Computational and Experimental Investigation of NO_x Emission of Hydrogen Blend on a Constant Speed Gasoline Engine

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Abstract – **Due to the rapid depletion of petroleum fuel and pollution problems today much work has been done for alternative fuels for fossil fuels and lowering the exhaust toxic components in the internal combustion engine. The present investigation is to find the NO_X emission characteristic of a single cylinder spark ignition engine operating with hydrogen blend. The hydrogen is blended in volume fraction of 12% of gasoline in a four stroke single cylinder Villiers's engine for different load. The load is varied from no load to full load in steps of one forth, half and three forth of the full load. The engine in which the experiment conducted is at constant speed of 3000 rpm. The NO_X emission is to be determined and compared with base line readings of petrol. Further, using the AVL BOOST simulation software, NO_X emission are determined for 12 % hydrogen blend with no load to full load and compared with experimental results. The results obtained from simulation are agreed well with the experimental results with average deviations of 7.71 % for nitric oxide emission.**

Index Terms—Hydrogen, Simulation, Oxides of nitrogen, AVL-BOOST software

I. INTRODUCTION

A large amount of research has been directed towards the development of alternative energy sources and alternative fuels. The enormous growth of the world population during the last decades, the strongly increased in technical development and standard of living in the developed nations have led to an intricate solutions in the field of energy supply [1]. The blending of hydrogen with gasoline seems to achieve lower emissions and higher thermal efficiencies than gasoline engine due to wide range of flammability and high flame speed of hydrogen [2]. A small amount of hydrogen addition produces a combustible mixture even at an equivalence ratio below the lean flammability limit of gasoline/air mixture. Therefore, lower temperature combustion which means, lower NO_X emission and lower heat transfer to the walls [3]. Hydrogen fuel exhibits desirable characteristics for the combustion in SI engines. Wide range of flammability limits enables a smooth engine operation at a very lean mixture with low NO_X level and the throttle control is unnecessary even at the idling condition in hydrogen engines. Also, the high burning velocity of hydrogen may contribute to the relatively high thermal efficiency with a shorter combustion period at the ignition timing close to top dead center [4]. The combustion and emission characteristics of hybrid hydrogen gasoline engine at various loads and lean conditions were studied. The test was conducted at a constant speed of 1400 rpm, which could represent the engine speed in the typical city driving with heavy traffic. Hydrogen volume fraction in total intake of 0 to 37% was achieved. The spark timing for maximum brake torque was adopted for all tests. The test proved the successful increase in brake thermal efficiency. The CO and UBHC were also reduced. But the NO_X emission increased [5]. The basic sub-model incorporated for the calculation of the reaction rates is the characteristic conversion time-scale method, meaning that a time-scale is used depending on the laminar conversion time and the turbulent mixing time, which dictates to what extent the combustible gas has reached its chemical equilibrium during a predefined time step. The Zimont/Lipatnikov approach for the modeling of the turbulent flame speed, whereas the NO_X emissions are calculated according to the Zeldovich mechanism. The NO_X emissions agreed well with the experimental result [6].

II. METHODOLOGY

A. *Development of experimental test rig*

To achieve the objectives of the investigation, the experimental test rig was developed as shown in the Figure 1. The tests are performed in the single cylinder Villiers gasoline engine operating with hydrogen blend. A single cylinder four stroke Villiers engine has a speed governor to control the speed of the engine by maintaining gasoline supply to the engine with change in the load. The laboratory consists of test benches involving hydraulic type dynamometer, exhaust emission analyzer, fuel metering device and auxiliary equipment. The load is measured with the aid of a hydraulic dynamometer. The engine is coupled with its original shaft to hydraulic dynamometer. The compressed hydrogen at 20 MPa is supplied by 50 kg steel gas tank. The hydrogen flow control system is mounted on the top end of the hydrogen cylinder which consists of hydrogen regulator and the hydrogen flow indicator. The hydrogen regulator system regulates the flow of hydrogen to the engine and the amount of hydrogen flow can be determined by hydrogen flow indicator. The gasoline engine is modified to hydrogen operated engine by adding hydrogen continuous injection system with the original gasoline injection system kept unchanged. The flame trap is situated in between the hydrogen cylinder and a hydrogen injector as shown in the figure. The exhaust emissions from the test engine are measured by exhaust gas analyser which is placed in the way of engine exhaust system.

