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Performance Enhancement of Internal Combustion Engines Using Alternative Biofuels

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Abstract- Due to the increasing demands for energy in the world coupled with increased environmental regulations, it is now necessary to use sustainable energy sources instead of the traditional fossil fuels for internal combustion engines. In this paper, a study on performance improvement in compression ignition engines through the use of alternative biofuels has been presented. The study focuses on hydrotreated vegetable oil (HVO), biodiesel blends and the use of dual fuel where the two fuels used include biogas and hydrogen. The results of experimental and computer simulations show that the use of HVO leads to reduction of NOx and CO by 9.0% and 38.7%, respectively, compared to fossil diesel. Turbocharged B20 biodiesel blends lead to fuel consumption reduction of 20% and brake torque increase of 75%. The canola biodiesel gives brake thermal efficiency of 31.2% and brake-specific fuel consumption of 0.26 kg/kWh.

Keywords- Biofuels, Internal Combustion Engines, Performance Enhancement, Hydrotreated Vegetable Oil, Biodiesel, Dual-Fuel Combustion, Emissions Reduction.

I. INTRODUCTION

Transportation accounts for about 14% of greenhouse gases globally, which is mainly caused by the use of ICE vehicles fueled with gas and diesel [2][6]. Internal combustion engine vehicles have always been integral in mobility for personal and business purposes due to their simplicity, low cost, and reliability [2][6]. Nonetheless, the extensive use of such cars leads to significant emissions of CO_2, NOx, HC, and PM, thereby causing air pollution and global warming [2][6]. As a result of the increasingly stringent emission standards, which include the upcoming Euro 7 emissions standards in the European Union, as well as agreements made internationally like the Paris Agreement and the UN sustainable development goals, there is an urgent need for decarbonization in the transportation sector [2][6].

Alternative biofuels have been introduced as viable, renewable, and biodegradable alternatives in tackling the dependency on and the adverse impacts of fossil fuels [6]. Biodiesel is extracted using organic and non-fossil sources, and it can be obtained from varied sources ranging from first-generation oils from vegetables, second-generation oils and fats from wastes, and third-generation microbe or microalgae-based oils [3][6]. The important features of biodiesel include availability from waste sources, renewability, non-toxic nature, and biodegradability, making biodiesel an alternative to diesel [3][6]. On the other hand, the use of pure vegetable oils directly into engines poses problems such as high viscosity, volatility, and carbon deposition on engine parts [3][6].

Hydrotreated Vegetable Oil (HVO) has been seen as a prospective alternative to fossil diesel with better combustion and sustainability aspects [1][5]. The use of HVO is commercialized in Europe and America [5]. HVO shows reduced ignition delay and lesser emission of CO, CO2, hydrocarbons, and particulate matter when compared with fossil diesel and fatty acid methyl esters (FAME) [1]. Apart from the direct use of biofuels, dual fuel combustion systems using renewable fuels like biogas, hydrogen, and ethanol in conjunction with biodiesel also have great potential [10].

Recently, due to developments in intelligent engine optimization, which involve AI and IoT, the real-time adaptive control of ignition timing, air-fuel ratio, and emissions parameters have led to thermal efficiency enhancement to 8% and reduction of emissions by more than 20% [8]. However, there is an absence of a framework that can concurrently assess multiple categories of biofuel, various blends, engine designs, and intelligent optimization methods [8].

This work aims to bridge the gap in the existing knowledge through conducting a comprehensive review of performance improvement in IC engines fueled with biofuels [2][3][6]. This study will examine blends of biodiesels, HVO, dual-fuels, and intelligent optimization methods [1][5]. The quantitative assessment will be done based on BTE, BSFC, power, and NOx, CO, HC, and CO_2 emissions [8].

II. LITERATURE SURVEY

Numerous studies have been undertaken into alternative fuels for internal combustion engines in relation to improved efficiency and emissions reductions [2][3][6]. A review of studies comparing bioethanol, compressed natural gas (CNG), hydrogen, fusel oil, biogas, biodiesel, vegetable oil, methanol, and butanol showed that the use of bioethanol and gasoline in blends increases thermal efficiency by up to 5% and engine power by 10% while reducing CO_2 and HC emissions by 30% and 40%, respectively [2]. The use of fusel oil and its blends (F20) increases engine power by 8% and reduces CO and HC emissions by 25-30%, with minor changes needed in the engine design [2]. Hydrogen is highly efficient and has zero emissions of CO_2, CO, and HC, though NOx emissions control is key [2].

