International Journal of
I.C. Engines and Gas Turbines
ISSN: 2582-290X
Volume 9, Issue 1, 2023
DOI (Journal): 10.37628/IJICEGT
http://mechanical.journalspub.info/index.php?journal=JIEGT&page=index
Review IJICEGT

Diesel Engine Combustion and Emission Characteristics Study, Taking into Account the Potential of Biogas Substitution for the Purpose of Enhancing Environmental Cleanliness and Promoting Health

M.S. Baranedharan[1,*], Ashis Acharjee[2]

Abstract

Necessity for alternative fuels arises from the escalating energy requirements and the detrimental effects of fossil fuel emissions on environmental well-being. Alternative fuels have been extensively researched to improve energy efficiency. A study examines how alternative fuel affects compression ignition (CI) engine performance, pollution, and combustion. Biogas is investigated as a diesel engine fuel substitute in this study using computational fluid dynamics (CFD). Upon doing a thorough examination of the existing studies, it can be concluded that biogas exhibits promising potential as a viable alternative to diesel engines. The process involved the conversion of diesel engines of moderate size to operate on biogas. The engine underwent comprehensive testing in many situations and was afterwards compared to a diesel-only engine. Biogas engines performed similarly to diesel engines in middle speed and high torque. The biogas engine exhibited inferior performance compared to the diesel engine when operating at higher velocities and lower levels of torque. The attainment of precision is accomplished through the utilization of computational fluid dynamics (CFD) for the purposes of conducting combustion and emission assessments. In the context of combustion, computational fluid dynamics (CFD) investigations have revealed the presence of a stable flow characteristic in layer formation systems, which has been found to enhance the accuracy of simulations.

Keywords: Alternative fuel, energy demand, environmental pollution, biogas, CI engine, CFD analysis

***Author for Correspondence**
M.S Baranedharan
E-mail: sbharaneed4@gmail.com

[1]Research Scholar, Department of Mechanical Engineering NIT Agartala, Tripura, India
[2]Assistant Professor, Department of Mechanical Engineering NIT Agartala, Tripura, India

Received Date: October 06, 2023
Accepted Date: October 19, 2023
Published Date: December 07, 2023

Citation: M.S. Baranedharan, Ashis Acharjee. Diesel engine combustion and emission characteristics study, taking into account the potential of biogas substitution for the purpose of enhancing environmental cleanliness and promoting health. International Journal of I.C. Engines and Gas Turbines. 2023; 9(1): 24–39p.

INTRODUCTION

Municipal and agricultural wastes are anaerobically digested to produce renewable biogas. Methane (CH_4) and carbon dioxide (CO_2) dominate biogas [2]. CH_4 content determines biogas heat [1]. Biogas from most anaerobic digesters is 40%–75% methane [6]. Methane weighs 0.75 kg/m3 at standard pressure and temperature. More carbon dioxide raises biogas density to 1.15 kg/m3. Pure methane has a maximum calorific value of 39.8 MJ/m_3, or 11.06 Kwh. Biogas digester plant (BDP) digestion time affects biogas quality (Reddy & Reddy, 2013 [3]). In oxygen, good biogas burns blue. BIOGAS is a good engine fuel since it emits little CO_2. High energy density at lean mixes increases the biogas-to-carbon ratio, lowering the ignition limit and enhancing power output. Compression ignition engines cannot consume biogas directly due to their high auto ignition temperature. Huang & Crookes [4] suggested pilot lighting biogas with diesel spark plugs or a little diesel fuel. Natural gas has a higher combustor gas temperature than biogas and air combustion (Mihic, 2004) [12]. CO_2/CH_4 ratio determines biogas combustion temperature (Razbani, et al., 2011) [13]. The CO_2/CH_4 ratio lowers biogas temperature by 37% for every 22% increase. Huang & Crookes [14] say biogas reduces combustor NOx emissions due to its lower heating value. High gas temperatures yield high NOx (mainly NO) emissions because thermal NOx emission is a function of gas temperature. Flame temperature and NO mass fractions decrease with biogas containing carbon dioxide and nitrogen. The biogas CO_2/CH_4 ratio reduces combustor outlet NOx emissions, but CO_2 emissions rise with CO_2 input. Adding CO_2 to methane absorbs combustion energy and slows flame burning. The composition of biogas impacts combustion emissions. Biogas fuel with higher CO_2 percentages reduces NOx and increases combustor exit CO_2 emissions. CO emissions decrease with greater CO_2 /CH_4 biogas fuel [7].

Biogas is produced through anaerobic digestion of municipal and agricultural wastes. Biogas is CH_4 and CO_2 [2]. Biogas warms better with CH_4 [5]. Biogas from most anaerobic digesters contains 40%-75% methane. Methane weights 0.75 kg/m3 at normal pressure and temperature. For heavier carbon dioxide, biogas density is 1.15kg/m3. Pure methane has a maximum calorific value of 39.8MJ/m_3, or 11.06 Kwh/m_3. With digestion time, biogas digester plant (BDP) biogas quality changes (Reddy & Reddy, 2013 [3]). Extra oxygen turns high-quality biogas blue. The low CO_2 emissions of biogas make it a good engine fuel. Biogas enhances energy density at lean mixtures, lowering the ignition limit and improving power output: biogas-to-carbon ratio. Biogas cannot be used in compression ignition engines due to its high auto ignition temperature. Huang and Crookes [4] suggested pilot lighting biogas with spark plugs or a little diesel gasoline. Biogas-air combustion produces lower combustor gas temperature than natural gas (Mihic, 2004) [12]. CO_2/CH_4 ratio determines biogas combustion temperature (Razbani, et al., 2011) [13]. Biogas temperature lowers 37% per 22% CO_2/CH_4 ratio increase. Huang & Crookes [14] showed that biogas reduces combustor NOx emissions due to its lower heating value. Gas temperature determines thermal NOx emission, hence high gas temperatures increase NOx (mainly NO) emissions. Carbon dioxide and nitrogen lower flame temperature and NO mass fractions. Higher biogas CO_2/CH_4 ratios lower NOx emissions at the combustor exit, while higher CO_2 fractions increase CO_2 emissions. Methane-containing non-reactive gas (CO_2) absorbs combustion energy and slows reaction zone flames. Biogas composition impacts combustion emissions. Higher biogas fuel CO_2 percentages reduce NOx and increase combustor exit CO_2 emissions. Increased biogas fuel CO_2/CH_4 ratio reduces CO emissions [8].

A dual-fuel compression ignition (CI) engine employing biogas and diesel is tested in this study. Biogas is renewable energy from biological waste. The input manifold is adapted to run on biogas and diesel to test an engine. Biogenic diesel fuel influences engine performance, including brake thermal efficiency, fuel consumption, and exhaust gas temperature, according to this study. The study examines these effects by changing engine load at rated speed. The trial found that 60% biogas and 40% diesel enhances engine braking thermal efficiency and fuel economy. Biogas-air rich mixtures demonstrated superior thermal efficiency than diesel-air mixtures under the same conditions. All test situations showed alternative fuels had lower exhaust gas temperatures than diesel.

When methane proportion increased in typical fuel mixes, diesel fuel injection timing had to advance. These decreased fuel usage, CO, HC, and exhaust smokiness and boosted thermal efficiency. We examine biogas's fundamental effects on internal combustion engines. The study found that biogas with CO_2 promotes thermal dissociation in IC engines. Energy absorption by methane combustion heats exhaust. The simulation showed that methane is biogas's most energy-efficient component. Thus, biogas may be a preferable fossil fuel substitute if CFD models are used for feasibility assessments before industrial application.

Experimental Investigation

NIT Agartala's Mechanical Engineering Department's IC Engine Lab conducted experiments. A 1-cubic-metre anaerobic digester produces biogas. This plant feeds the engine petrol after eliminating CO2 and moisture. A single-cylinder 5 kW diesel engine powered the experiment. 1500-rpm water-cooled engine. Table 1 show the lists of engine parameters and Table 2 show the properties of biogas and diesel [12]. Biogas and air are mixed in the engine's intake manifold gas kit. This mixture goes to the engine's inlet manifold through a T-joint. During suction, the engine takes air and biogas from the air filter. Engine diesel mass was measured with a manometer [13]. A gas flow metre measures digester gas before it reaches the engine. Valve design boost air and biogas flow based on engine load [14]. The experimental setup is schematically shown in Figure 1 and photographed in Figure 2.

