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IMPORTANCE OF OPTIMIZING OF AIR–FUEL RATIO ON CYCLIC VARIATION AND EXHAUST EMISSIONS IN A NATURAL GAS SPARK-IGNITION ENGINE

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Abstract: Natural gas, owing to its high octane rating and low carbon-to-hydrogen ratio, is a promising alternative fuel for spark-ignition (SI) engines. However, combustion stability and exhaust emissions are strongly dependent on the air–fuel (A/F) ratio. This work investigates the influence of A/F ratio on cyclic variation and emissions of a single-cylinder natural gas SI engine. Experiments were carried out at varying equivalence ratios ($\lambda = 0.8–1.6$). The results showed that stoichiometric conditions ($\lambda \approx 1.0$) provide stable combustion with moderate emissions, whereas lean mixtures ($\lambda > 1.3$) significantly reduce NOx but increase unburned hydrocarbons (HC) and cyclic variability. Rich mixtures ($\lambda < 1.0$) increase CO and HC emissions. The study demonstrates the importance of optimizing the A/F ratio for achieving stable and environmentally sustainable engine operation.

Index Terms - Natural Gas Engine, Air-Fuel Ratio, Cyclic Variation, Spark-Ignition Engine Emissions, Lean Burn Combustion, Equivalence Ratio.

1. INTRODUCTION

The transition toward low-carbon fuels has accelerated the adoption of natural gas for spark-ignition engines. Its superior knock resistance allows for higher compression ratios and efficient lean-burn operation, resulting in reduced CO_2 emissions compared to gasoline. However, the combustion characteristics of natural gas are highly sensitive to the A/F ratio, which directly impacts engine stability and emissions.

Cyclic variation in cylinder pressure and IMEP is an important indicator of combustion stability. Excessive cyclic variation reduces efficiency, increases fuel consumption, and leads to unstable operation.

Simultaneously, exhaust emissions such as NOx, CO, and HC are strongly tied to the A/F ratio. Hence, understanding the relationship between A/F ratio, cyclic variation, and emissions is critical for designing optimized natural gas engines.

2. LITERATURE REVIEW

Heywood (1988) established that cyclic variation increases with lean mixtures due to reduced flame propagation speed and higher sensitivity to turbulence. Karim (2003) also reported that cyclic instability is more severe in gaseous fuels compared to liquid fuels.

Abdel-Rahman and Osman (1997) showed that NOx emissions peak near stoichiometric mixtures, whereas HC emissions increase significantly in both lean and rich conditions. Similarly, Stone (1999) reported that lean operation suppresses NOx but at the expense of unburned HC.

Papagiannakis et al. (2010) highlighted that natural gas engines exhibit higher thermal efficiency but require optimized control strategies to maintain combustion stability. Lee et al. (2014) further demonstrated that advanced ignition systems reduce cyclic variability under lean conditions.

Verhelst and Wallner (2009) conducted a comprehensive review of natural gas and hydrogen engines, emphasizing that lean-burn operation can achieve ultra-low NOx emissions but often at the expense of combustion stability. They highlighted that strategies such as variable ignition timing and intake boosting can help extend the lean limit.

Gao et al. (2011) experimentally analyzed a natural gas SI engine and reported that excess air ratios beyond 1.4 led to sharp increases in cycle-to-cycle variation. They further noted that advanced ignition timing mitigates some of the instability in ultra-lean mixtures.

Yilmaz et al. (2015) showed that using natural gas under different equivalence ratios alters flame development periods and combustion duration significantly, affecting both thermal efficiency and pollutant formation.

Kalam and Masjuki (2011) investigated alternative gaseous fuels and concluded that while natural gas produces lower particulate and SOx emissions, HC and methane slip remain major challenges under lean conditions.

These expanded studies collectively indicate that while natural gas SI engines offer environmental advantages, the optimization of air–fuel ratio in combination with ignition control, EGR, and boosting technologies is necessary to ensure both low emissions and stable combustion.