Valeika et al. studied the effect of HVO and biobutanol blends on energy parameters of a compression ignition engine through a turbocharged direct injection engine [1]. They found that HVO100 fuel was associated with 1.7% to 28% reduction in brake-specific fuel consumption than fossil diesel [1]. HVO100 however caused a 4.4% decline in brake thermal efficiency when the engine speed was 4500 rpm [1]. Four types of HVO-biobutanol blends (HVO100, HVOB5, HVOB10 and HVOB20) were used as an alternative to fossil diesel in the study [1].

Nagappan et al. carried out a detailed review on biodiesel, bio-alcohol, bio-oil and plastic oil as an alternative fuel [3]. In their review, they showed that oxygenated biofuels lower particulate matter, carbon monoxide and unburned hydrocarbons but may cause an increase in nitrogen oxides emission while pure biofuels generate slightly less power than conventional diesel [3]. The review stressed the significance of optimizing the fuel through better engine control, dual fuel and additive concepts [3].

A comparative study between naturally aspirated and turbocharged engines running on waste oil biodiesel and diesel blends showed that use of turbocharge with B20 blend significantly lowered emissions but had performance almost similar to conventional diesel [4]. Turbocharging reduced fuel consumption by up to 20% and increased brake torque by up to 75%, while B20 provided almost similar performance as petroleum diesel [4]. Unburnt hydrocarbon emissions decreased by around 6% under boost conditions [4].

The computational fluid dynamic (CFD) study of HVO and biogas dual fuel combustion in CI engines indicated that HVO fuel combustion alone resulted in reduction of NOx emission by 9.0%, CO emissions by 38.7%, and provided slightly higher combustion efficiency [5]. The combination of HVO-biogas dual fuel combustion gave lowest NOx emissions amongst all the cases, and this reduction was up to 25.7% [5]. The CFD simulation provided good agreement for pressure and heat release characteristics [5].

Kumar & Kumar conducted research to investigate animal tallow-based microemulsion hybrid biofuel in CI engines and noted an increase in brake thermal efficiency of between 7.3% and 20.6% at part load [7]. Microemulsion hybrid biofuel made from a combination of animal tallow (68%), ethanol (20%), and butanol (12%) provided stable and homogenous fuel characteristics [7].

In the study of the multi-feedstock biodiesel-hydrogen synergies through a hybrid AI technique, Canola biodiesel produced a 31.2% BTE, 0.26 kg/kWh BSFC, low emissions such as 0.03% CO, 24 ppm HC, and 770 ppm NOx [8]. The hybrid algorithm comprised of machine learning and prediction models found that Canola oil was superior to other biodiesel variants [8].

The impact of EGR and hydrogen on liquid biofuel engines indicated that there is great potential for the reduction in emissions by liquid biofuels engines [9]. The table analysis of studies showed that biodiesel blends tend to reduce the emissions of CO and HC while increasing the NOx emission [9][10]. There is no doubt that biofuels have many environmental advantages, but it is necessary to use optimizing approaches including blending ratios, engine modification, and intelligent systems [8].

III. PROPOSED METHODOLOGY

Research Framework

The study uses a comprehensive methodology involving experimental studies, computational fluid dynamic simulations, and an artificial intelligence hybrid model to analyze performance improvement in internal combustion engines through alternative biofuels. The methodology includes

- Characterization of fuel and blend formulation
- Experimental studies on the engine
- CFD combustion simulations with experimental validation
- Performance prediction and optimization by AI

Fuel Preparation and Characterization

Some of the alternative biofuels researched in the past include biodiesel produced from various sources (Canola, Rapeseed, Jatropha, Pongamia, Mahua, waste cooking oil), hydrotreated vegetable oil (HVO), biobutanol, biogas, and hydrogen. The biodiesel production process involves the optimization of the transesterification process by using methanol to oil ratio of 6:1 for increased conversion rate.

