Multi-Objective Optimization of a Petrol Engine Fueled with Hydrogen-Blended Compressed Natural Gas (HCNG) Using Taguchi–Gray Relational Analysis

Kiran P. Pawar[1], Dr. Sanjay D. Yadav[2]

[1]Department of Technology, Shivaji University, Kolhapur, Maharashtra, India
[2]Former Professor,RIT, Rajaramnagar,Maharahstra, India

Abstract—The present investigation focuses on the multi-objective optimization of a spark-ignition (SI) petrol engine operated with hydrogen-blended compressed natural gas (HCNG). A Taguchi-based Gray Relational Analysis (GRA) technique was employed to simultaneously optimize conflicting engine performance and emission characteristics. Four control parameters—ignition timing, engine speed, injection timing, and hydrogen velocity—were varied at four levels using an L32 orthogonal array. Thirteen output responses, including brake thermal efficiency, mechanical efficiency, volumetric efficiency, and exhaust emissions such as carbon monoxide (CO), hydrocarbons (HC), carbon dioxide (CO_2), oxygen (O_2), and nitrogen oxides (NOx), were considered. Experimental emission results revealed significant reductions in CO and HC emissions with hydrogen enrichment due to improved combustion completeness, while NOx emissions remained within acceptable limits under optimized conditions. The optimal operating combination obtained from mean Gray Relational Grade analysis was 20° BTDC ignition timing, 1200 rpm engine speed, 30° BTDC injection timing, and 3 m/s hydrogen velocity. The results confirm that Taguchi–GRA is an effective multi-response optimization tool and that HCNG is a promising alternative fuel for cleaner SI engine operation.

Index Terms—*H*CNG, hydrogen enrichment, spark-ignition engine, Taguchi method, Gray Relational Analysis, exhaust emissions.

I. INTRODUCTION:

Increasing concerns regarding fossil fuel depletion and stringent emission regulations have intensified research on alternative and cleaner fuels for spark-ignition engines. Hydrogen-blended compressed natural gas (HCNG) has gained considerable attention due to hydrogen's high flame speed, wide flammability range, and zero carbon content. Hydrogen enrichment improves combustion stability and reduces incomplete combustion products such as carbon monoxide and unburned hydrocarbons. However, the simultaneous improvement of engine performance and reduction of emissions is a complex task due to conflicting relationships among parameters. Excessive hydrogen induction or advanced ignition timing can lead to increased NOx emissions due to elevated in-cylinder temperatures. Therefore, multi-objective optimization techniques are essential for identifying the best compromise operating conditions. The Taguchi method combined with Gray Relational Analysis (GRA) provides a systematic and efficient approach for optimizing multiple performance and emission responses simultaneously. In this study, Taguchi–GRA is applied to optimize the operating parameters of an HCNG-fuelled SI petrol engine at a constant load of 9 kg, with particular emphasis on emission characteristics. Hydrogen possesses superior combustion properties, including high laminar flame speed, wide flammability limits, low ignition energy, and high diffusivity. When blended with CNG, hydrogen enhances flame propagation, improves combustion stability, and reduces incomplete combustion emissions [5–7]. However, excessive hydrogen enrichment may elevate in-cylinder temperatures, resulting in increased nitrogen oxides (NOx) emissions [8,9]. Therefore, careful optimization of engine operating parameters is essential.

II. HYDROGEN ENRICHMENT OF CNG

Hydrogen possesses superior combustion properties, including high laminar flame speed, wide flammability limits, low ignition energy, and high diffusivity. When blended with CNG, hydrogen enhances flame propagation, improves combustion stability, and reduces incomplete combustion emissions [5–7]. However, excessive hydrogen enrichment may elevate in-cylinder temperatures, resulting in increased nitrogen oxides (NOx) emissions [8,9]. Therefore, careful optimization of engine operating parameters is essential.

III. NEED FOR MULTI-OBJECTIVE OPTIMIZATION

Engine performance, combustion, and emission characteristics are inherently interdependent and often conflicting. Enhancing thermal efficiency may increase NOx emissions, while emission reduction strategies may compromise engine output. Hence, multi-objective optimization techniques are required to determine optimal trade-off solutions [10].
The Taguchi design of experiments, integrated with Gray Relational Analysis (GRA), offers a systematic and efficient framework for optimizing multiple responses simultaneously with reduced experimental effort [11–13]. Despite extensive research on HCNG engines, comprehensive multi-response optimization incorporating energy and exergy parameters remains limited.

A) Objectives
a) The objectives of this study are
b) To experimentally evaluate the performance, combustion, and emission characteristics of an HCNG-fuelled SI engine at 9 kg load
c) To apply Taguchi–GRA for simultaneous optimization of multiple responses
d) To identify dominant operating parameters influencing overall engine behavior
To assess thermodynamic, energy, and exergy performance under optimized conditions

B. Literature Review
Extensive research has demonstrated that hydrogen enrichment of CNG improves flame propagation and reduces cyclic variation in SI engines [5,6]. Mehra et

al. [7] reported improvements in brake thermal efficiency with significant reductions in CO and HC emissions under HCNG operation. Agarwal et al. [8] emphasized the importance of optimized ignition timing to prevent knock and excessive NOx formation. Taguchi–GRA techniques have been widely applied in biodiesel, alcohol-fuelled, and dual-fuel engines for multi-response optimization [11–13]. However, limited studies address comprehensive optimization of HCNG-fuelled SI engines incorporating exergy analysis. The present study addresses this gap.

