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# Combustion Performance and Emission Characteristics of Hydrogen as an Internal Combustion Engine Fuel

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***Abstract: Energy sector is presently facing two major problems of future energy crisis and environmental degradation. To combat the above mentioned difficulties, use of hydrogen as an energy carrier may be a strategic plan in near future. Researchers are working on this issue throughout the world in the quest of powering two- and three-wheelers as well as passenger cars and buses) to decrease local pollution at an affordable cost. This paper offers a comprehensive overview of the fundamentals of hydrogen combustion, dedicated hydrogen engine features, the effect of mixing hydrogen with other hydrocarbons and the related performance and emissions. The high octane number and the low lean-flammability limit of hydrogen provide the necessary elements to attain high thermal efficiencies in an engine. The brake thermal efficiency and most of the emissions are improved when hydrogen blends are used as fuels in IC engine.***

## 1. INTRODUCTION

Fossil fuel consumption is steadily rising in industrial as well as in transportation sector as a result of population growth in addition to improvements in the standard of living. The continually depleting resources of fossil fuel and the highly toxic emissions which are produced due to these fuels have largely hastened the need for alternate fuels for internal combustion (IC) engines. Several fuels have been tried for running internal combustion engines. These include straight vegetable oil, biodiesel, alcohol, natural gas and hydrogen. Hydrogen has been found to have several properties which are essential for a green alternate fuel to be used in IC engines. Its high auto ignition temperature and low ignition energy coupled with its various other combustive properties help in enhancing engine performance. The high diffusivity of hydrogen which is about four times that of gasoline improves the mixing process of fuel and air. As the burning velocity rises the actual indicator diagram is nearer to the ideal diagram and the thermodynamic efficiency increases [1]. However, due to the high adiabatic flame temperature of hydrogen, the pure hydrogen-fuelled engine always suffers a poor $NO_x$ emissions performance, which has become the biggest barrier for its wide commercialization [2]. Andrea *et al.* [3] investigated the effect of various engine speeds and equivalence ratios on combustion of a hydrogen blended gasoline engine and found that the combustion duration decreased with the increase of hydrogen blending fraction. Li *et al.* [4] demonstrated that the $NO_x$, HC and CO emissions from a hydrogen enriched gasoline engine were reduced. Dimopoulos [5] indicated that greenhouse emissions can be effectively reduced by hydrogen addition. Ji and Wang [6] investigated the effect of hydrogen addition on a gasoline-fuelled SI engine performance under idle and stoichiometric conditions.

Apostolescu and Chiriac [7] showed that hydrogen addition during combustion reduced cyclic variation. Recent research thrust and progress on this front is the development of advanced hydrogen engines with improved power densities and reduced $NO_x$ emissions at high engine loads. Hydrogen can be produced from fossil fuels as well as from different renewable sources such as biomass. However, there are serious challenges to overcome when hydrogen is to be used as an energy carrier. This paper provides a brief summary of the combustion, performance and the emission characteristics of hydrogen as IC engine fuel with respect to other traditional fuels.

## 2. PROPERTIES OF HYDROGEN AS IC ENGINE FUEL

The various properties of hydrogen, has prompted researchers to consider it to be one of the leading alternate fuels, especially for SI engines. Various properties of hydrogen and other known fuels are presented in table 1 following the work of White *et al.* [8]. Table 1 shows that hydrogen has several combustive properties which are superior to the traditional fuels and if certain deficiencies and hurdles can be overcome with further researches, it is widely expected that hydrogen can successfully become a green alternate fuel in future.

**Table 1:- Properties of different fuels**

| Property | Hydrogen | CNG | Gasoline |
|---|---|---|---|
| Density | 0.0824 | 0.72 | 730 |
| Flammability limits (ø) | 10-0.14 | 2.5-0.62 | ≈1.43-0.25 |
| Auto ignition T in air (K) | 858 | 723 | 550 |
| Min. ignition energy (MJ) | 0.02 | 0.28 | 0.24 |
| Flame velocity(m/s) | 1.85 | 0.38 | 0.37-0.43 |
| Adiabatic flame T (K) | 2480 | 2214 | 2580 |
| Stoichiometric fuel/air ratio | 0.029 | 0.069 | 0.068 |
| Lower heating value (MJ/kg) | 119.7 | 45.8 | 44.79 |
| Research octane number | >120 | 140 | 91-99 |

## 3. COMBUSTION AND PERFORMANCE ANALYSIS

In this section a brief analysis of the performance of hydrogen as a fuel for IC engines is done with the help of examining the various properties of hydrogen which are relevant to that of a fuel for IC engines.