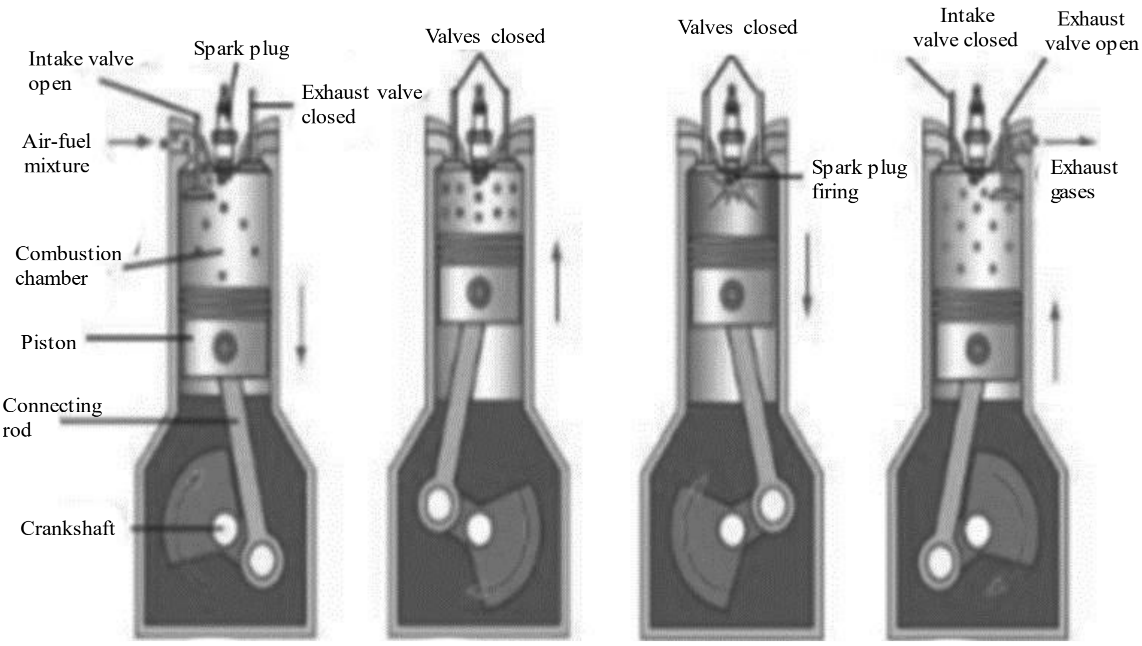

Figure 1. Modified version of Semin (2008) [15]'s four-stroke cycle.

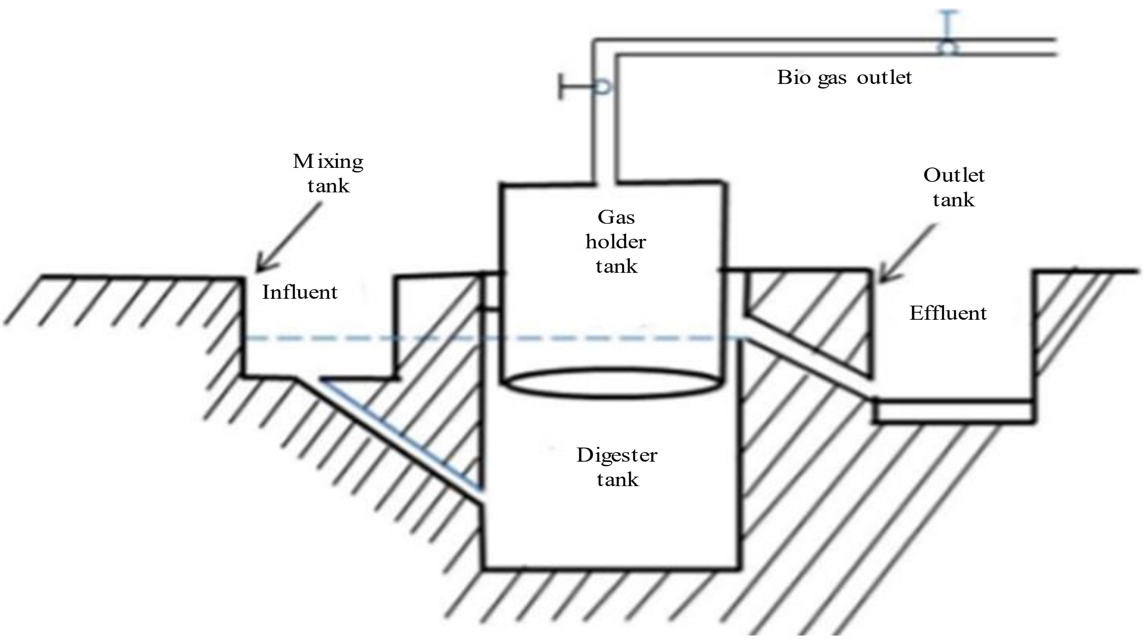

Figure 2. Construction of a Biogas Plant.

Table 1. Engine specifications change as Experimental Diesel engine specification.

Engine	**Kirloskar**
Type	Water cooled
BHP	5kW
No. of cylinders	1
Bore	87. 5
Stroke	110mm
Rated speed	1500 rpm
Combustion	Compression ignition

Table 2. Properties of biogas and diesel.

Property	**Biogas**	**Diesel**
Cetane number	-	50
Heating value(MJ/Kg)	24. 50	45. 92
viscosity@40°c	-	3. 32
Specific gravity@15°c	0. 001	0. 830
Sulphur content(%wt.)	0. 12	0. 037

Experimental Methodology

The experiment was run in a constant-speed compression ignition (CI) engine. The engine ran idle for a set time. Effective mechanical loading systems were used to manipulate the load during the experiment Figure 3. Equation 1 maintains a consistent speed from no load to maximum engine load.

Figure 3. Photographic view of experimental set up.

Brake power = Torque x angular velocity = (T1-T2) x Re x 2πN (1)

N = 1500 rpm

Re = Torque arm length= 0. 305 m

This study compares the performance of a compression ignition (CI) engine running on diesel and biogas at 20%, 40%, 60%, and 80% loads. To determine fuel consumption across load conditions, engine fuel consumption duration was also measured [15]. Biogas volume varied greatly with load. Equation 2 calculated brake thermal efficiency, brake specific fuel consumption, and exhaust gas temperatures.

Fuel Consumption [FC]

$$\left(\frac{\mathbf{10}}{\boldsymbol{Tavg}}\right) \boldsymbol{x\ specific\ graviy\ of\ fuel\ x\ Density\ of\ water} \qquad –2(i)$$

Specific Fuel Consumption [SFC]

$$= \frac{\boldsymbol{fuel\ consumption}}{\boldsymbol{brake\ power}} \qquad –2(ii)$$

Fuel Power

$$= \frac{\boldsymbol{fuel\ consumption}}{\boldsymbol{heating\ value\ of\ fuel}} \qquad –2(iii)$$

Brake Thermal Efficiency

$$= \frac{\boldsymbol{brake\ power}}{\boldsymbol{fuel\ power}} \qquad –2(iv)$$

RESULTS AND DISCUSION

The experiment changed load at 1500 rpm. This engine ran on diesel with varied biogas-diesel mixes under identical conditions. Diesel engines brake harder than biogas ones. Its higher calorific value makes diesel fuel different [9]. Figure 4 shows brake power varies with load. Engine braking power increases with load at rated speed. Biogas combination decreases engine brake power. Fuel mixtures may be less energetic. Experimental results demonstrate diesel brake power is consistently higher than diesel-biogas. IC Engine Combustion Analysis Software 9.0 measures brake power, fuel, thermal efficiency, and exhaust gas temperatures. This research uses diesel, VCR, and smoke metre.