B. *Engine model development and simulation*

In this study a single cylinder, four stroke spark ignition engine is simulated by using AVL BOOST. The Figure 2 illustrates the basic layout in AVL BOOST of a naturally aspirated engine model, arrows show the flow of mass (both air and fuel) from ambient conditions through the engine and then exhausted to ambient conditions again. The engine model is setup by defining some relatively basic inputs and then some more advanced inputs that require some engine testing as shown in Figure 3. C1 represent engine cylinder and MP1, MP2, MP3 represents measuring points. SB1, SB2 are for the system boundary and I1 represent hydrogen fuel injector.

The system boundaries, engine, cylinder, injector are connected to each other. The system boundaries like pressure, temperature, air fuel ratio and cylinder dimensions like stroke, bore, length of the connecting rod are specified. The valve seat diameter, valve lift, flow coefficient are also mentioned. The lower calorific value of the blend mixtures and mass fractions of the species concentration are defined. The constants to which the engine to be modelled like engine speed and load are entered in a parameter table. Once the basic inputs are defined, the advanced inputs that define the cylinder head such as port flow coefficients, valve lift per crankshaft rotation are specified. When the basic and advanced inputs have been satisfied, the simulation format is setup and the model is saved and run. The graphs obtained are compared with the experimental data.

III. RESULTS AND DISCUSSIONS

The present study concentrates on the experimental investigation of NO_X emission characteristic of 12% of hydrogen blend to single cylinder gasoline engine at different loads. The experimental results were analysed using AVL BOOST code at different loads varying from no load to full load.

A. *Experimental results for 12 % hydrogen with gasoline*

The Figure 4 shows the variation of oxides of nitrogen with increase in percentage of load for different hydrogen blends. As the percentage of hydrogen blend increases the emission of NO_X increases. This is because the increase of hydrogen blend will lead to rise in combustion temperature due to wide range of flammability. Nitric oxides are formed in high concentrations when the combustible mixture is slightly fuel-lean. Although maximum flame temperature will occur at a stoichiometric air fuel ratio, the maximum NO_X is formed at a slightly lean ratio. At this condition flame temperature is still high, and in addition there is an excess of oxygen that can combine with the nitrogen to form various oxides.

B. *Simulation results for oxides of nitrogen*

Nitric oxide emission studies have been accomplished with the calculated results not only being compared with the measured exhaust NO_X ones, but also further processed for conducting an in-depth investigation of the dependence of NO_X production on the spatial distribution of in-cylinder gas temperature. It is revealed that for lower fuel-air ratio the burned gas temperature is held at low level and the heat loss ratio is quite low. The estimation of the residual gas mass fraction plays an important role in the value of the laminar flame speed. At intake valve closing, the initial mixture is composed of H_2, O_2, N_2, H_2O and the mass content of each of these species is affected by the residual gas mass fraction. The high increase of the burned gas temperature for the stoichiometric mixtures for both compression ratios is evident. It should be mentioned that the elaborated temperatures are the mean temperatures of the burned and unburned gas, since for leaner mixtures there are some cells that contain burned gas with much higher temperature (especially near the spark-plug).

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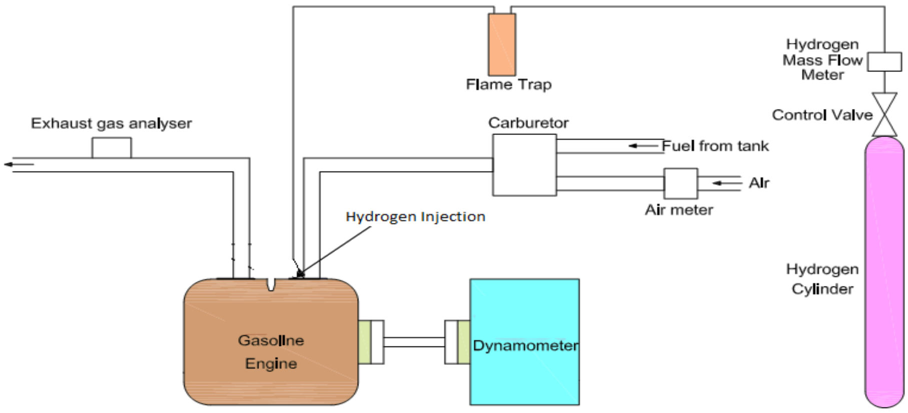