### *3.1 Flammability and Flame Properties*

The high flammability range of hydrogen (0.1<ø<7.1), [8] shows that engines run on hydrogen will operate stably under highly dilute conditions, allowing better emission reduction and fuel consumption. The burning velocity of hydrogen being six times higher than gasoline enhances the brake thermal efficiency. The variation of laminar burning velocities with equivalence ratios for hydrogen-air mixtures and gasoline-air mixtures have been shown in figure 1 from the work of Lewis and Elbe [9] and Heywood [10]. Taylor [11] and Vagelopoulos *et al.* [12] measured the burning velocities of hydrogen-air mixtures at various equivalence ratios. Later, Liu and MacFarlane [13] and Koroll *et al.* [14] improved the former work and reported consistently higher burning velocities, especially for leaner mixtures.

Ilbas *et al.* [15] observed that with the increase in hydrogen percentage in the mixture, the resultant laminar burning velocities as well as the flammability limit increased. The adiabatic flame temperature of hydrogen against equivalence ratios is plotted in Fig. 2 as per the works of Drell and Belles. [16]. It has been experimentally indicated that, if hydrogen content was increased, the burn duration decreased and no knocking or backfire phenomena were observed during engine operations for all the fuel conditions.

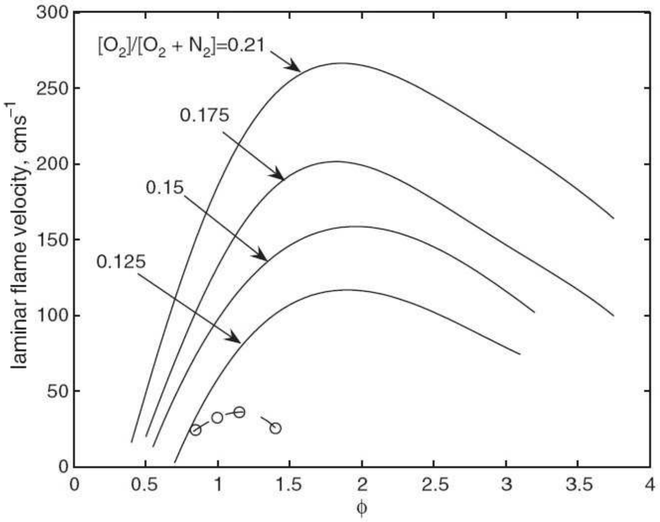

**Figure 1. Laminar flame velocities for H$_2$, O$_2$, N$_2$ mixtures (-○-) for gasoline and air mixture**

### *3.2 Ignition Properties and Peak Power Output*

The high auto ignition temperature, finite ignition delay and the high flame velocity of hydrogen show that knocking is less likely for hydrogen relative to gasoline. The research octane number (RON) for hydrogen is higher in comparison to gasoline as shown in table 1.