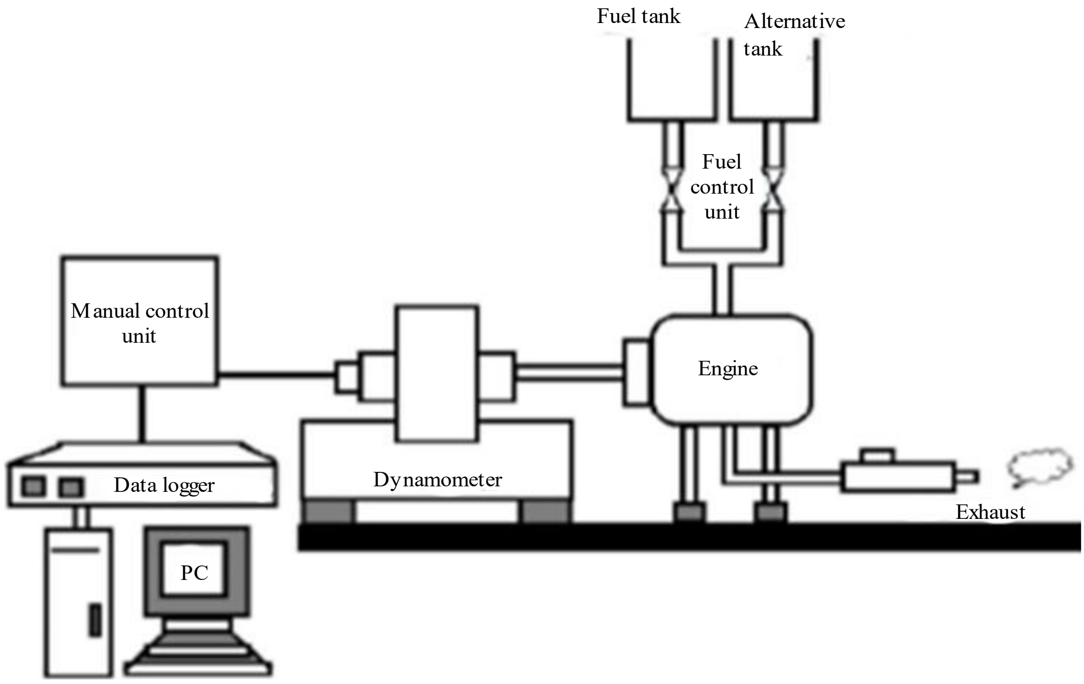

Figure 4. Experimental diesel engine installation change as Experimental Diesel engine line diagram layout

Load

5.9 kg, 7.5 kg, 8.6 kg, 9.5 kg, 10.9 kg.

BIOGAS AND DIESEL BLENDS

Engine settings were similar while biogas and diesel mixtures were varied. Diesel consistently has more brake power than a diesel-biogas blend, according to experiments. Diesel and diesel-biogas engines have similar specific fuel consumption (SFC) at idle. The graphs are shown (Figures 5–8).

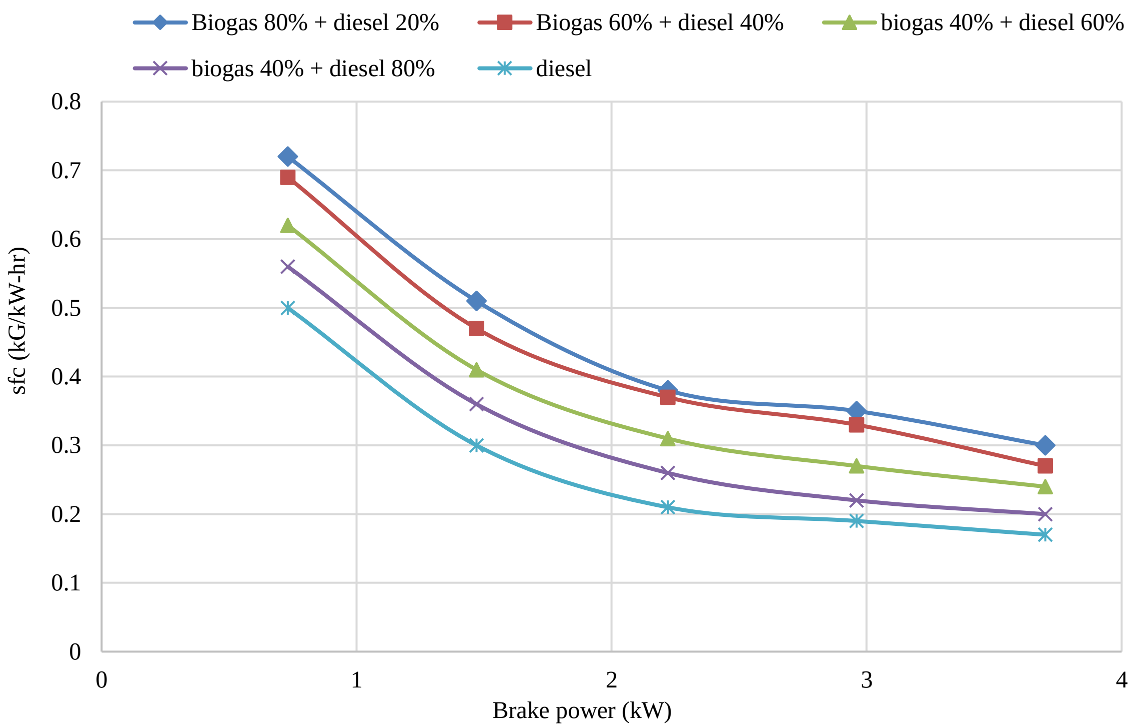

Figure 5. Power dissipated by the brakes as a function of load.

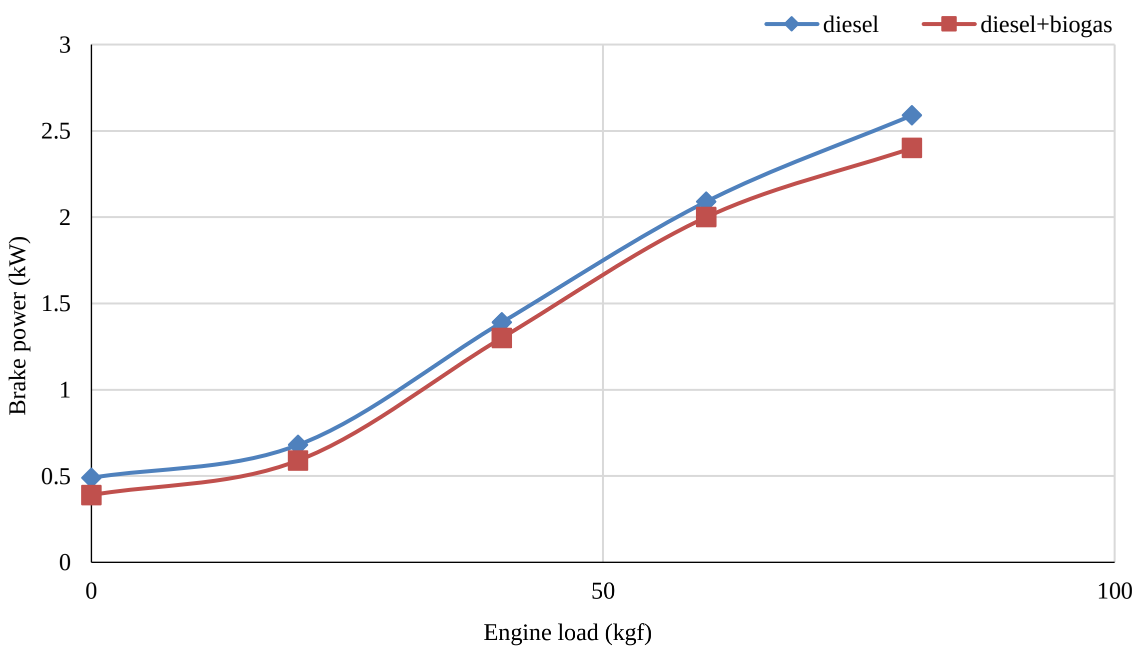

Figure 6. Variation between specific fuel consumption (SFC) and brake power.

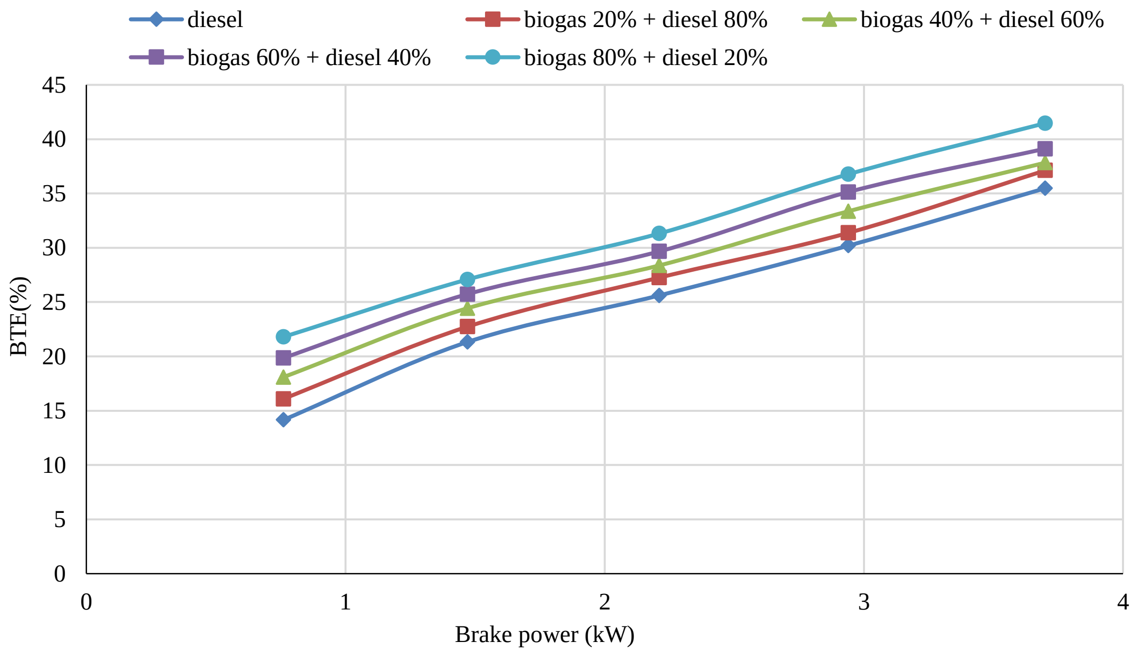

Figure 7. Variation of BTE Vs brake power.

