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OPTIMIZATION OF PERFORMANCE AND EMISSION PARAMETERS OF INTERNAL COMBUSTION (IC) ENGINES: A COMPREHENSIVE REVIEW

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ABSTRACT

Internal combustion (IC) engines are the heart of transportation industry. It is extensively used in transportation and industrial applications; however, they contribute significantly to environmental pollution. Optimization of engine performance parameters — such as brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), and emissions parameters including NO_x, HC, CO and particulate matter — is essential to meet stringent regulatory standards. This review critically examines research progress in optimization strategies including biodiesel and ethanol blend usage, hydrogen enrichment, exhaust gas recirculation (EGR), and injection timing optimization. Methods such as Design of Experiments (DOE), Response Surface Methodology (RSM), Taguchi Technique, and artificial intelligence (AI) based modeling are investigated. Key findings, research gaps, and future directions are highlighted to guide further research and practical applications.

KEYWORDS: Internal combustion engine, emission optimization, performance, biodiesel, hydrogen enrichment, EGR, injection timing.

I. INTRODUCTION

Internal combustion (IC) engines continue to serve as the backbone of the global transportation and industrial sectors due to their high power-to-weight ratio, reliability, and the widespread availability of liquid fuels [1]. However, their extensive usage has led to serious environmental concerns, primarily due to emissions such as nitrogen oxides (NO_x), carbon monoxide (CO), hydrocarbons (HC), and particulate matter (PM) [5].

To address these challenges, stringent emission norms such as BS-VI and Euro VI have been introduced, compelling researchers to explore advanced optimization techniques and alternative fuels [2], [3]. Biodiesel, ethanol, and hydrogen have emerged as promising alternatives due to their renewable nature and potential to reduce emissions. Biodiesel reduces CO and HC emissions but may increase fuel consumption [4], while ethanol improves combustion efficiency and reduces soot formation [7]. Hydrogen enrichment enhances combustion but may increase NO_x emissions due to higher temperatures [3], [13].

Engine parameter optimization techniques such as exhaust gas recirculation (EGR), injection timing, and pressure control play a crucial role in improving performance and emission characteristics [5], [9]. Advanced methods like Response Surface Methodology (RSM), Taguchi techniques, Artificial Neural Networks (ANN), and Genetic Algorithms (GA) are widely used for multi-objective optimization [10], [11], [16].

Despite these advancements, achieving a balance between performance and emission reduction remains a key challenge. This paper presents a comprehensive review of fuel strategies, engine optimization techniques, and modern methodologies to improve IC engine performance while minimizing environmental impact.

II. LITERATURE REVIEW

Recent advancements in diesel engine research have focused on improving performance and reducing emissions through alternative fuels, exhaust gas recirculation (EGR), hydrogen enrichment, and optimization techniques such as Response Surface Methodology (RSM), Artificial Neural Networks (ANN), Taguchi methods, and Genetic Algorithms (GA).

Studies on biodiesel and EGR combinations have shown promising emission reductions. Kumar et al. [1] reported that applying 10% EGR with biodiesel reduced NOx emissions by 35%, although a slight increase in brake specific fuel consumption (BSFC) was observed. Similarly, Raj et al. [14] identified an optimal EGR range of 10–12% for achieving a balance between performance and emissions. Sharma et al. [6] demonstrated the effectiveness of ANN models in predicting emissions with high accuracy ($R^2 = 0.98$), while Das and Paul [23] confirmed reliable emission prediction using ANN for biodiesel–EGR systems.