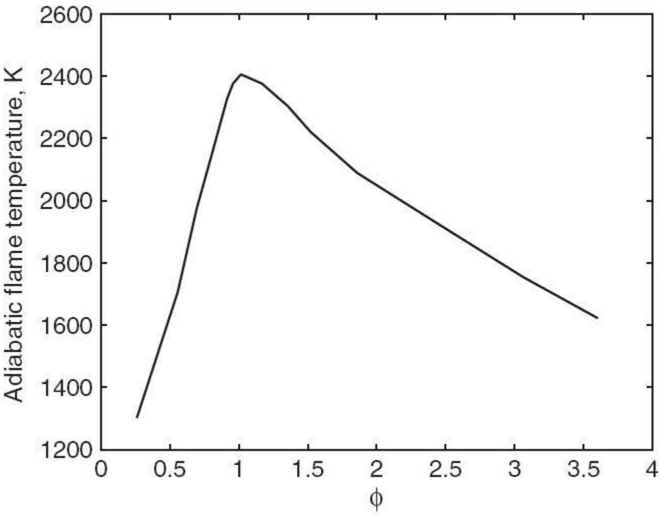

**Figure 2. Flame temperature changes for H$_2$-air blends.**

Minimum ignition energy plays an important role in case of combustion and it varies with equivalence ratio. One of such variation for three fuel mixtures has been taken from the work of Lewis *et al.* [11] and shown in Fig. 3. The low ignition energies of hydrogen causes predisposition of the engines to limiting effects of pre-ignition. In practical applications pre-ignition should be avoided. Further studies have indicated that at pressures varying from 0.2–1atm and mixture temperatures varying from 273–373K, the minimum ignition energies of hydrogen–air mixtures vary inversely with the square of the pressure and inversely with temperature [10]. As seen from Fig. 3 the minimum ignition energy for hydrogen is a decreasing function of the equivalence ratio with the minimum at, ø ≈ 1. For practical application, the maximum ø, and, peak power output is limited by the pre- ignition limit. Stockhausen *et al.* [17] found a pre-ignition limit of, ø ≈ 0.6 for a 4-cylinder engine at an engine speed of 5000 rpm. However, the engine peak power output was reduced by 50% compared to engine operation with gasoline.

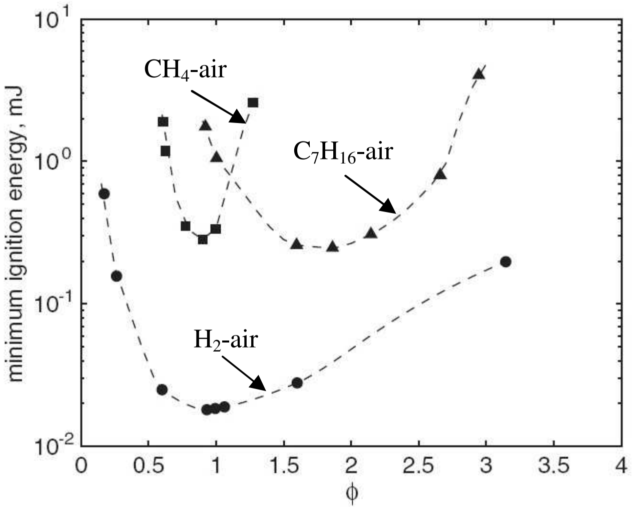

**Figure 3. Minimum ignition energy variation with Φ.**

### *3.3 In-cylinder Temperature and Pressure*

The fast burning characteristics of hydrogen contributes to higher cylinder temperature. The in-cylinder temperature for post-combustion period decreases with the increase of hydrogen fraction, causing the reduced exhaust losses. The variation of in cylinder temperature with crank angle has been partially reproduced from the work of Ji and Wang [18] for 1400 rpm in figure 4.

The figure indicates that the peak temperature increases and its relevant crank angle advances with the increase of hydrogen addition fraction either at stoichiometric or lean conditions. Due to the high flame temperature and high flame speed of hydrogen, the peak cylinder pressure increases with hydrogen addition. It is observed that, the in-cylinder pressure for a hydrogen enriched engine after reaching its peak value drops more quickly than the original engine, as the post combustion duration is reduced with hydrogen enrichment. The peak cylinder pressure is raised with hydrogen enrichment at stoichiometric and lean conditions and the variations of indicated mean effective pressure show the same trend with brake mean effective pressure (BMEP). Figure 5 represents the in-cylinder pressure profiles against crank angles at 1400 rpm, MAP = 61.5 kPa and l = 1.26 in accordance to the works of Ji and Wang [18].

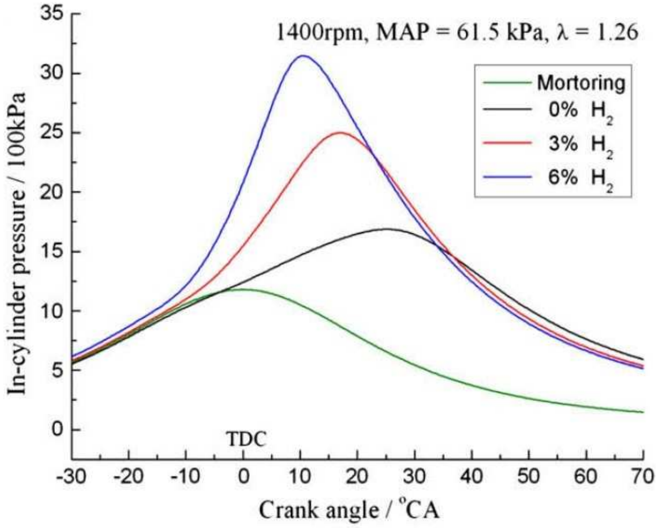

**Figure 4. In cylinder temp. variation with crank angle.**

The figure shows that at constant spark timing, the pressure profiles for hydrogen fraction of 3% and 6% are higher than the gasoline engine pressure profile. The high flame speed and flame temperature of hydrogen enhances the cylinder pressure with addition of hydrogen to the mixture and also reduces the post combustion emission to a considerable extent. The engine working capability depends on the peak cylinder pressure value to some extent. The cylinder pressure rise depends upon piston compression and in-cylinder air–fuel mixture combustion. At a given hydrogen addition level and spark timing, the combustion duration is extended with the increase of excess air ratio, causing reduced in-cylinder combustion temperature and pressure.

