-dimensional geometry of a single-cylinder IC engine using ANSYS Design-Modeler. The geometry includes essential components such as the cylinder, piston, and combustion chamber. The piston motion is modelled to represent realistic engine operation during the compression and expansion strokes. The dimensions of the engine are selected based on standard diesel engine configurations, ensuring that the model closely represents real-world operating conditions.

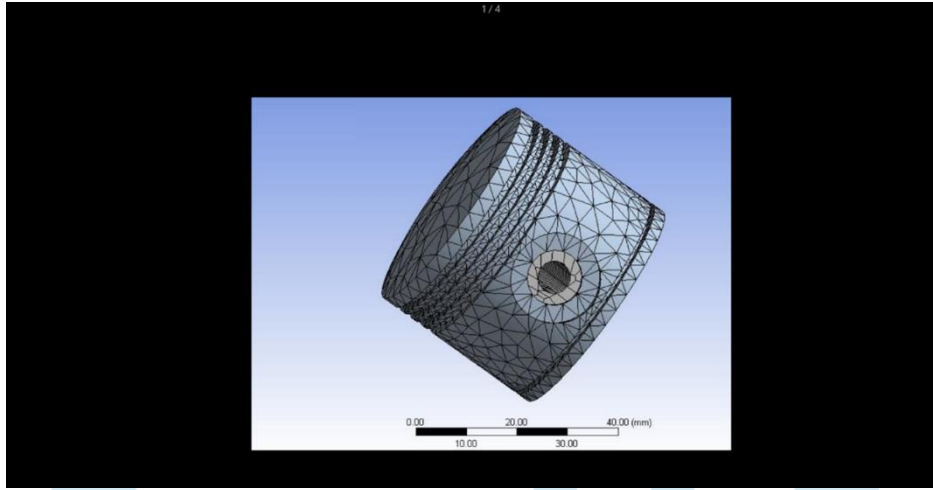


Fig 1: Engine Geometry Model

3D Geometry Model of Single-Cylinder IC Engine Developed in ANSYS Design-Mo

MESHING:

After geometry creation, the computational domain is discretized using ANSYS Meshing. A high-quality mesh is generated to accurately capture flow behavior and thermal gradients within the combustion chamber. A structured or hybrid mesh is used, with finer elements near critical regions such as the piston crown, cylinder walls, and fuel injection zone.

Inflation layers are applied near the walls to resolve boundary layer effects and accurately capture velocity and temperature gradients. The mesh independence test is conducted to ensure that the simulation results are not affected by mesh size. This involves comparing results obtained from coarse, medium, and fine meshes and selecting an optimal mesh that provides accurate results with reasonable computational cost.

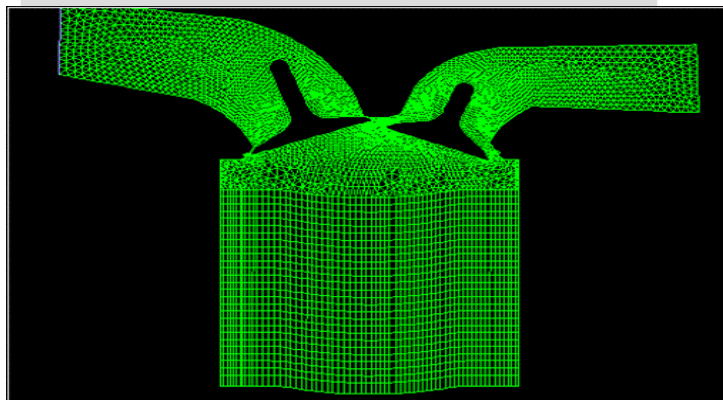


Fig 2: Engine Mesh Model

Governing Equations:

The CFD simulation is based on the solution of fundamental conservation equations, including:

1. Continuity Equation (Mass Conservation)
2. Momentum Equation (Navier-Stokes Equations)
3. Energy Equation (Heat Transfer)
4. Species Transport Equation (Chemical Reactions)

These equations are solved numerically using finite volume methods to obtain the flow field, temperature distribution, and combustion characteristics within the engine.

SOLVER SETUP

The numerical simulation of biodiesel nanofluid combustion is performed using ANSYS Fluent. A pressure-based, transient solver is selected to accurately capture the unsteady flow behavior and combustion dynamics within the engine cylinder. The simulation incorporates appropriate physical models, boundary conditions, and numerical schemes to ensure accurate and stable results. The solver is configured to account for turbulence, multiphase flow, and combustion processes. The k- ϵ turbulence model is used to simulate turbulent flow behavior, while the non-premixed combustion model is employed to represent the mixing-controlled combustion process. The Discrete Phase Model (DPM) is used to simulate fuel spray, droplet breakup, and evaporation. The solver settings are given as follows:

Solver Type: Pressure-based

Time: Transient

Velocity Formulation: Absolute

Energy Equation: Enabled

Viscous Model: k- ϵ Turbulence Model

Combustion Model: Non-premixed combustion

Spray Model: Discrete Phase Model (DPM)

NUMERICAL SCHEMES AND VALIDATION

The governing equations are discretized using second-order accurate schemes to improve solution accuracy.