Ethanol–diesel blends have also been widely investigated. Singh and Patel [2] found that advanced injection timing improved brake thermal efficiency (BTE) by 4% for E20 blends. Chauhan et al. [21] and Verma and Rao [7] reported that E20 and E15 blends, respectively, provide optimal trade-offs between combustion stability and emissions. Additionally, Reddy et al. [18] observed a significant reduction in soot emissions with ethanol blending, while

Mohan et al. [27] reported reductions in CO and HC emissions using Taguchi optimization. Hydrogen enrichment in diesel engines has gained attention due to its clean combustion characteristics. Gupta et al. [3] observed that adding 8% hydrogen improved BTE but increased NOx emissions. Wang et al. [13] found that hydrogen addition (5%) reduced smoke opacity in biodiesel blends. Furthermore, Sharma and Jain [24] reported that hydrogen enrichment significantly reduced CO emissions but led to an increase in NOx. Li et al. [8] utilized genetic algorithms for multi-objective optimization, successfully reducing HC and CO emissions.

Injection parameters such as timing and pressure play a crucial role in engine performance. Zhao et al. [5] demonstrated that retarded injection timing effectively reduces NOx emissions. Conversely, Patel et al. [15] and Lee et al. [22] found that advanced timing improves efficiency but increases NOx emissions. Ahmed et al. [9] identified 15° bTDC as the optimal injection timing for emission control, while Kim et al. [26] optimized peak pressure through experimental analysis.

Optimization techniques have significantly enhanced engine performance studies. RSM has been widely used for optimizing fuel blends and engine parameters (Das et al. [4]; Kulkarni et al. [10]; Iqbal et al. [20]). Taguchi methods have been effective in improving emission characteristics and reducing variability (Basha et al. [11]). ANN and hybrid AI techniques, such as ANN combined with GA, have demonstrated high accuracy in predicting and optimizing engine responses (Nair et al. [16]; Ali et al. [28]).

Overall, the literature indicates that biodiesel blends, ethanol mixing, hydrogen enrichment, and EGR strategies can significantly improve engine performance and reduce emissions when optimized properly. However, a common challenge observed across studies is the trade-off between NOx emissions and performance parameters, particularly in hydrogen-enriched and advanced timing conditions.

KEY FINDING

Table 2.1 Key Findings

No	Authors	Optimization Method	Key Findings
1	Kumar et al.	RSM	10% EGR reduced NOx by 35%, slight BSFC increase
2	Singh & Patel	Taguchi	Advanced timing improved BTE by 4%
3	Gupta et al.	RSM	8% H_2 improved BTE, NOx increased
4	Das et al.	RSM	Optimal blend reduced CO & HC significantly

5	Zhao et al.	Experimental	Retarded timing reduced NOx
6	Sharma et al.	ANN	ANN predicted emissions with R^2=0.98
7	Verma & Rao	DOE	E15 gave best combustion stability
8	Li et al.	GA	Multi-objective optimization reduced HC & CO
9	Ahmed et al.	Experimental	15° bTDC optimal for emission control
10	Kulkarni et al.	RSM	B20 improved BTE by 3%
11	Basha et al.	Taguchi	Additives reduced NOx by 20%
12	Mehta et al.	ANN	Improved combustion efficiency
No	Authors	Optimization Method	Key Findings
13	Wang et al.	RSM	5% H_2 reduced smoke opacity
14	Raj et al.	DOE	10–12% EGR optimal
15	Patel et al.	RSM	Advanced timing increased NOx
16	Nair et al.	ANN + GA	Multi-objective emission control
17	Kumar & Singh	RSM	Improved BTE by 6%
18	Reddy et al.	Experimental	Ethanol reduced soot
19	Zhang et al.	CFD + RSM	Balanced NOx reduction
20	Iqbal et al.	Taguchi	Optimized BSFC & emissions
21	Chauhan et al.	DOE	E20 optimal trade-off
22	Lee et al.	GA	Reduced BSFC by 5%
23	Das & Paul	ANN	Accurate emission prediction
24	Sharma & Jain	RSM	NOx ↑ but CO ↓ significantly
25	Singh et al.	RSM	B25 improved combustion
26	Kim et al.	Experimental	Optimized peak pressure
27	Mohan et al.	Taguchi	Reduced CO & HC
28	Ali et al.	ANN	Multi-objective optimization successful