### *3.4 Brake Thermal Efficiency*

Brake thermal efficiency is one of the key factors in determining the engine performance and is defined as the fuel consumption rate to generate unit power. The high research octane number [RON] and low lean-flammability limit of hydrogen helps in attaining high brake thermal efficiency in an IC engine. Ji and Wang [18] plotted the brake thermal efficiencies against the excess air ratios for three different hydrogen volume fractions [0%, 3% and 6%] from their experimental data. The same has been shown in Fig. 6 and it shows that brake thermal efficiencies of the hydrogen-enriched engines are higher than the gasoline one especially at lean conditions. Also, brake thermal efficiencies after hydrogen addition increase slightly and vary smoothly with excess air ratio, with high values even at quite lean conditions. The peak brake thermal efficiency under the test conditions increases from 26.4% at λ = 1.09 for the original engine, to 31.6% at λ = 1.31 for 6% hydrogen addition. Brake thermal efficiencies change with excess air ratio between 14% and 26.4% without hydrogen addition increases between 29.2% and 31.6% with 6% hydrogen addition under the experimental conditions.

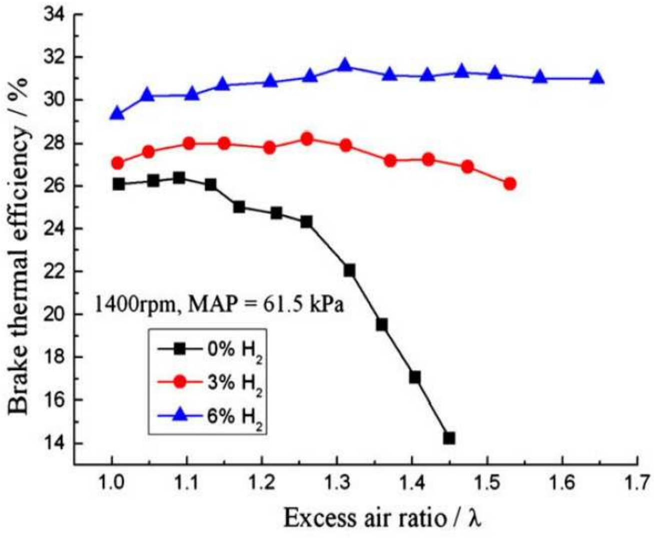

**Figure 5. Variation of BTE against excess air ratio.**

Hydrogen-enriched engines can produce roughly constant brake thermal efficiencies in a wide range of excess air ratio compared with the pure gasoline engine. Lucas and Richards found that if hydrogen is induced in to the cylinder by mixing with gasoline at a constant flow rate, the engine thermal efficiency increased by 10% [19]. According to Lyon's research, the engine efficiency can be increased till 6%, under no cycle variation [20]. Meanwhile, lean combustion has been proved to be an effective way for obtaining a higher engine thermal efficiency [21]. For a gasoline SI engine, high efficiency combustion occurs near the stoichiometric in a narrow range of excess air ratio. So with the increase of excess air ratio a gasoline engine goes into more and more serious incomplete combustion, producing much lower power output and brake thermal efficiency. On the other hand, Tang *et al.* [22] presented a plot for brake thermal efficiency [BTE] against BMEP which shows a drop-off at high loads is likely due to increasing heat transfer losses. Shudo *et al.* [23] showed that for hydrogen fuelled IC engine the relative fraction of the heat release lost by heat transfer to the cylinder walls increased with increasing equivalence ratio.

## 4. EMISSION ANALYSIS

The major toxic pollutants present in the emissions of internal combustion engines constitute of HC, CO and $NO_x$ mainly along with $CO_2$. In this context, an analysis of the emissions from hydrogen fuelled IC engines is done and a brief discussion is provided about the variation of concentration of pollutants present in emission at various hydrogen fractions.

