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Experimental investigation on effects of compression ratio and exhaust gas recirculation on backfire, performance and emission characteristics in a hydrogen fuelled spark ignition engine

*B.L. Salvi, K.A. Subramanian**

Engines and Unconventional Fuels Laboratory, Centre for Energy Studies, Indian Institute of Technology Delhi, New Delhi 110016, India

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ABSTRACT

The experimental study was conducted on single cylinder, forced air cooled hydrogen fuelled spark ignition (SI) generator set, which was converted from gasoline fuelled generator set with rated power 2.1 kVA at 3000 rpm. The study was carried out at various compression ratios (4.5:1, 6.5:1 (base) and 7.2:1), spark timings (2–20 °CA before top dead centre (bTDC)) and exhaust gas recirculation (EGR) up to 25% by Volume. Furthermore, the experimental tests were conducted on the engine with varied start of gas injection (SOI) at various compression ratios in order to find the backfire limiting start of injection (BFL-SOI). The results indicated that engine operation at higher compression ratio improved the brake thermal efficiency and reduced the backfire occurrence as residual gas fraction decreased with increased compression ratio. However, NO_x emission increased with increased compression ratio. In order to reduce the NO_x emission at source level, the engine was operated with retarded spark timings and different EGR percentage. The relative NO_x emission decreased up to 10% with the spark time retarding of 2° CA bTDC from maximum brake torque (MBT) whereas it decreased about 57% with 25% by volume EGR. The delay in gas injection could reduce the chance of backfire occurrence and the BFL-SOI decreased with increased compression ratio. A notable point emerged from this study is that in hydrogen fuelled spark ignition engine the spark time retarding is not a suitable strategy for NO_x emission reduction whereas the EGR at the optimum level (20%) is a better strategy that could reduce the NO_x emission up to 50% as compared to base hydrogen engine without EGR.

* *Corresponding author.*
E-mail address: subra@ces.iitd.ac.in (K.A. Subramanian).

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Nomenclature

BDC	bottom dead centre
BFL-SOI	backfire limiting start of injection
BMEP	brake mean effective pressure
BTE	brake thermal efficiency
CNG	compressed natural gas
COV	coefficient of variance
CR	compression ratio
ECU	electronic control unit
EGR	exhaust gas recirculation
ER	equivalence ratio
IMEP	indicated mean effective pressure
MBT	maximum brake torque
rpm	revolution per minute
SOI	start of injection
STV	spark timing variation
TDC	top dead centre
TMI	timed manifold injection
WOT	wide open throttle

Introduction

The hydrogen gas as clean fuel for spark ignition (SI) engines is gaining more attention worldwide and its utilization in existing engine infrastructure can help for sustainable development in energy sector. Recent development in Government policies and advancement in technology for production and storage of hydrogen have motivated the researchers for more research in utilization of hydrogen in SI engines. The SI engine tuned for particular fuel require some variation in operating and design parameters in order to operate satisfactorily with another fuel, as the fuels have different physical and chemical properties. The hydrogen as an alternative fuel in SI engine have attractive features including high flame speed (hydrogen: 2.65–3.25 m/s, methane: 0.37–0.45 m/s and gasoline: 0.37–0.43 m/s) and wider flammability range (4–75 volume %) as compared to gasoline and CNG fuels [1–4]. The hydrogen as fuel for SI engines does not have the problems associated with liquid fuels, such as vapour lock and wall quenching [5]. Sierens and Verhelst [6] reported that hydrogen fuelled SI engine require the spark plug gap smaller than usual in gasoline fuelled engines and comparatively lower ignition voltage.

Many researchers including White et al. [2], Huynh et al. [3], Sierens and Verhelst [5] and Das [7] carried out experimental studies and reported that 'backfire' is an undesirable combustion phenomenon in hydrogen fuelled SI engines. The backfire is defined as ignition of fuel-air charge in the intake manifold during charge induction into hydrogen fuelled SI engine. The backfire in hydrogen fuelled SI engine occurs when fresh hydrogen-air charge interacts with the hot residual gas in the cylinder in early phase of intake valve open during suction stroke. As the minimum ignition energy required for the hydrogen-air mixture is the lowest (0.02 mJ) as compared to methane (0.29 mJ) and gasoline (0.24 mJ), the fresh charge could get pre-ignition resulting in combustion and pressure rise in the intake manifold [3,8,9]. The backfire could lead to raise the intake manifold pressure up to 4 bar [10].

The wide flammability limit enables a hydrogen fuelled SI engine for quality governing using timed manifold injection (TMI) and engine operation results into higher thermal efficiency [11]. The ideal efficiency of an internal combustion engine working on air standard Otto cycle can be written as a function of the engine's compression ratio (r_c) and the specific heat ratio of in-cylinder gas [12], as given by Eq. (1).

$$\eta_{ith} = \left(1 - \frac{1}{(r_c)^{\gamma-1}}\right) \times 100 \qquad (1)$$

It can be observed from Eq. (1) that increase in compression ratio would increase the ideal efficiency of the engine. Further, it should be noted that indicated thermal efficiency given by Eq. (1) is independent of the fuel and other engine design and operating parameters except compression ratio. But, in practice the engine efficiency depends on other parameters also. Hence, experimental studies on SI engines operating at various compression ratios become important. De Boer and Hulet [13] conducted an experimental study with varying compression ratio (5:1 to 12:1) and reported that hydrogen engine operating at high compression ratios had a great tendency to knock. Further, they reduced the compression ratio and reported the optimum compression ratio in the range from 6:1 to 7:1. Ma et al. [14] reported that higher compression ratio results into the higher indicated thermal efficiency, but it is limited by knocking tendency. Mathur and Das [11] and Mathur and Khajuria [15] in their experimental study with varying compression ratio (6:1–11:1) reported the increased indicated thermal efficiency and NO_x emission with increased compression ratio, but the compression ratio was limited by pre-ignition at high load and knocking. Similar study was carried out by Killingsworth et al. [16] and reported that higher compression ratios are limited by knock, but the spark timing was not limited by knock. Zhao et al. [17] in their experimental study reported the increased total hydrocarbon (THC) emission and NO_x emission with increased compression ratio.

The in-cylinder NO_x formation is majorly attributed to in-cylinder combustion temperature and its retention period [18], which must be reduced in order to reduce NO_x formation at source level. Some studies have been carried out on retarded spark timing and reported NO_x reduction in hydrogen-natural gas fuelled SI engines [19–21], but for hydrogen fuelled SI engines this technique is not suitable without penalty on power and brake thermal efficiency [22].

Exhaust gas recirculation (EGR), where some of the exhaust gas is recycled back into the engine cylinder with intake charge, is one of the methods to reduce the in-cylinder combustion temperature. The early use of EGR was started long back in 1940 by Berger et al. [23], as reported by Caton [24], than further research work was carried out in 1980s onward. Das and Mathur [25] carried out an experimental study on hydrogen supplemented multi-cylinder SI engine and reported that EGR is an effective method of controlling the NO_x emission. Many researchers including Das and Mathur [25], Abd-Alla [26], Subramanian et al. [27] and Wei et al. [28] worked on effects of EGR on performance and emission characteristics, and reported that EGR reduced the pumping