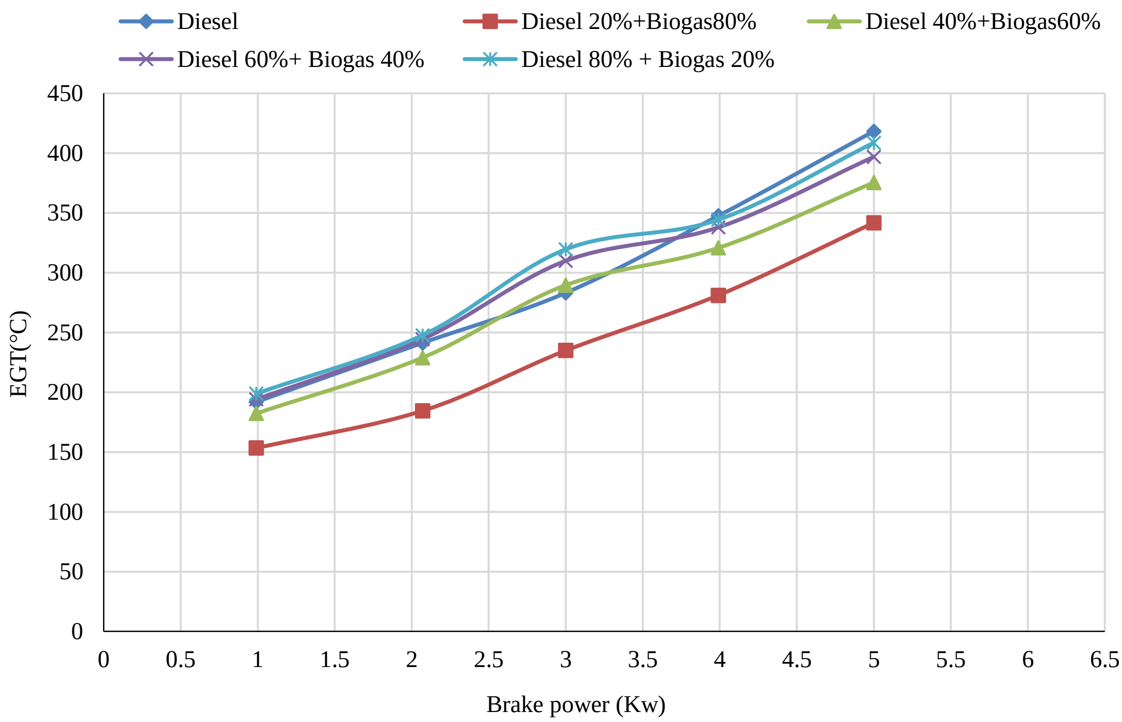

Figure 8. Variation of EGT Vs brake power.

CFD Analysis of Combustion, Emission model and Performance of CI Engine

IC chambers and combustion processes are designed and investigated using many computational tools to increase combustion efficiency. Calculate combustion-dependent parameters and analyse combustion processes with CFD. CFD numerically solves non-linear partial differential equations to predict fluid flow. CFD is essential for complex engineering challenges. Problems include turbulence, hot spots, compression ratios, ignition constraints, ignition time optimisation, exhaust pollutants, and combustor performance. A user entered a number. Computational fluid dynamics uses continuity, momentum, and energy equations [10]. This work formulates equations using three key parameters.

(a) Mass is conserved. (continuity equation)
(b) $F_{net} = ma$ (Newton's second law), momentum is conserved
(c) Energy is conserved.

The Navier-Stokes (NS) equations characterise fluid flow using non-linear partial differential equations that relate fluid stress to velocity gradients and pressures [11]. The Navier-Stokes equation ignores fluid molecule discreteness. The shift from laminar to turbulent flows is often described by Reynolds number. The conservation laws state that the temporal derivative of mass, momentum, or energy within a volume is equal to their influx over its limits and the internal generation rate [3].

CFD Analysis

FLUENT was utilised for CFD analysis of biogas-diesel dual fuel mode combustion and exhaust. The study altered fuel mixture biogas replacement. This study just presents emission analysis results. The diesel fuel was introduced with a 0.15-unit nozzle. The combustion chamber received biogas at 60 bar and air at 160 bar. Experiments proved dual fuel exhaust species analysis. Experimental and computer simulation and CFD results were compared to validate the code and model. Diesel and biogas received a 200-degree injection angle before top dead centre. The amounts of NOx, N_2, CO_2, and H_2O were monitored following 20% hydrogen concentration variations. All analyses included temperature and pressure. Simulation results were compared to data. The code was verified by comparing simulation and CFD results to experimental data.

RESULT AND DISCUSIONS

Analysis of Effect of Compression Ratio

Compression Ratio and Combustion Velocity: As compression ratio increases, working mixture pressure and temperature rise. Thus, the early preparation phase of combustion decreases, requiring less ignition advance. High pressures and temperatures accelerate secondary combustion. Increased compression ratio reduces clearance volume, increasing gas density in the cylinder during combustion. Peak pressures and temperatures rise, but combustion duration decreases. Figures 9 and 10 show that larger compression ratios increase flame speeds. Increasing the compression ratio from 16.35 to 24.5 increased flame speed by 46.9%.

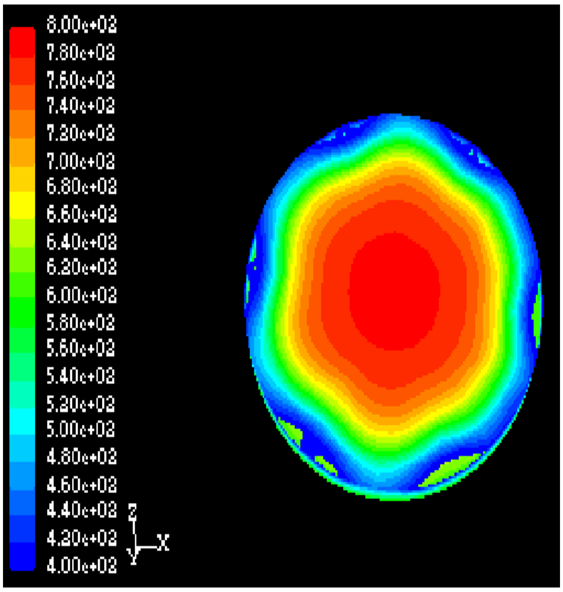

Figure 9. CFD Analysis of Combustion Velocity for CR 24.5, 20% Biogas.

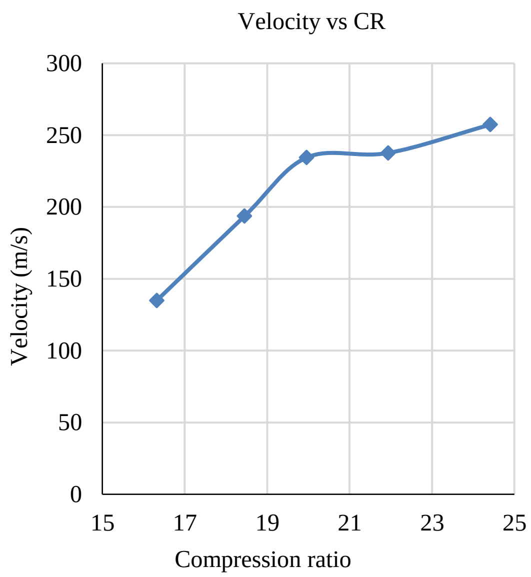

Figure 10. Effect of compression ratio on combustion velocity.

Effect of Compression ratio on Turbulent Kinetic Energy with(T.K.E.)

Based on the data presented in Figures 11 and 12, the study reveals a significant increase of 49.8% in turbulent kinetic energy when the CR (compression ratio) was altered from 16.35 to 24.5. The red patches in Figure 13 indicate regions of elevated turbulent kinetic energy (T.K.E) near the walls of the cylinder.