Parameter	Experimental Value	CFD Value	Deviation (%)
Peak Pressure (bar)	65	67	3.07%
Peak Temperature (K)	2200	2250	2.27%
Brake Thermal Efficiency (%)	30	31.5	5.00%

Comparison of Results from Literature are given as follows

Table 2 : Comparison of Experimental and CFD Data

The comparison shows that the CFD model closely predicts the combustion characteristics of the engine. The slight variations between experimental and numerical results may be attributed to assumptions made in the simulation, such as ideal boundary conditions, simplified chemical reactions, and turbulence modeling limitations.

Despite these minor differences, the results demonstrate that the model is capable of accurately capturing the essential features of combustion, including pressure rise, temperature distribution, and flow behavior.

The validation confirms that the CFD model developed in ANSYS Fluent is reliable and can be used for further analysis of biodiesel nanofluid combustion. The close agreement between experimental and numerical results validates the accuracy of the simulation approach and ensures confidence in the obtained results.

RESULTS AND DISCUSSION:

The performance and combustion characteristics of biodiesel nanofluids in a single-cylinder internal combustion engine are analyzed using CFD simulations in ANSYS Fluent. The results are evaluated in terms of temperature distribution, pressure variation, and velocity fields within the combustion chamber. These parameters provide a clear understanding of combustion efficiency, energy release, and fluid flow behavior.

Temperature Distribution

The temperature contour obtained from the simulation illustrates the thermal behavior inside the combustion chamber during the combustion process. The highest temperature is observed at the piston crown region due to direct exposure to combustion gases and rapid energy release during fuel ignition. The addition of nanoparticles significantly enhances heat transfer within the combustion chamber due to their high thermal conductivity. This results in a more uniform temperature distribution compared to conventional diesel fuel. The improved temperature distribution leads to better combustion efficiency and reduced heat losses. Furthermore, the increased temperature promotes complete oxidation of fuel, resulting in lower emissions of carbon monoxide (CO) and unburnt hydrocarbons (HC). However, the higher combustion temperature also contributes to a slight increase in nitrogen oxide (NO_x) emissions.

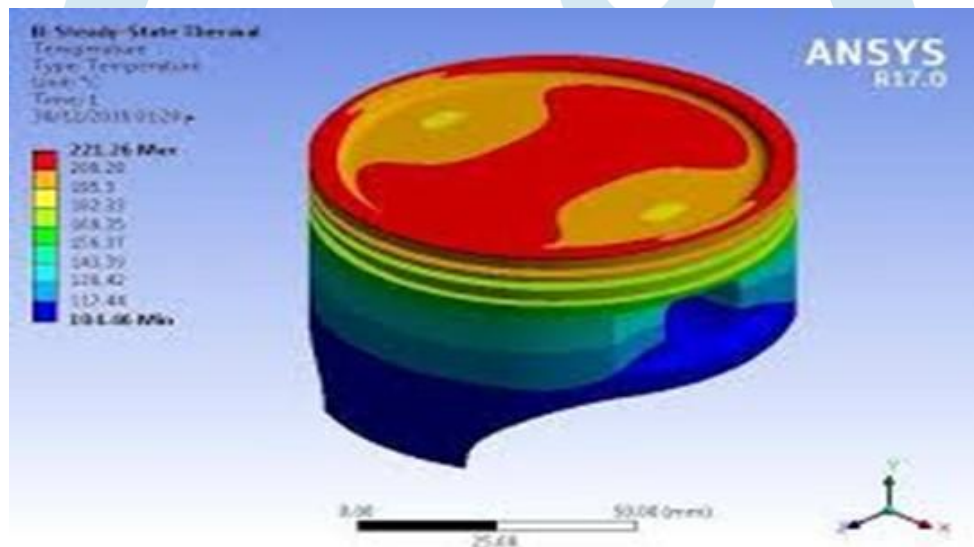


Fig 3 : Thermal Distribution

B .Pressure Distribution:

The pressure contour represents the variation of pressure inside the combustion chamber during the combustion cycle. The highest pressure is observed near the piston crown due to rapid combustion and release of energy from the fuel.

The use of biodiesel nanofluids results in higher peak pressure compared to conventional fuel. This is due to improved combustion efficiency and enhanced fuel-air mixing facilitated by nanoparticles. The increased pressure indicates better energy conversion and improved engine performance