Figure 1: The Experimental set up diagram

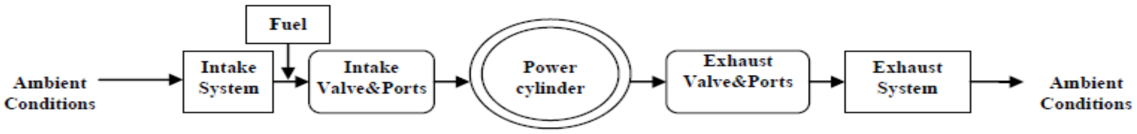

Figure 2: Schematic representation of engine model

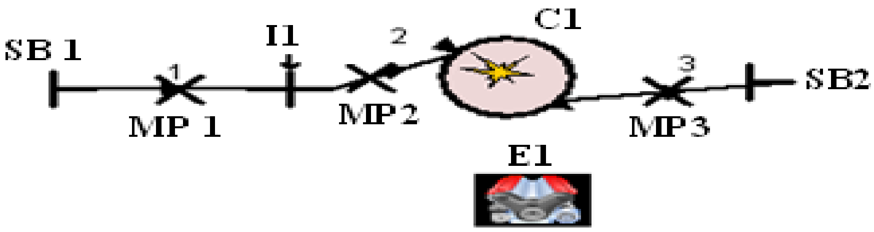

Figure 3: The engine model for simulation

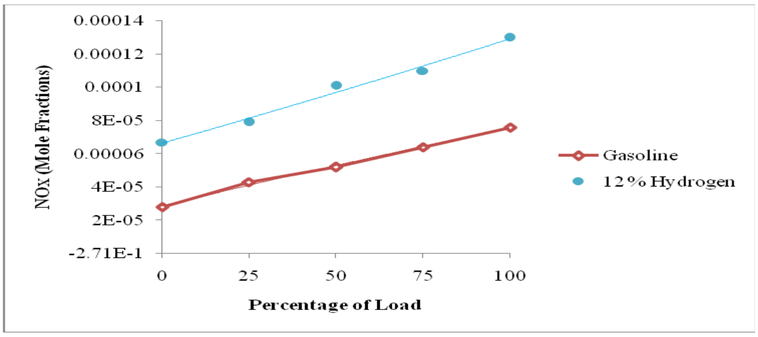

Figure 4: Variation of oxides of nitrogen with percentage of load for gasoline and 12 % hydrogen blends

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One should notice the different contour range for the temperature and the NO_X mass fraction as the equivalence ratio changes. It can be observed with higher detail, how the NO_X production strictly follows the temperature variation. For the richer mixture case, during the late stages of combustion when the gas temperature decreases due to expansion, the NO_X production process has actually terminated having a more homogeneous distribution inside the cylinder in contrast to the early stages of combustion. Nevertheless closer to the spark-plug, the NO_X concentration is slightly higher than in the outer regions close to the cylinder liner.

Hydrogen blending also improves combustion efficiency and therefore the point of maximum rate of heat release moves closer toward top dead centre. Also the maximum rate is increased due to faster flame front propagation. The accumulated heat release increase initially as a result of hydrogen blending due to high rate of mass burning but with further increase in the percentage of hydrogen the accumulated heat release decreases due to the reduction in total fuel energy. The combustion duration decreases as the percentage of hydrogen blending increases. This is due to the increase in the flame front speed which makes the time required to complete the combustion shorter. The reason is may be the crevice and blow by effects are not considered in the simulation process.