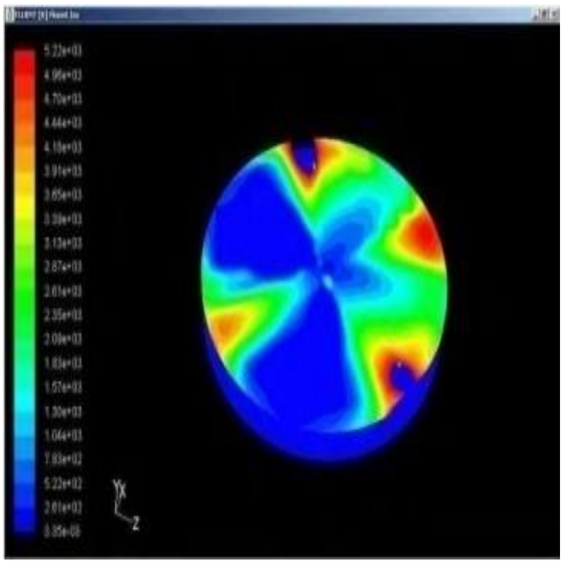

Figure 11. CFD Analysis of Turbulent K.E. For CR 24.5, 20% Biogas.

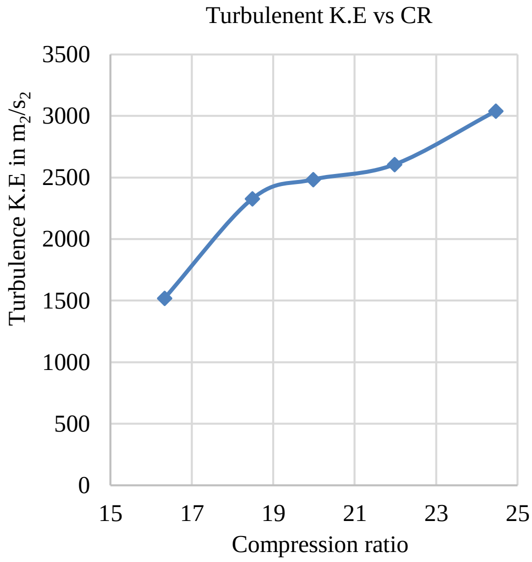

Figure 12. CFD Results Analysis of Turbulent Kinetic Energy vs Compression ratio.

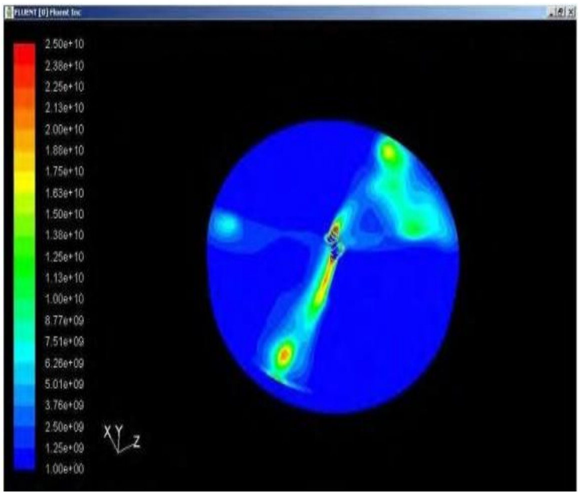

Figure 13. CFD Analysis of Turbulent Dissipation rate for CR 24.5, 20% Biogas

Effect of compression ratio on Turbulent Dissipation Rate

Flame velocity is modest in non-turbulent mixes but rises with turbulence. This occurs because the leading edge of the flame mixes combusted and uncombusted particles, increasing the chemical reaction through increased intermolecular contact. Turbulence increases heat transmission to the cylinder walls. Blending fuels and oxygen speeds up the chemical process, minimising the requirement for spark advance. Figures 14 and 15 of the outcome analysis reveal that compression ratio increases turbulent kinetic energy and dissipation rate. Reduced combustion duration reduces aberrant combustion. Biogas burns three times faster than petrol. Diesel-biogas combustion is faster with this trait. Additionally, this combination increases turbulent kinetic energy and dissipation rate while reducing aberrant combustion. The turbulent dissipation rate increased 91.4% when the compression ratio (CR) was increased from 16.35 to 24.5.

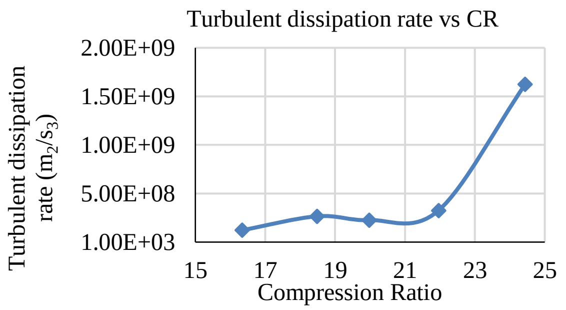

Figure 14. CFD Results Analysis of Turbulent Dissipation Rate vs Compression ratio.

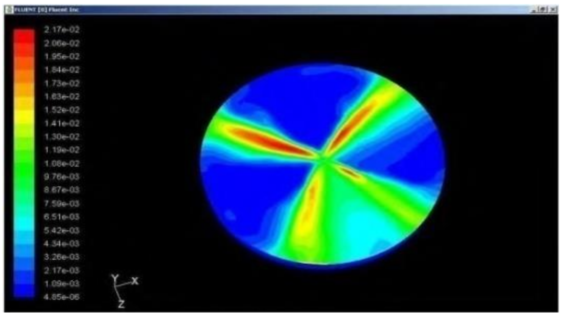

Figure 15. CFD Analysis of turbulent viscosity for CR 24.5, 20% Biogas.

Effect of Compression Ratio on Turbulent Viscosity

The turbulent viscosity exhibits an upward trend as the distance from the central region of the nozzle section increases the more visual representation.

Effect of compression ratio on NOx

As observed in the aforementioned analysis, the emission of nitrogen oxides (NOx) exhibits a positive correlation with the compression ratio. Specifically, a significant rise of 56.5% in NOx emissions was observed when the compression ratio was altered from 16.35 to 24.5. Localised areas with elevated concentrations of nitrogen oxides (NOx) are observed inside the NOx contours.

Effect of Biogas substitution

CFD was used to analyse how biogas replacement affects combustion parameters at 24.5 compression ratio. Biogas substitution ranges from 20% to 80%. The impact of this variation is then investigated. Biogas is injected into the combustion chamber through a hydrogen injector at 50–60 bar. The diesel injection pressure was 160 bar, and air intake was atmospheric.

Effect of Biogas substitution on NOx

The contours and graphs in the mole fraction of NOx changes with biogas %. As biogas content rises, NOx mole fraction falls. The main cause is the mixture's biogas proportion, which raises moisture content, notably H_2O mole fraction. Increased moisture lowers combustion temperature. As combustion temperature decreases, NOx generation decreases, lowering NOx concentration and increasing biogas substitution.

Effect of Biogas substitution on Density

Figure 16 illustrates that a rise in hydrogen substitution results in a decrease in density. This is in contrast to the observed trend of rising density with compression ratio. The density of biogas is approximately one-tenth that of petrol, therefore, an increase in biogas results in a decrease in density. This observation is further supported by the density contours.

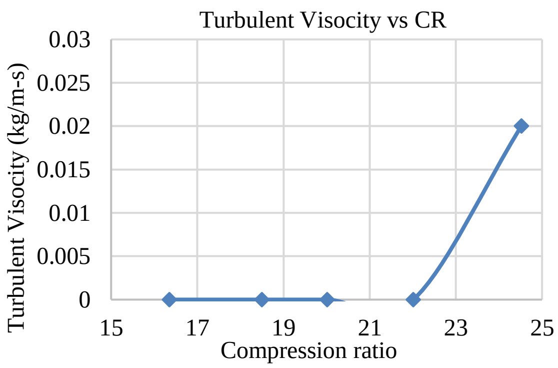

Figure 16. CFD Results analysis of turbulent viscosity Vs compression ratio.

Effect of Biogas substitution on Turbulent Kinetic energy

Figures 17 and 18 indicate that biogas content increases turbulent kinetic energy, indicating rapid combustion and energy release. Turbulence boosts combustion, diffusion, and flame front speeds. diesel-style dual fuel mode features two stages. First, the diesel spray burns diesel and biogas, then biogas is burned via flame propagation from the ignition centres. The second step is stronger because biogas combustion by flame propagation produces more heat than diesel. Biogas substitution releases heat quicker at high outputs. Replacement becomes richer biogas-air combinations as biogas % rises. This accelerates combustion, increasing dual fuel mode pressure. Second-phase diesel spray flame propagation consumes biogas after diesel injection initiates the flame. Two fuels provide additional heat due to linked combustion. This boosts dual fuel mode thermal efficiency at high outputs.