Fuel characterization is done by measuring the density, kinematic viscosity, calorific value, cetane number, and cold flow properties according to ASTM. Blending is done on a volumetric basis (B5, B10, B20, B50, B60, B100, HVO100, HVOB5, HVOB10, HVOB20).

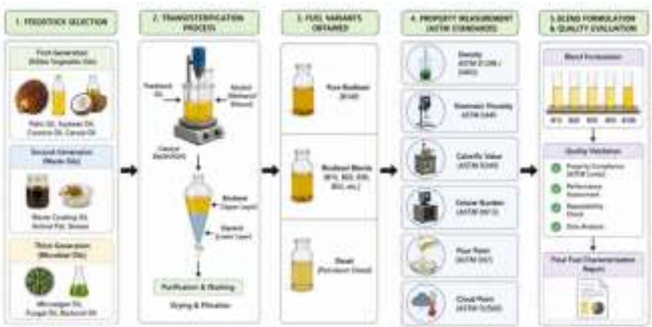

Figure 1: Fuel Characterization Process for Alternative Biofuels

Figure 1 shows the fuel characterization process starting from the selection of the feedstock up to transesterification, measurement of properties, and blends preparation. Some of the properties measured include density, viscosity

Experimental Engine Setup

Experiments are carried out using CI engines having following specifications:

- Single Cylinder, Four Stroke, Direct Injection, 1500 rpm, Power rating of 5.5 to 7.4 kW.
- Types of engines used are naturally aspirated and turbocharged engines. The test conditions include various engine loads (25%, 50%, 75%, 100%) and various engine speeds (1000 – 4500 rpm) and constant speed with variable loads.
- Instruments used for the experiment are as follows:
- Pressure sensors for measuring cylinder pressure,
- Thermocouples for measuring temperatures, Dynamometer for loading,
- Exhaust Gas Analyzer for measuring CO, CO2, NOx, HC, Smoke Opacity.

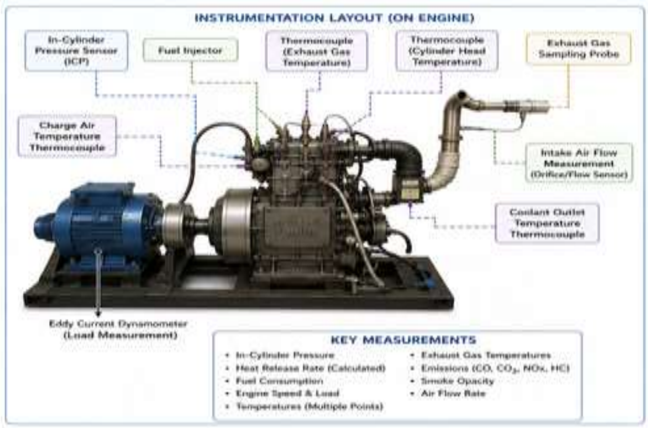

Figure 2: Experimental Engine Test Bench Configuration

Figure 2 shows the experimental engine test bench set up. It includes specifications of the engine, instrumentation set up and data acquisition system.

CFD Combustion Modeling

CFD analysis is conducted to study the combustion process of HVO and the dual fuel HVO biogas cycle. CFD analysis involves the use of the RANS approach through CONVERGE software using n-heptane as diesel equivalent via 550-component mechanism. The design of the combustion chamber is designed to include the shape of the piston bowl and injector layout. Parameters that are analyzed in the CFD analysis involve the spray angle, injection pressure, and boundary conditions.

The CFD simulation is verified with experimental data on pressure and heat release rate. Outputs from the CFD analysis involve the in-cylinder temperature, velocity fields, and emissions concentration.

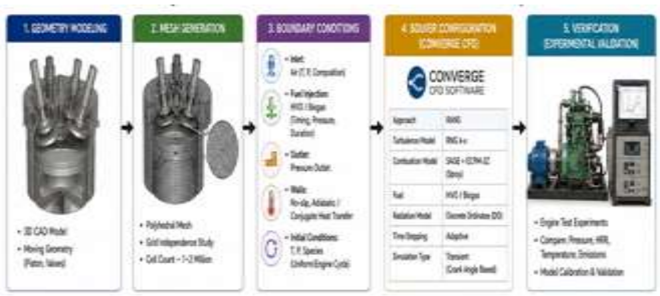

Figure 3: Work Flow for CFD Simulation of Combustion Analysis

Figure 3 illustrates the work flow for CFD simulation including the creation of the model geometry, meshing, the imposition of boundary conditions, configuring of the solver, and verification via experiments. Sample outputs of temperature distribution, pressure, and species concentration are included.