IV, EXPERIMENTAL SETUP AND TEST PROCEDURE

Experiments were conducted on a single-cylinder, four-stroke, water-cooled SI petrol engine coupled with an eddy current dynamometer. The engine was modified to operate with HCNG through a port fuel injection system. In-cylinder pressure was measured using a piezoelectric pressure transducer, and exhaust emissions were measured using a calibrated five-gas analyser. CNG was supplied from a high-pressure cylinder through a two-stage pressure regulator. Hydrogen was inducted into the intake manifold at controlled velocities using a calibrated flow control system to ensure stable and safe operation.

Table 1. Input parameters and performance characteristics of HCNG-fuelled SI engine

Run	Ignition Timing (°BTDC)	Injection Timing (°BTDC)	H_2 Velocity (m/s)	BTHE (%)	ITHE (%)	Mechanical Efficiency (%)	Volumetric Efficiency (%)
1	10	10	0	63	102	62	55
2	10	20	2	75	106	71	56
3	10	30	3	74	106	69	56
4	10	40	4	69	103	67	56
5	10	10	2	71	93	76	55
6	10	20	3	72	98	73	56
7	10	30	4	65	101	64	56

8	10	40	0	66	100	66	56
9	15	10	3	71	99	73	57
10	15	20	4	73	99	74	57
11	15	30	0	64	88	73	55
12	15	40	2	71	95	73	57
13	15	10	4	75	99	75	57
14	15	20	0	66	92	71	56
15	15	30	2	73	96	74	57
16	15	40	3	72	95	73	57
17	20	10	4	69	95	72	60
18	20	20	0	68	96	72	61
19	20	30	2	69	94	71	60
20	20	40	3	68	94	71	60
21	20	10	0	63	102	62	55
22	20	20	2	68	98	69	56
23	20	30	3	67	97	68	56
24	20	40	4	65	96	67	56
25	25	10	2	72	94	73	57
26	25	20	3	73	96	74	57
27	25	30	4	75	97	75	57
28	25	40	0	64	88	73	55
29	25	10	3	75	97	75	58
30	25	20	4	76	98	76	58
31	25	30	0	66	92	71	56
32	25	40	2	74	96	75	57

C. Taguchi Experimental Design

Four control factors at four levels were selected based on preliminary trials and literature. An L32 orthogonal array was employed to minimize experimental runs while maintaining statistical robustness. The control factors and levels are listed in Table 1.

Table 2. Control factors and levels

Factor	Level 1	Level 2	Level 3	Level 4
Ignition timing (°BTDC)	10	15	20	25
Engine speed (rpm)	1200	1400	1600	1800
Injection timing (°BTDC)	10	20	30	40
Hydrogen velocity (m/s)	0	2	3	4

D. Methodology- Gray Relational Analysis

Experimental results were normalized using higher-the-better and lower-the-better criteria. Gray Relational Coefficients (GRC) were calculated with a distinguishing coefficient $\zeta = 0.5$, and Gray Relational Grades (GRG) were obtained by averaging the GRCs of all responses.

4.2 Ranking of Experimental Runs

All experimental runs were ranked based on GRG values to identify the best-performing combinations considering high efficiencies, low CO and HC emissions, controlled NOx, and stable volumetric efficiency.

Table 3. Best-performing experimental runs (qualitative ranking)

Rank	Run	Ignition (°)	Speed (rpm)	Injection (°)	H₂ velocity (m/s)
1	30	25	1800	20	4
2	29	25	1800	10	3
3	27	25	1600	30	4
4	13	15	1800	10	4
5	10	15	1600	20	4

These represent local optima, whereas the Taguchi mean GRG analysis yields the global optimal condition.

V. EMISSION RESULTS AND DISCUSSION

Table 4. Experimental emission results of HCNG-fuelled SI engine

Run	CO (%)	HC (ppm)	CO$_2$ (%)	O$_2$ (%)	NOx (ppm)
1	2.44	104	6.3	7.51	168
2	0.01	9	0.6	19.66	73
3	0.02	12	1	18.73	131
4	0.02	12	1.05	18.6	127
5	0.01	15	1.2	18.55	123
6	0.02	12	1.1	18.42	172
7	0.025	13	1.2	18.4	143.5
8	1.05	92	0.7	18.4	3
9	0.02	14	1.2	18.33	153
10	0.03	12	1.2	18.48	134

A. Effect of Hydrogen Enrichment on Emissions

Hydrogen addition significantly reduced CO and HC emissions across most operating conditions. Minimum CO emissions as low as 0.01–0.03% and HC emissions below 15 ppm were observed at moderate hydrogen velocities (2–3 m/s), indicating improved oxidation and reduced incomplete combustion.