In the present case, as the fuel is hydrogen and gasoline, only thermal mechanism is applicable. The thermal mechanism dominates in high-temperature combustion over a fairly wide range of equivalence ratios. It appears that N_2O-intermidiate mechanism plays an important role in the production of NO in very lean, low-temperature combustion processes. The mechanism of NO_X formation from atmospheric nitrogen has been studied extensively. It is generally accepted that in combustion of near stoichiometric fuel-air mixtures the principle reactions governing the formation of NO_X from molecular nitrogen are

$$O + N_2 = NO + N \qquad (1)$$

$$N + O_2 = NO + O \qquad (2)$$

$$N + OH = NO + H \qquad (3)$$

This is often called the extended Zeldovich mechanism. The NO formation rate may then be written as

$$\frac{d[NO]}{dt} = \frac{6\times10^{16}}{T^{1/2}} exp\left(\frac{-69090}{T}\right) [O_2]_e^{1/2} [N_2]_e \qquad (4)$$

Where $[N_2] = x_{N2} \frac{P}{R_u T}$ (5)

$$[O_2] = x_{O2} \frac{P}{R_u T} \qquad (6)$$

x_{N2}=Mass fractions of N_2, x_{O2}=Mass fractions of O_2, e= equilibrium approach, P=Pressure of the exhaust gas, T=temperature of the exhaust gas.

The Figure 5 to Figure 9 shows the variation in NO_X at no load, one fourth load, half load, three fourth load and full load for 12% hydrogen blend respectively. The nitric oxides were reached the mass fraction of 7.5 * 10^{-7}, 8.5 * 10^{-7}, 10 * 10^{-7}, 12 * 10^{-7} and 14 * 10^{-7} at no load, one forth load, half load, three forth load and full load respectively and the curve remains constant. The results are taken on the basis of cycle simulation and observing when the graphs appear to be steady. Due to the relatively low combustion temperatures at low loads, the reduced thermal load of the engine and the increase in required ignition energy for lean hydrogen–air mixtures, this lean operating strategy also effectively avoids combustion anomalies. Due to increase in temperature, there is an increase in NO_X emissions at higher loads. At higher loads the combustion is more effective and also lesser amount of residual gases. The NO_X formation is a strong function of combustion temperature. Due to blending of hydrogen at higher loads the numbers of cycles are reduced for combustion. But the hydrogen gas has got lower ignition energy and higher flammability, the combustion temperature is increased.

C. *Comparison between experimental and simulated results for oxides of nitrogen*

The Figure 10 shows the comparison between simulated and experimental results. It was found that the experimental results were agreeing well with the simulated results. There is an average difference of 7.71 % between the experimental and simulated results.

Hydrogen continuous injection is probably the most common hydrogen mixture formation strategy and is employed in a variety of variants that differ in multiple aspects including part-load control, air fuel ratio and charging strategy. It is important to understand the principal correlation between the air fuel ratio and oxide of nitrogen emission that is applicable for all homogeneous mixture formation concepts. Some of the specifications like piston wall temperature, cylinder wall temperature, combustion temperature, pressure, electrode gap and valve overlap were assumed suitably according to standard SI engines. The cylinder pressure is assumed to be the same for the burned and unburned zones. The contents of the cylinder are fully mixed and spatially homogeneous in terms of composition and properties during intake, compression, expansion, and exhaust processes. All gases are considered to be ideal gases during the engine thermodynamic cycle. These lead to some deviations from the experimental results.

IV. CONCLUSIONS

Recent drastic increase in the price of petroleum, rapid increase in emission of green house gases and very strict environmental legislations are major motivating factors for usage of hydrogen in internal combustion engines. The following conclusions can be made from the investigation.

1) The NO_x increases as the percentage of hydrogen blends increases. There is an average increase of 61.2% for the hydrogen blends of 12% respectively with respect to gasoline.
2) The experimental and simulated results agree very well for nitric oxide emission. There is an average difference of 7.71 %.

V. ACKNOWLEDGEMENT

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VI. REFERENCES

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