Hybrid Artificial Intelligence Modeling

- Hybrid artificial intelligence modeling incorporating k-means clustering and prediction models is adopted for biodiesel performance optimization. The steps are:
- Clustering biodiesel variants depending on fatty acids' properties and parameters
- Building the prediction models of BTE, BSFC, and emissions using machine learning algorithms
- Determining optimal biodiesel variants from different biodiesel variants depending on the performance metrics in relation to ASTM specifications.

Model evaluation criteria include root mean square error (RMSE), mean absolute percentage error (MAPE), and the coefficient of determination (R^2).

Dual-Fuel Combustion Analysis

The effectiveness of dual-fuel combustion systems is assessed using HVO along with biogas and hydrogen. In dual-fuel combustion system, the primary fuel (biogas/hydrogen) is fed into the intake manifold and HVO is injected in small amounts for combustion ignition. The amount of fuel substitution varies from 10% to 70%.

Algorithm 1: Dual-Fuel Operation Performance Evaluation

```
Input: Primary fuel composition Fp, Pilot fuel composition Fd, Fuel substitution rate R
Output: Performance metrics P, Emissions E

function EVALUATE_DUAL_FUEL(Fp, Fd, R)
    Define engine operating conditions (speed, load)
    Calculate fuel energy content: EF = (1-R)·EFd + R·EFp
    for each operating condition:
        Measure in-cylinder pressure Pcyl(θ)
        Calculate heat release rate dQ/dθ
        Calculate ignition delay ID
        Compute brake power BP
        Compute BTE = BP / (ṁf · LHV)
        Compute BSFC = ṁf / BP
        Measure exhaust emissions (NOx, CO, HC, CO2)
    end for
    Validate CFD predictions against experimental data
    return {BTE, BSFC, BP, NOx, CO, HC, CO2}
end function
```

Algorithm 1 assesses the performance of dual-fuel mode using the calculation of brake thermal efficiency, brake-specific fuel consumption, and exhaust emissions based on fuel energy, power, and emission concentration.

IV. ANALYSIS

Performance Indicators and Assessment

Analysis of performance improvement is carried out using several indicators such as brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), brake power, torque generation, and combustion process. Emission analysis takes

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into account NOx, CO, HC, CO_2, and smoke opacity. Comparison is done for neat biofuels, blends, and dual-fuels against fossil diesel.

Performance Results

Brake Thermal Efficiency (BTE): Biodiesel blends display varied BTE behavior. Canola biodiesel displays 31.2% BTE under optimum conditions. Waste cooking oil biodiesel blends display BTE levels similar to those of diesel under full load conditions with an increase of 7.3%–20.6% for part load. The dual fuel operation of HVO-biogas shows low efficiency because of the low energy density and delayed combustion of biogas; however, the emissions are much better despite reduced efficiency.

Brake-Specific Fuel Consumption (BSFC): HVO100 offers 1.7%–28% improvement in BSFC compared to fossil diesel. The animal tallow-based microemulsion offers BSFC reductions of 25% and 50% load. Biodiesel blends offer high BSFC compared to diesel because of low calorific value, although optimization offers some improvements.

Power and Torque: The combination of turbocharger and biodiesel blend offers fuel reduction of up to 20% while increasing brake torque by 75%. MHBF offers high brake power levels at 50% and 100% loads. The HVO fuel offers slightly low power compared to diesel but offers better emissions.