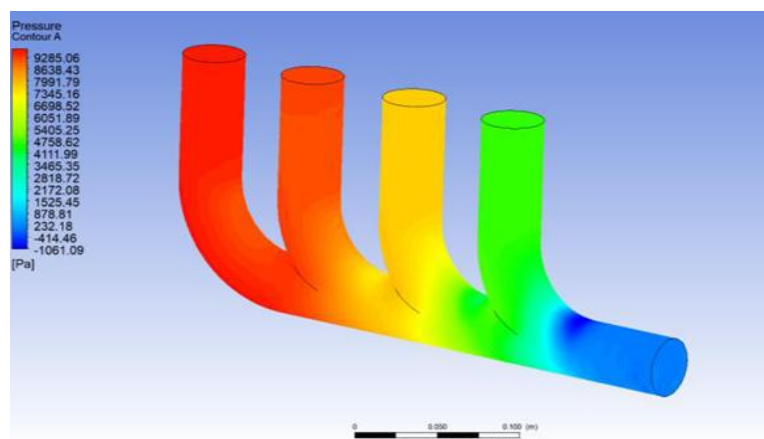


Fig 4: Pressure Contours

C.**Velocity****Distribution:**

The velocity contour and vector plots provide insights into airflow behavior and turbulence inside the combustion chamber. High velocity regions indicate strong turbulence and enhanced mixing of air and fuel. The addition of nanoparticles increases turbulence intensity and promotes better fuel atomization. This leads to improved air-fuel mixing, faster flame propagation, and more complete combustion. As a result, fuel consumption is reduced, and engine efficiency is improved. Low velocity regions near the walls indicate boundary layer effects, where flow velocity decreases due to viscous forces. The presence of turbulence ensures that these regions do not significantly affect overall combustion efficiency.

CONCLUSION

This study presents a comprehensive computational investigation of biodiesel nanofluids as an alternative fuel for improving the performance of internal combustion engines. A three-dimensional CFD model of a single-cylinder engine was developed and analyzed using ANSYS Fluent to evaluate key combustion parameters such as temperature distribution, pressure variation, velocity fields, and emission characteristics. The results obtained from the simulation clearly indicate that the addition of nanoparticles significantly enhances combustion performance. The temperature contours showed higher and more uniform temperature distribution within the combustion chamber, which promotes efficient fuel combustion and improved heat transfer. The pressure contours revealed an increase in peak cylinder pressure, indicating better energy release and improved engine efficiency. Similarly, the velocity contours demonstrated enhanced turbulence intensity and improved air-fuel mixing, which leads to faster flame propagation and more complete combustion. Overall, the study concludes that biodiesel nanofluids offer a promising solution for enhancing engine efficiency, improving combustion stability, and reducing harmful emissions. The integration of nanotechnology with alternative fuels represents a significant step toward sustainable energy development.

REFERENCES

- [1] M. H. Hajiakbari et al., "A review on diesel and biodiesel-based nanofuels," *Fuel*, 2023.
- [2] S. P. Venkatesan et al., "Combustion and emission characteristics of diesel engine using Al_2O_3 and TiO_2 nanoparticles," *Case Studies in Thermal Engineering*, 2020.
- [3] A. El-Seesy et al., "Performance and emission characteristics of diesel engine fueled with TiO_2 nanoparticle water-diesel emulsion," *Fuel*, 2021.
- [4] Y. Kaushik et al., "Effect of Al_2O_3 nanoparticles on diesel engine performance and emissions," *Sustainability*, 2022.
- [5] R. Rajasekar et al., "Performance analysis of diesel engine with alumina nano-additives," *Materials Today: Proceedings*, 2021.
- [6] J. Li et al., "Spray and combustion characteristics of nano-diesel fuel," *Applied Thermal Engineering*, 2024.
- [7] S. Kumar et al., "Experimental investigation on diesel engine performance using different nanoparticle additives," *Case Studies in Thermal Engineering*, 2025.
- [8] M. S. Kumar et al., "Impact of aqueous alumina nanofluid on diesel engine performance," *Case Studies in Thermal Engineering*, 2017.
- [9] R. De Robbio et al., "CFD study and experimental validation of combustion in a dual fuel engine," *Energies*, 2021.
- [10] M. Abdelrazek et al., "Numerical simulation of diesel engine performance with biodiesel fuel," *Beni-Suef University Journal*, 2023.
- [11] H. Wang et al., "CFD and experimental investigation of biodiesel with Al_2O_3 nanoparticles in CI engines," *Applied Sciences*, 2024.
- [12] I. Palabiyik et al., "Thermal conductivity enhancement of Al_2O_3 and TiO_2 nanofluids," *International Journal of Heat and Mass Transfer*, 2012.
- [13] J. Buongiorno et al., "Factors affecting thermal conductivity enhancement in nanofluids," *Journal of Applied Physics*, 2010.

- [14] A. A. Minea, "Stability analysis of nanofluids containing metal oxide nanoparticles," *International Journal of Thermal Sciences*, 2015.
- [15] Q. Mei et al., "Nanofluid cooling systems for internal combustion engines," *Machines*, 2023.
- [16] S. Dhar et al., "Effect of cerium oxide nanoparticles on diesel engine performance," *Energy Conversion and Management*, 2019.
- [17] A. Sharma et al., "Hybrid nanoparticle additives in diesel fuel for improved combustion," *Energy Reports*, 2022.
- [18] B. Patel et al., "CFD analysis of nanofluid combustion in compression ignition engines," *Applied Thermal Engineering*, 2023.