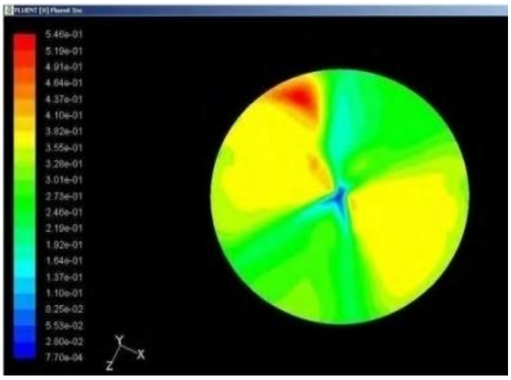

Figure 17. CFD Analysis of NOx for CR 24.5, 20% Biogas.

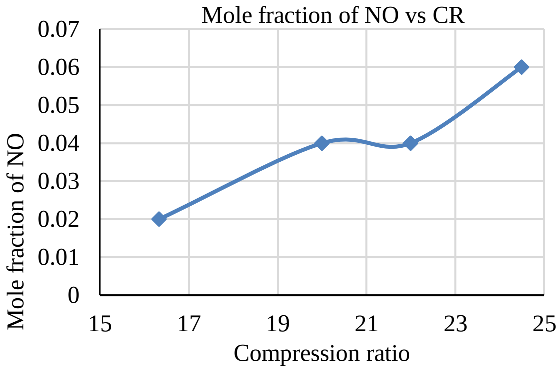

Figure 18. CFD Results Analysis of Mole Fraction of NOx Vs Compression ratio.

Effect of Biogas substitution on Turbulent Dissipation Rate

The contour plots in Figures 19 and 20 demonstrate a significant rise in turbulent dissipation rate as the percentage of biogas increases. This observation can be attributed to the same underlying mechanism as discussed for the variation in turbulent kinetic energy.

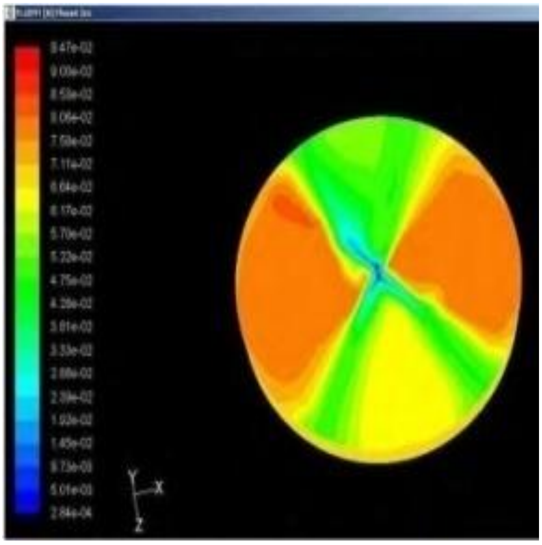

Figure 19. 20% Biogas.

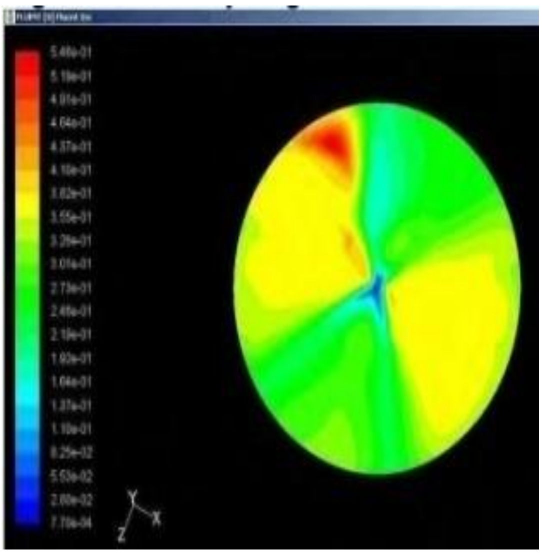

Figure 20. 40% Biogas.

Effect of Biogas substitution on Mole fraction of H_2O

The mixture's mole fraction of H_2O (moisture) increases with biogas proportion (Figure 21). As moisture increases, cylinder peak combustion temperatures decrease (Figure 22), reducing NOx production.

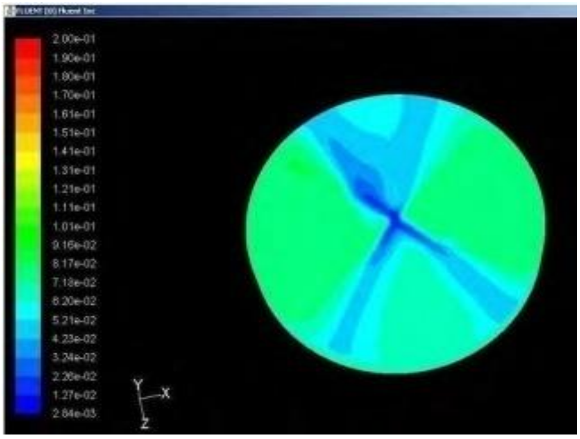

Figure 21. 60% Biogas.

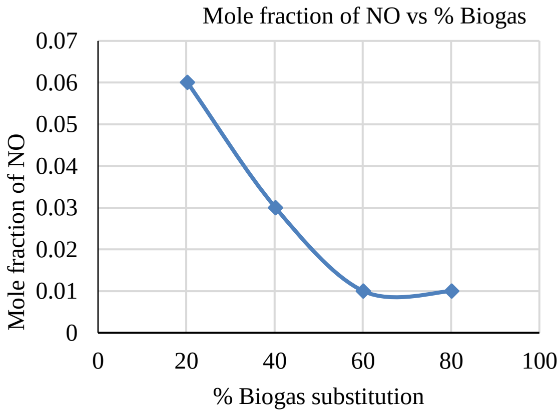

Figure 22. CFD Results analysis of NOx vs % biogas substitution.

Effect of Biogas substitution on Combustion velocity

Figures 23 and 24 show that combustion velocity increases dramatically with biogas proportion. It grew roughly twice as much with 20% substitution as with 80% substitution. The biogas is highly flammable. Experimental heat release rate and peak pressures for various compression ratios are illustrated in figures 25 and 26. The values match predictions. Figures 27 to 29 indicate expected CO_2 and NOx emissions. In Figure 30 to 35 show the Compression ratios.

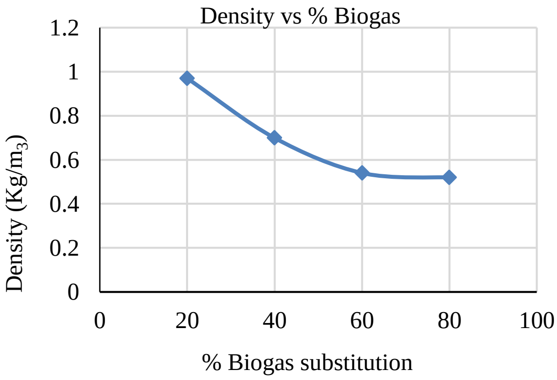

Figure 23. CFD Results analysis of density Vs % biogas substitution.

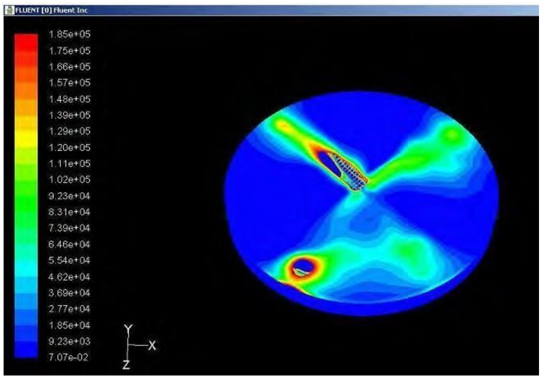

Figure 24. Turbulent K.E. at 60% Biogas.

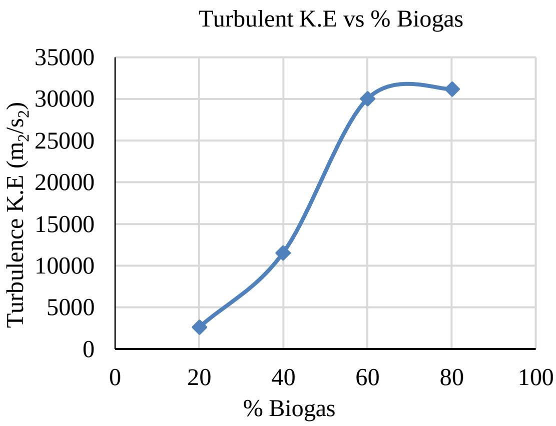

Figure 25. CFD Results Analysis of Turbulent Kinetic energy Vs % Biogas Substitution.