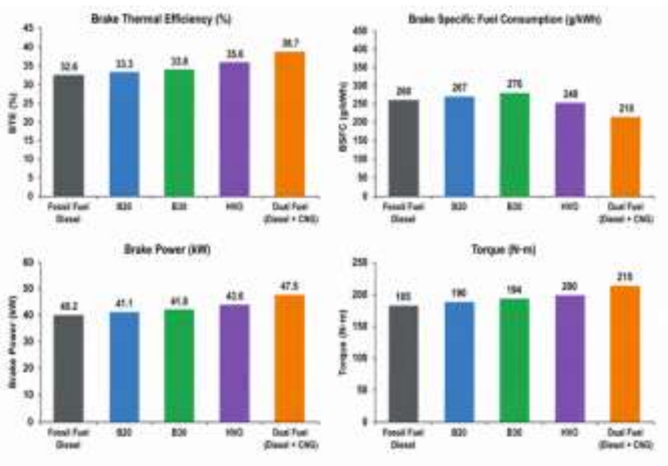

Figure 4: Performance Comparison of Alternative Fuels with Fossil Fuel Diesel

Figure 4 provides comparisons in the form of bar graphs between brake thermal efficiency, brake specific fuel consumption, brake power, and torque for the different biofuels including biodiesel blends, HVO, and dual fuel.

Emission Results

- **Nitrogen Oxides (NOx):** Neat HVO produces a decrease of NOx of 9.0% compared to diesel. HVO-biogas dual-fuel produces an up to 25.7% NOx reduction. The use of biodiesel blends increases the NOx emissions by 5–15% because of high oxygen content and combustion temperature. The canola biodiesel produces 770 ppm NOx, showing good characteristics.
- **Carbon Monoxide (CO):** HVO decreases CO by 38.7% compared to fossil diesel. Biodiesel blends decrease CO emissions by 20–50% owing to oxygenated combustion. Dual-fuel biogas increases CO emissions due to incomplete combustion process which needs to be optimized.
- **Hydrocarbons (HC):** HVO does not produce any changes in unburned HC. Biodiesel blends decrease HC emissions by 30–50%. Turbocharging decreases HC by 6%.

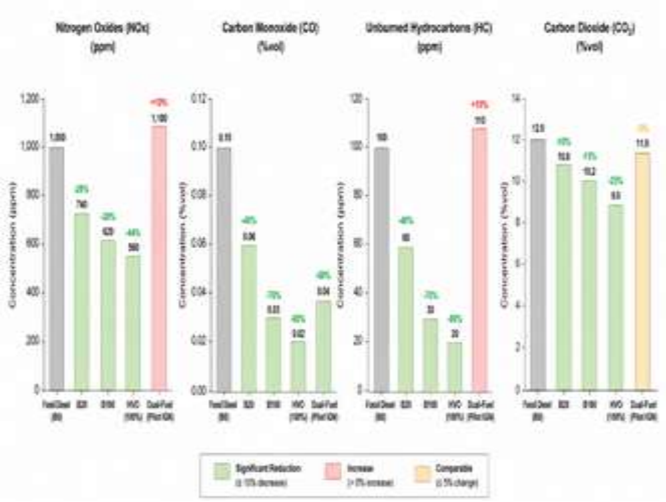

Figure 5: Emissions Comparision in Biofuels Categories

Figure 5 shows emissions comparision for NOx, CO, HC, and CO2 in various biodiesel blends, HVO, and dual fuels. The percentage decrease in comparison with fossil diesel is presented.

Comparative Analysis

Table 1: Comparative Performance and Emissions Analysis

Fuel Type	BTE (%)	BSFC (kg/kWh)	NOx Reduction (%)	CO Reduction (%)	HC Reduction (%)
HVO100	32.5	0.245	9.0	38.7	0
HVO-Biogas	28.5	0.280	25.7	-226	-902
B20 Biodiesel	34.5	0.255	-	20-40	30-50
Canola Biodiesel	31.2	0.260	-	Significant	Significant
Animal Tallow Microemulsion	29.5	0.270	-	Reduced	Reduced
Fossil Diesel (Baseline)	33.0	0.250	-	-	-

Table 1 shows performance and emissions data of various biofuels categories. HVO shows excellent performance regarding emissions and good efficiency while dual-fuel biogas provides low NOx emissions and reduced efficiency.

Discussion

These findings confirm that alternative fuels can provide good performance and emissions reduction for IC engines. The HVO fuel is especially promising to be used instead of the conventional diesel fuel as it provides the emissions reduction without any changes to the engine. It is shown that the reduction of 9.0% in NOx emissions and 38.7% in CO emissions can be achieved using HVO fuel.