### *4.1 HC Emissions*

A lot of research work has shown that HC emissions gradually decrease with increase in hydrogen fraction present in the mixture. With increase in hydrogen addition the formation of $OH^-$ radicals are accelerated and this results in decreasing HC emissions with increase in hydrogen fractions. The small quenching distance of hydrogen (three times smaller than gasoline) between the position of flame extinguishment and the cylinder wall helps to reduce HC emissions with increase in hydrogen fractions. Wang *et al.* [24] showed that HC emissions are effectively reduced with the increase of hydrogen blending ratio, in a spark ignited ethanol engine and reach the minimum value of 1019 ppm at a $H_2$= 5.49%. The above said fact can be clearly observed from the figure 7 which has been taken from their works. Ji *et al.* [18] found that for normal gasoline fuel, the HC emission abruptly increases after a certain value of excess air ratio [λ = 1.36] which, can be decreased by increasing hydrogen content, as the high flammability of hydrogen helps in complete combustion of the fuel. The works of Dimopoulos *et al.* [5] state that hydrogen addition in fuel reduces unburnt hydrocarbons to an extent of 6 to 20% depending on fuel consideration.

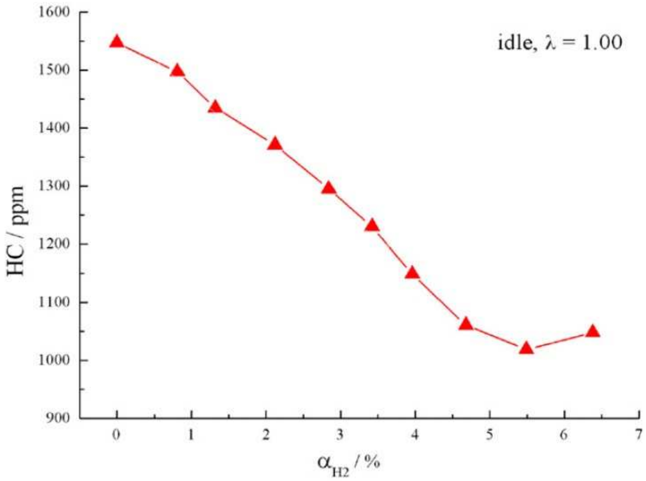

**Figure 6. HC emission variation with hydrogen fraction for SI hydrogen-ethanol engine.**

### *4.2 CO and $CO_2$ Emissions*

CO emission increases with the hydrogen addition fraction when the excess air ratio is near stoichiometric conditions. As hydrogen has higher air-to-fuel ratio than gasoline, combustion of hydrogen in the cylinder can cause some lean oxygen area due to the inhomogeneity of the fuel–air mixture, which reduces the oxidation rate for CO into $CO_2$. If the engine is run under lean conditions, CO emission is improved by enhancing hydrogen addition fraction as there is ample oxygen available for CO to be converted into $CO_2$. The increased in-cylinder temperature after hydrogen addition also contributes to stimulating the oxidation reaction of CO into $CO_2$. CO emission from the gasoline SI engine increases again at $\lambda > 1.36$ since the increased excess air ratio stimulates the possibility of partial misfire, resulting in reduced in-cylinder temperature, slowing down the reaction kinetics of CO oxidation into $CO_2$.The results from the work of Ji and Wang [18] has been plotted to show the variation in CO emission with change in hydrogen fractions.

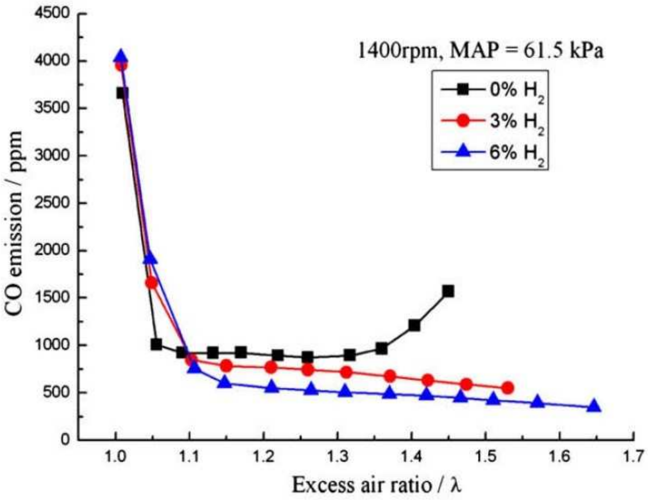

**Figure 7. CO emission variation vs. excess air ratio.**

However, Roy *et al.* [25] has experimentally shown that the maximum CO emission with neat $H_2$ operation was more than 99% less than other fuels and satisfied all sorts of emission regulations. As for $CO_2$ emission is concerned, the $CO_2$ emission decreases with increase in hydrogen content. Hydrogen being carbonless fuel, its combustion generates no $CO_2$. At a specified excess air ratio, the carbon content in the gasoline–hydrogen fuel mixture is reduced after hydrogen enrichment, causing lesser $CO_2$ emission. $CO_2$ emission can be further reduced in hydrogen–gasoline mixture fuelled engine by adopting large excess air ratios.