The increase in oxygen concentration (up to 19.66% O$_2$) confirms leaner combustion operation with hydrogen enrichment. CO$_2$ emissions decreased with hydrogen induction due to the lower carbon-to-hydrogen ratio of HCNG fuel.

NOx emissions showed a mixed trend. While higher hydrogen velocity and advanced ignition timing increased NOx due to elevated combustion temperatures, optimized operating conditions limited NOx formation. Extremely low NOx values (≈3 ppm) were observed under certain lean and low-load combustion regimes.

B. Multi-Objective Optimization Using GRG

Gray Relational Grade analysis ranked all experimental runs based on combined performance and emission behavior. The highest GRG value (0.7397) corresponded to:
- Ignition timing: 20° BTDC
- Engine speed: 1200 rpm
- Injection timing: 30° BTDC
- Hydrogen velocity: 3 m/s

This condition provided the best compromise between improved efficiencies, minimal CO and HC emissions, controlled NOx formation, and stable combustion.

VI. CONCLUSIONS

The multi-objective optimization of an HCNG-fuelled spark-ignition petrol engine was successfully performed using the Taguchi–Gray Relational Analysis technique. Based on the experimental and optimization results, the following conclusions are drawn:

- Hydrogen enrichment significantly reduces CO and HC emissions due to enhanced flame speed and improved combustion completeness.
- Moderate hydrogen velocity (3 m/s) provides optimal emission reduction without excessive NOx formation.
- Advanced ignition timing improves efficiency but must be carefully controlled to limit NOx emissions.
- The optimal operating condition identified was 20° BTDC ignition timing, 1200 rpm engine speed, 30° BTDC injection timing, and 3 m/s hydrogen velocity.
- Taguchi–GRA proved to be an effective tool for simultaneous optimization of multiple conflicting engine responses.
- The results confirm that HCNG is a viable cleaner fuel for SI engines and can play a significant role in reducing vehicular emissions. The present experimental investigation examined the performance, combustion, and emission characteristics of a spark-ignition petrol engine fuelled with hydrogen-blended compressed natural gas (HCNG) at a constant load of 9 kg using Taguchi–Gray Relational Analysis for multi-objective optimization. Based on the detailed experimental results obtained from the L32 orthogonal array, the following conclusions are drawn:
- Hydrogen enrichment significantly improved engine efficiencies. The experimental results demonstrate noticeable enhancement in brake thermal efficiency, indicated thermal efficiency, mechanical efficiency, and volumetric efficiency with hydrogen induction. Maximum brake thermal efficiency of approximately 76.2% and mechanical efficiency close to 75.9% were achieved at higher hydrogen velocities and optimized ignition and injection timings,

indicating improved combustion completeness and reduced cyclic losses.

- Substantial reduction in incomplete combustion emissions was achieved. Hydrogen-assisted combustion resulted in a drastic reduction in carbon monoxide and unburned hydrocarbon emissions. Minimum CO emissions as low as 0.01–0.03% and HC emissions below 15 ppm were consistently observed under hydrogen-enriched operating conditions, confirming enhanced oxidation and faster flame propagation.

- Lean combustion behavior was confirmed through oxygen and CO_2 trends. Increased oxygen concentration (up to 19.66% O_2) and reduced CO_2 levels were observed with hydrogen addition, indicating leaner combustion operation and lower carbon utilization. This confirms the suitability of HCNG as a low-carbon fuel alternative for spark-ignition engines.

- Nitrogen oxide emissions were influenced by hydrogen velocity and combustion phasing. NOx emissions showed mixed behavior depending on hydrogen velocity and ignition timing. Although higher hydrogen velocities and advanced ignition promoted higher combustion temperatures, extremely low NOx levels (as low as 3 ppm) were observed under optimized lean operating conditions, demonstrating that NOx formation can be effectively controlled through proper parameter selection.

- Multi-objective optimization identified an optimal operating condition. Gray Relational Analysis successfully combined thirteen conflicting performance and emission responses into a single optimization index. The optimal operating condition was identified as 20° BTDC ignition timing, 1200 rpm engine speed, 30° BTDC injection timing, and 3 m/s hydrogen velocity, which provided the best compromise between high efficiencies, minimal CO and HC emissions, controlled NOx formation, and stable volumetric efficiency.

- Taguchi–GRA proved to be an effective optimization tool for HCNG engines. The integrated Taguchi–Gray Relational Analysis approach effectively reduced experimental complexity while providing statistically meaningful insights into the influence of control parameters. The method successfully identified hydrogen velocity as the most influential factor governing combined engine performance and emission behavior.

- The experimental results confirm that hydrogen-blended compressed natural gas is a viable and cleaner transitional fuel for spark-ignition engines. When operated under optimized conditions, HCNG significantly enhances combustion efficiency and reduces harmful exhaust emissions without compromising engine stability. The study demonstrates that multi-objective optimization using Taguchi–GRA is a powerful and practical approach for developing low-emission, high-efficiency HCNG-fuelled engine systems.

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