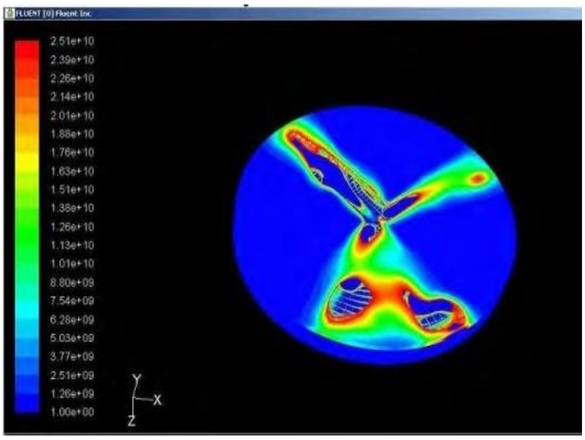

Figure 26. Turbulent dissipation rate at 60% Biogas.

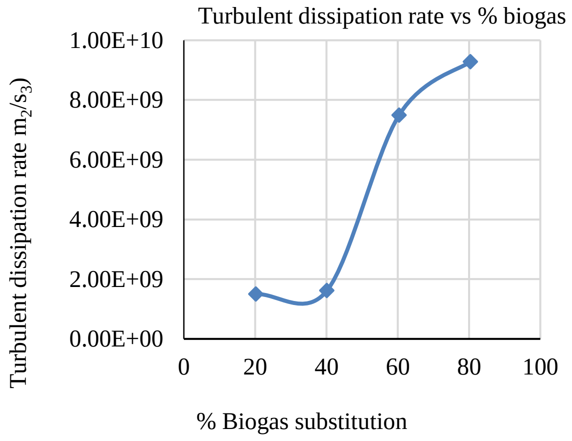

Figure 27. CFD Results analysis of turbulent dissipation rate vs % biogas substitution.

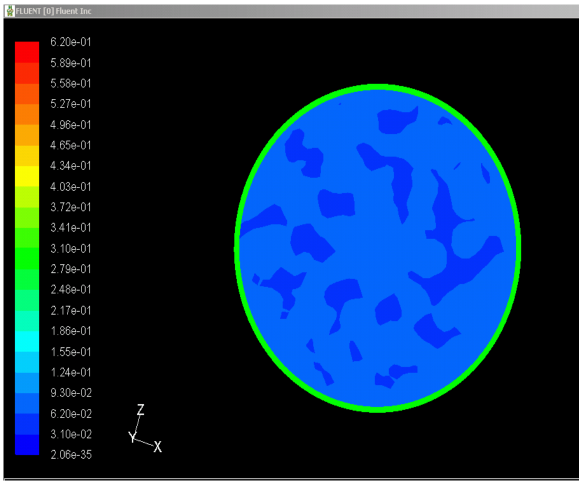

Figure 28. 80% Biogas.

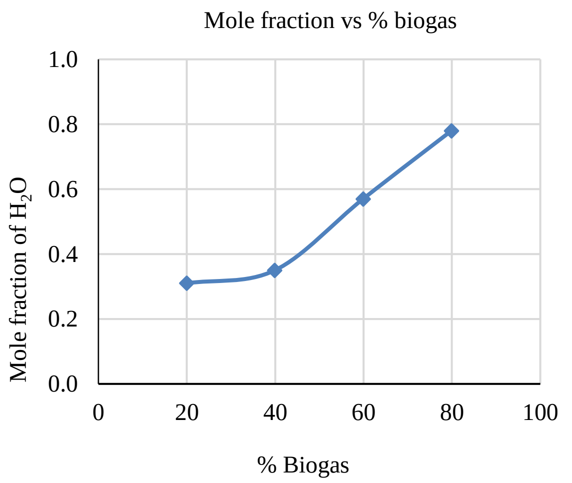

Figure 29. CFD Results Analysis of Temperature vs % Biogas substitution.

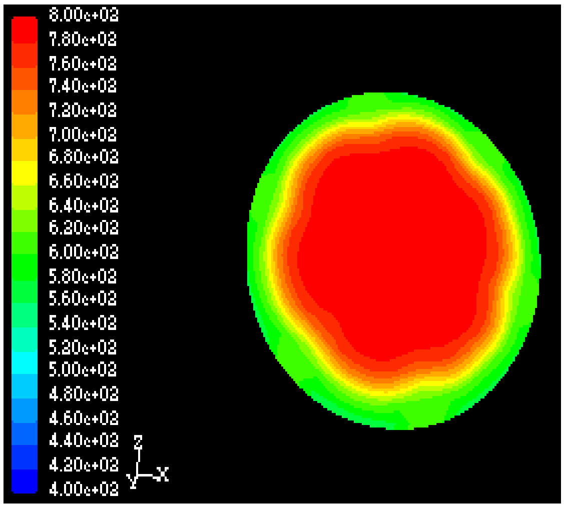

Figure 30. Combustion velocity at 80% Biogas substitution

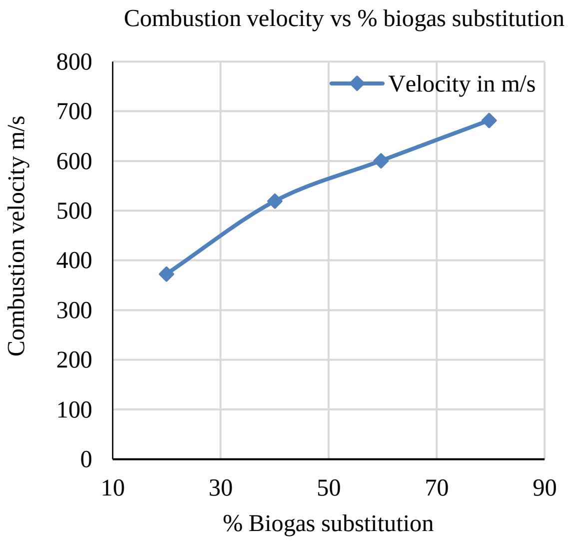

Figure 31. CFD Results analysis of combustion velocity vs % biogas substitution.