### *4.3 $NO_x$ Emissions*

$NO_x$ emissions are found to increase with increase in hydrogen fractions in the mixture mainly in case of an SI engine. $NO_x$ emissions depend upon conditions like temperature and oxygen concentration present in the cylinder. The peak in-cylinder temperature increases with increase in percentage of hydrogen for a given excess air ratio and constant oxygen concentration, thus increasing $NO_x$ concentration. Ji *et al.* [18] showed that with increase in hydrogen content, the relevant excess air ratio for the maximum $NO_x$ emissions slightly increase as with higher hydrogen addition fraction, more air is needed fully burning hydrogen to produce higher in-cylinder temperature. Although the hydrogen-enriched engine ejects more $NO_x$ emissions when the excess air ratio is around stoichiometric conditions, $NO_x$ emissions for all hydrogen enrichment levels drop to an acceptable value when the engine runs under quite lean conditions, [$\lambda > 1.5$]. Dimopoulos *et al.* [5] showed that hydrogen addition in the fuel results in more favourable efficiency-raw $NO_x$ trade-off. Stebar [26] found that, the engine lean burn limit was extended after hydrogen enrichment and $NO_x$ emissions were decreased. Another work of Ji and Wang [27] showed that for a hybrid hydrogen-gasoline engine at lean burn limits, $NO_x$ emissions are found to decrease with addition of hydrogen at lean burn limit as excess air ratio increases on enhancing hydrogen fraction. Thus, the total fuel energy flow rate at the lean burn limit decreases with the increase of hydrogen addition fraction, causing reduced in-cylinder temperature and thus $NO_x$ formation is constrained. The results from the above work has been shown graphically in Fig. 9 and it shows drop in $NO_x$ emissions from 52 ppm at the original engine to a largely lower value at 4.5% of the hydrogen enriched gasoline engine. The potential to expand the power band while maintaining near-zero $NO_x$ emissions is possible by improving lean power density with pressure boosting.

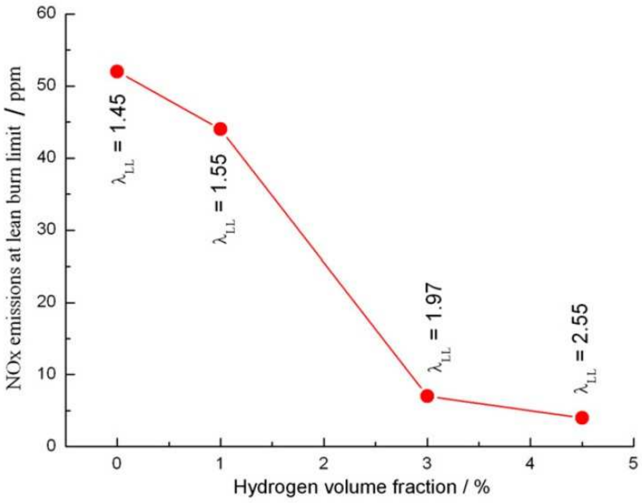

**Figure 8. $NO_x$ emission variation at lean burn limit vs. hydrogen volume fraction at 1400 rpm and 61.5 KPa**

## 5. CONCLUSION

Hydrogen seems to be a viable solution for future transportation. In order for hydrogen vehicles to become commercially feasible, challenging tasks in hydrogen production, distribution and storage have to be addressed properly. The wide flammability limits, low ignition energy and high flame speeds can result in undesirable combustion anomalies, including surface ignition and backfiring as well as auto ignition. However, the works so far reported in the literature show encouraging results from the performance and emission points of view. It is observed that thermal efficiency is improved with hydrogen addition to gasoline as fuel. For the mixed fuel, HC and $CO_2$ emission are found to decrease. CO emission is noted to be more particularly near stoichiometric air fuel ratio conditions.

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