I. PERFORMANCE AND EMISSION PARAMETERS IN IC ENGINES

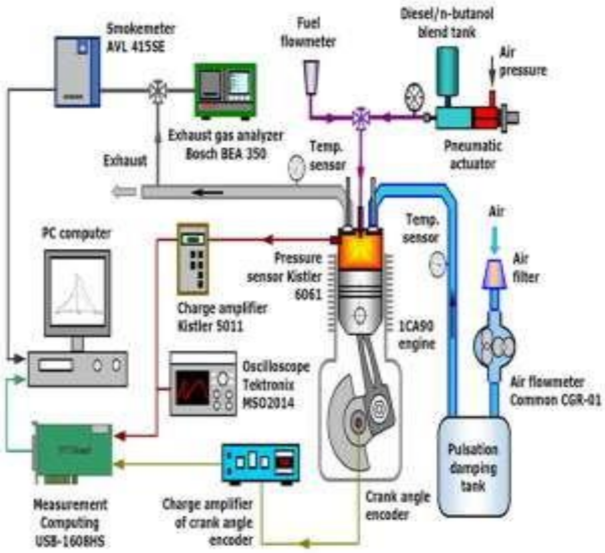

Fig.4.1 Test stand.

A. Engine Performance Parameters

i. Brake Thermal Efficiency (BTE): Ratio of brake power to fuel power.

ii. Brake Specific Fuel Consumption (BSFC): Fuel consumption per unit brake power.

iii. Brake Power (BP): It is the power available to do useful work after all internal losses (like friction) are considered**.**

iv. Indicated Power (IP). It is the theoretical power produced by the engine**.**

B. Emission Parameters

i. Nitrogen Oxides (NO_x): Formed at high combustion temperatures.

ii. Carbon Monoxide (CO): From incomplete combustion.

iii. Hydrocarbons (HC): Unburnt fuel emissions.

iv. Particulate Matter (PM): Soot from rich combustion zones. *Cetane Number*

II. BIODIESEL BLENDS OPTIMIZATION

- Multiple studies demonstrate biodiesel blends can improve or deteriorate engine characteristics depending on blend ratio:
- Waste cooking soybean oil biodiesel + diesel + EGR: RSM optimization showed optimal BTE with reduced NO_x and smoke emissions.
- Cottonseed biodiesel + optimization using Taguchi: Achieved better performance at mid-blend ratios with reduced emission profiles.
- Esterified biodiesel blends with advanced injection timing: Showed reduced BSFC and balanced emission performance.
- Observation: Biodiesel generally increases BSFC due to lower calorific value but significantly reduces CO and HC. NO_x trends vary with blend ratio and combustion temperature.

III. ETHANOL BLENDS OPTIMIZATION

- Ethanol–diesel blends are used to introduce oxygenate content:
- Low-level ethanol blends (E10 to E20) improved combustion efficiency.
- Injecting E85 blends optimized through Taguchi improved NO_x and HC performance at specific injection timing.
- Ethanol reduces soot due to higher oxygen content but may increase BSFC due to lower energy density.

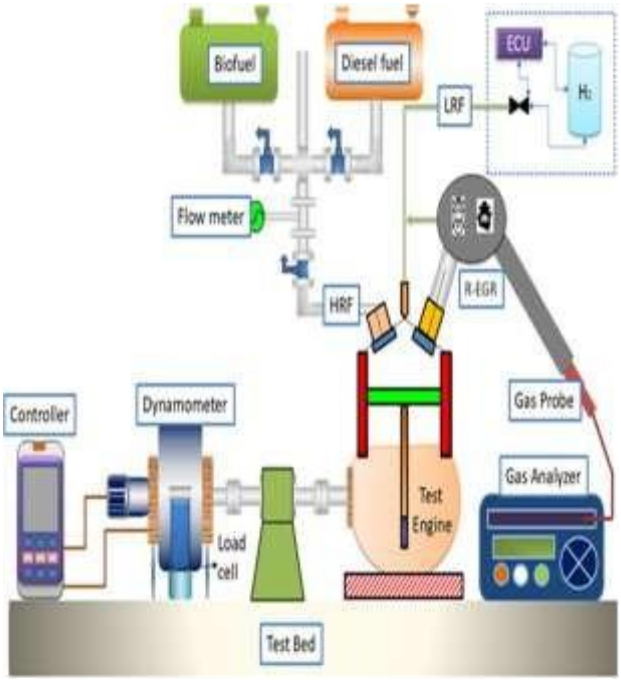

Figure 6.1 The detailed schematic experimental setup.