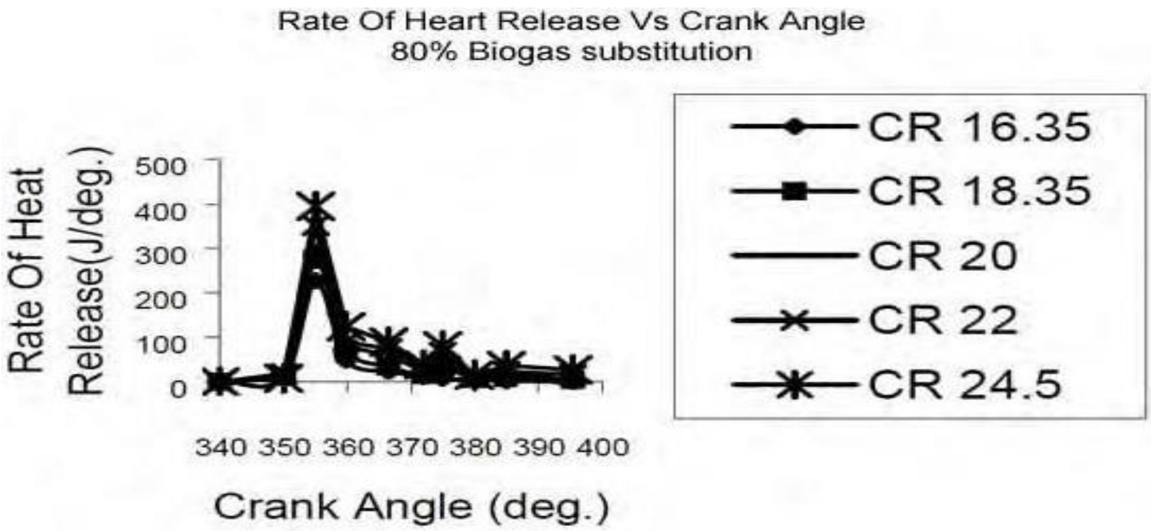

Figure 32. Heat Release rate at different Compression ratios

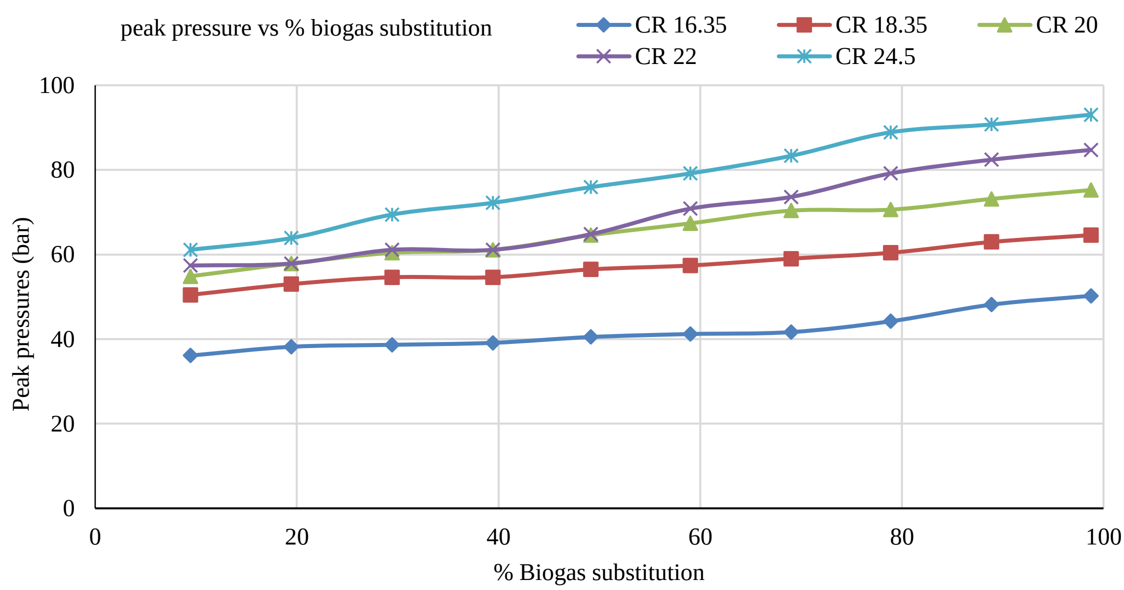

Figure 33. Peak pressures at different Compression ratios.

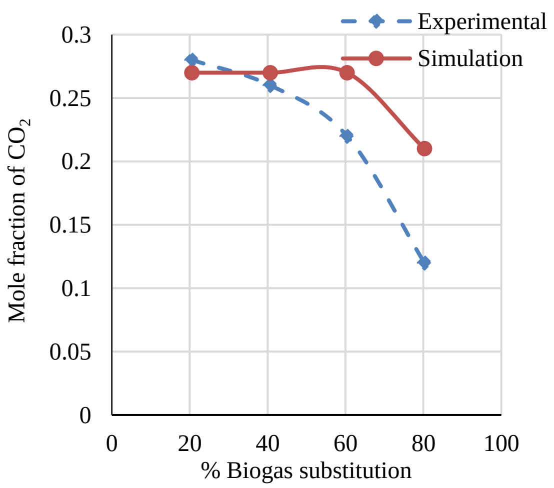

Figure 34. Comparisons of CO_2

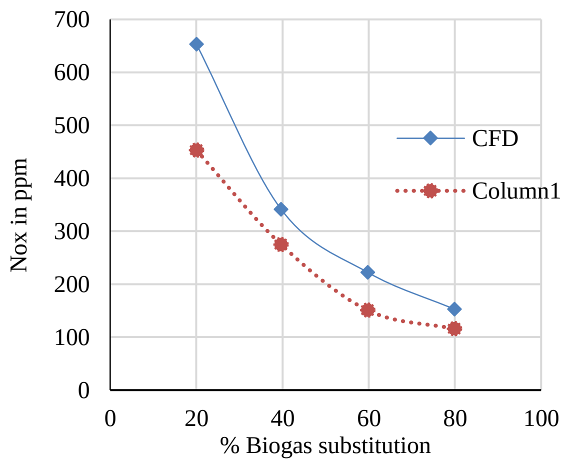

Figure 35. Comparisons of Nox.

GENERAL CONCLUIONS

This study indicated that biogas in a diesel engine required injection timing adjustment. Exhaust pollutant concentrations, except NOx, rose with petrol supply without engine control system changes.

Smokiness, CO, and HC in exhaust decreased as air/fuel ratio increased, whereas NOx increased. Although promising, the high air/fuel ratio increased fuel consumption and decreased thermal efficiency.

Adjusting diesel fuel injection timing enhanced many traits. Diesel fuel injection timing was advanced to improve thermal efficiency, fuel consumption, CO and HC concentrations, and exhaust smokiness as methane content increased. NOx pollution increased as a result.

Using a petrol with 30% methane (M95% at 30 l/min) in a diesel engine running at 2500 min-1 at 60 N m with a mean effective pressure of 0.6 MPa reduced diesel fuel consumption and NOx concentration by 1.5-fold. The essential impacts of biogas ignition in an IC engine were modelled and reviewed. Study: biogas CO_2 promotes thermal dissociation in IC engines. Methane combustion causes its high exhaust temperature. The computer study showed that biogas's valuable energy is methane.

Future Scope

It can be asserted that biogas has the potential to serve as a more viable alternative to fossil fuels, contingent upon the conduction of computational fluid dynamics (CFD) simulation feasibility studies prior to its commercial adoption. Further study is necessary in order to enhance the efficiency of Biogas.

Acknowledgements

The authors express their gratitude to the Director of NIT Agartala and the Head of the Department of Mechanical Engineering for their support in facilitating the research conducted at the Department of Mechanical Engineering. Additionally, the authors extend their thanks to all those who provided assistance, both directly and indirectly, throughout the course of this research.

Data Availability

The authors confirm that this study's data are in this research report.

Conflict of Interests

All the authors contributed equally and has no conflict of interest in any way with this paper.

Funding Statement

The present research report is grounded on a research project conducted at the M.tech level. The writers of the article affirm that financial resources were not utilised in the execution of this research manuscript.

REFERENCES

1. Kalsi, S.S., & Subramanian, K.A. (2017). Effect of simulated biogas on performance, combustion and emissions characteristics of a bio-diesel fueled diesel engine. Renewable Energy, 106, 78–90.
2. Yilmaz, I. T., & Gumus, M. (2017). Investigation of the effect of biogas on combustion and emissions of TBC diesel engine. Fuel, 188, 69–78.
3. Makareviciene, V., Sendzikiene, E., Pukalskas, S., Rimkus, A., & Vegneris, R. (2013). Performance and emission characteristics of biogas used in diesel engine operation. Energy Conversion and Management, 75, 224–233.

4. Deheri, C., Acharya, S. K., Thatoi, D. N., & Mohanty, A. P. (2020). A review on performance of biogas and hydrogen on diesel engine in dual fuel mode. Fuel, 260, 116337
5. Henham, A., & Makkar, M. K. (1998). Combustion of simulated biogas in a dual-fuel diesel engine. Energy Conversion and Management, 39(16– 18), 2001–2009.
6. Ambarita, H. (2017). Performance and emission characteristics of a small diesel engine run in dual-fuel (diesel-biogas) mode. Case studies in thermal engineering, 10, 179–191.
7. Cacua, K., Amell, A., & Cadavid, F. (2012). Effects of oxygen enriched air on the operation and performance of a diesel-biogas dual fuel engine. Biomass and bioenergy, 45, 159–167.
8. Barik, D., & Murugan, S. (2016). Experimental investigation on the behavior of a DI diesel engine fueled with raw biogas–diesel dual fuel at different injection timing. Journal of the Energy Institute, 89(3), 373–388.
9. Senthilkumar, K., & Vivekanandan, S. (2016). Investigating the biogas as secondary fuel for CI engine. *International Journal of Applied Environmental Sciences*, *11*(1), 155–163.
10. Hussain, S. M., Kumar, D. B. S. P., & Reddy, K. V. K. (2012). CFD analysis of combustion and emissions to study the effect of compression ratio and biogas substitution in a diesel engine with experimental verification. *International Journal of Engineering Science and Technology*, *4*(2), 473–492.
11. Mukumba, L. M. D. P. CFD Contextual Modeling of Biogas Combustion in Internal Combustion Engine: A Review.
12. Mihic, S., (2004). Biogas Fuel for internal combustion Engines, Annals of Faculty Engineering, Hunedoara. Vol 2 (3), 411.
13. Mihic, S., (2004). Biogas Fuel for internal combustion Engines, Annals of Faculty Engineering, Hunedoara. Vol 2 (3), 411.
14. Huang, J. and Crookes, R. J. (1998). Assessment of simulated biogas as a fuel for the spark ignition engine. Fuel, London, v. 77, n. 15, p. 17931801, 1998.
15. Semin, R.A.B., (2008). A technical review of compressed natural gas as an alternative fuel for internal combustion engines. American J. of Engineering and Applied Sciences, 1(4), pp.302–311[1]