Sustainability through valorization is one of the benefits of the use of waste materials such as cooking oil and animal tallow as biodiesel feedstock. Turbocharging solves the problems of power and efficiency that exist in biodiesel engines by lowering fuel consumption up to 20%. Optimal blend ratio together with turbocharging can attain performance almost equivalent to fossil diesel with minimal emission levels.

Dual fuel combustion of HVO and biogas gives the lowest NOx emissions for all cases considered. Efficiency loss and rise in CO and HC emissions necessitate further optimization of the fuel. The CFD model calibrated using experimental results makes it easy to optimize the dual fuel combustion processes.
AI-based optimization using hybrid machine learning is very effective in biodiesel optimization by ensuring that the best biodiesel feedstocks and blend ratios are found out. Canola biodiesel has shown good results with BTE of 31.2% along with lower emissions, and it is because of the better fatty acid content in it.

EGR and hydrogen combined with liquid biofuels can yield synergistic emission reduction benefits. The addition of hydrogen enhances the combustion process and reduces carbonaceous emissions, but NOx control is still essential. Intelligent control systems using AI and IoT technologies allow optimizing the process of fuel injection, combustion timing, and air-fuel ratios, which adds up to the efficiency increase of up to 8.2% and emissions reduction greater than 20%.

Problems include fuel viscosity regulation for pure vegetable oils, fuel storage and transportation problems, materials compatibility for alcohol-rich biofuels, and economic considerations. New generation biofuels utilizing cutting-edge conversion technologies such as hydrothermal liquefaction, microwave-assisted pyrolysis, and CRISPR technology-based metabolic engineering could help solve these problems.

V. CONCLUSION

A holistic approach to improving engine performance through the use of alternative fuels has been considered in the present paper. The research was carried out through the use of biodiesel blends, hydrotreated vegetable oil, and a dual fuel approach with biogas and hydrogen by means of experimental investigation, CFD simulation, and hybrid artificial intelligence optimization.

The multi-dimensional method provided an opportunity for quantitative assessment of the engine's brake thermal efficiency, brake-specific fuel consumption, power generation capability, and emissions. Based on experimental data, HVO can reduce the level of NOx emissions by 9.0% and the level of CO emissions by 38.7%, retaining competitiveness in terms of efficiency. Turbocharged B20 biodiesel blends have reduced fuel consumption up to 20% and brake torque increased by 75% in comparison with naturally aspirated diesel. Canola biodiesel has reached 31.2% of brake thermal efficiency with good emissions characteristics; it has been proven to be the best of multi-feedstock fuels by the hybrid AI optimization.

The results show that alternative biofuels can become a means to achieve sustainable transport by means of their optimization in terms of blends, engine modifications, and intelligent control system. HVO already has environmental advantages compared to traditional fossil fuels without engine adjustments. Biodiesel from waste material is a tool of realization of circular economy principles because of the waste reuse. The dual-fuel concept makes possible gradual fossil fuel replacement using renewable gas. AI optimization allows optimal fuel choice and precise engine control.

These implications of the study are relevant to different types of stakeholders. For automotive engineers and manufacturers, the study provides quantitative criteria for selecting fuels and calibrating engines. For policy makers and regulatory agencies, the potential for emissions reduction will allow them to create the corresponding framework for biofuels usage. For researchers, the study creates baseline information for further investigations.

Among the limitations of the study is the use of simulations and laboratory testing instead of practical field testing, lack of long-term durability testing of biofuel engine operations, and economic evaluation not within the scope of the investigation.

Further areas of study that should be considered include:

- Conducting long-term durability tests for engines running on different biofuels
- Optimizing the combustion of hvo-biogas dual-fuel system to optimize efficiency and emissions trade-off
- Developing next generation biofuels through advanced conversion technologies
- Using artificial intelligence and internet of things in engine optimization
- Conducting techno-economic and life cycle analysis of biofuel supply chain
- Exploring the potential of hybrid fuels that comprise biofuels, hydrogen and electricity in future engines.

In summary, improving the performance of internal combustion engines by utilizing alternative biofuels is an essential step towards securing sustainable and low carbon transportation for energy transitions in the world.

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