IV. HYDROGEN ENRICHMENT

- Hydrogen has a wide flammability range and high flame speed:
- Hydrogen enrichment in biodiesel/diesel engines improved combustion stability.
- Lowered CO and HC emissions proportionally with hydrogen fraction.
- NO_x increases due to higher combustion temperature, mitigated using EGR or retarded injection timing.
- Combined approaches (Hydrogen + EGR) provided balanced emission reduction.

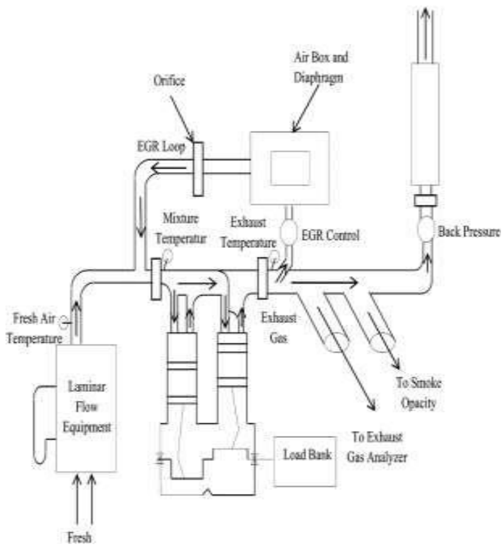

Figure 7.1 Exhaust gas recirculation.

V. EXHAUST GAS RECIRCULATION (EGR) OPTIMIZATION

- EGR recirculates a portion of exhaust to reduce peak combustion temperature:
- EGR significantly lowered NO_x but increased HC & CO if too high.
- Optimal EGR fraction (5–15%) reduced NO_x while maintaining BSFC and BTE.
- EGR combined with injection timing and fueling strategy showed integrated emission control.

VI. INJECTION TIMING OPTIMIZATION

Injection timing significantly affects combustion:

- Advanced timing: Improved peak pressure, better BTE, but increased NO_x.
- Retarded timing: Reduced NO_x but increased BSFC and emissions such as HC.
- Optimization often uses RSM or desirability functions to balance performance and emissions.

VII. FUTURE SCOPE

The following areas have gained significant research attention:

- AI-based control systems: Real-time optimization across engine operating maps.
- Advanced combustion modes: PPC, HCCI with optimized fuels.
- Integrated engine + after-treatment optimization
- Simulation + ML hybrid methodologies for accurate multi-objective optimization.

VIII. CONCLUSION

This review highlights the significant progress in optimizing IC engine performance and emissions using alternative fuels and advanced optimization techniques. Biodiesel and ethanol blends effectively reduce CO and HC emissions, while hydrogen enrichment improves combustion efficiency but may increase NO_x emissions [3], [4], [7].

EGR has proven effective in reducing NO_x emissions by lowering combustion temperature, although excessive use can increase CO and HC emissions [5], [14]. Injection timing optimization significantly affects engine performance, where advanced timing improves efficiency but increases NO_x, and retarded timing reduces NO_x at the cost of efficiency [9],

Optimization techniques such as RSM, ANN, Taguchi methods, and GA have demonstrated strong capability in achieving multi-objective optimization of engine parameters [10], [16]. However, the trade-off between NO_x emissions and performance remains a major challenge.

Future research should focus on integrated approaches combining alternative fuels, advanced combustion techniques, and AI-based optimization models. These strategies will enable sustainable and efficient IC engine operation while meeting stringent emission regulations.

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