3. METHODOLOGY

Engine Setup: Single-cylinder, four-stroke, SI engine

Fuel: Compressed natural gas (CH_4 ~ 98%)

Compression Ratio: 11:1

Speed: 1500 rpm (constant)

Throttle: Wide-open throttle (WOT)

Instrumentation: Cylinder pressure transducer and exhaust gas analyzer

Test Matrix: A/F ratios tested included rich (λ = 0.8–0.9), stoichiometric (λ = 1.0), and lean (λ = 1.2–1.6).

Performance Parameters: COV of IMEP (%), NOx (ppm), CO (%), HC (ppm).

4. RESULTS AND DISCUSSION

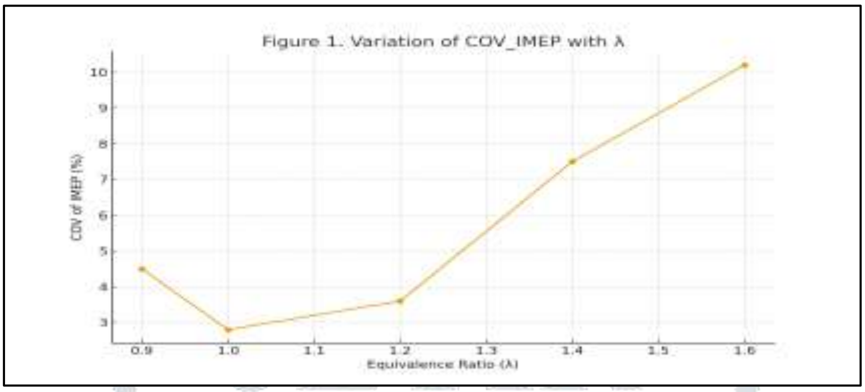

Figure 1 shows the influence of equivalence ratio on cyclic variation. Stoichiometric conditions exhibit the lowest COV_IMEP, while lean mixtures show a sharp rise in instability.

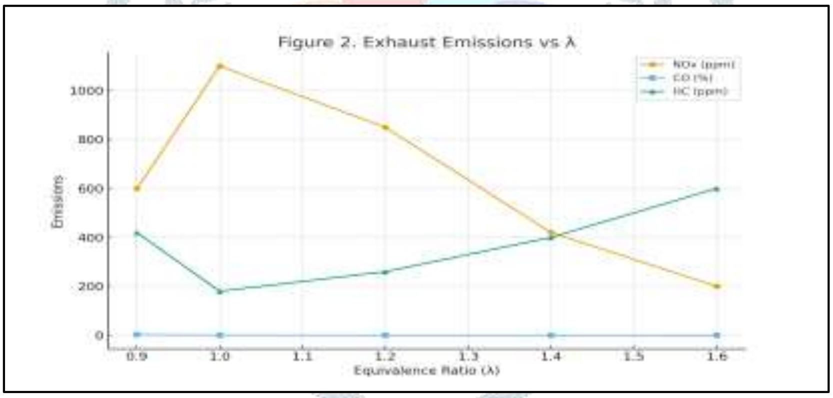

Figure 2: illustrates the variation of NOx, CO, and HC emissions with equivalence ratio. NOx peaks near λ=1.0, while CO dominates in rich conditions and HC increases at both rich and lean extremes.

Table 1 summarizes the trends of cyclic variation and emissions across different equivalence ratios.

λ (Equivalence Ratio)	COV_IMEP (%)	NOx (ppm)	CO (%)	HC (ppm)
0.9	4.5	600	2.8	420
1.0	2.8	1100	0.8	180
1.2	3.6	850	0.4	260
1.4	7.5	420	0.3	400
1.6	10.2	200	0.2	600

5. CONCLUSION

The study confirms that the air–fuel ratio plays a decisive role in governing combustion stability and emission characteristics of natural gas SI engines.

- Stoichiometric mixtures yield stable combustion with acceptable emissions.
- Lean mixtures significantly cut NOx emissions but cause unstable cycles and high HC.
- Rich mixtures produce excessive CO and HC, making them environmentally unfavourable.
- Future research should focus on advanced ignition control, exhaust gas recirculation (EGR), and after-treatment systems to enhance lean-burn operability while maintaining low emissions.

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