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Computational and experimental study on oxygen enriched intake of a spark ignition engine

Shashank SAKLESHPUR NAGARAJA[1], Chandan NAGARAJ [2], Kumar GN [3]

[1] *MSc Student, Clean Fossil and Alternative Fuels Energy, Silesian University of Technology, e-mail: shashank.sn92@gmail.com*
[2] *Graduate Engineer Trainee, Hero Motocorp, India*
[3] *Assistant Professor, National Institute of Technology Karnataka, Surathkal, India*

Abstract

A numerical and experimental study was carried out on oxygen enriched intake in an spark ignited (SI) engine. The study aims at validation of Wiebe function for oxygen enriched intake. This computational study was carried out at full load conditions at four engine speeds (2500, 3000, 3500 and 4000 rpm) for different blends of oxygen enriched gasoline (4%, 8% and 12% by mass of oxygen) in AVL BOOST, a one dimension engine analysis software. The computational and experimental results complement each other validating the use of AVL Boost for oxygen enriched intake. HC and CO emissions decreased drastically with increasing concentration of oxygen. However, there was abrupt increase in concentration of NOx emissions.

Keywords: Oxygen Enriched Intake, SI Engine, Emission Parameters

Sreszczenie

Obliczeniowe i eksperymentalne badania wzbogacania tlenem na wlocie silnika z zapłonem iskrowym

Obliczeniowe i eksperymentalne badania przeprowadzono na silniku z zapłonem iskrowym (SI) wzbogaconym przy wlocie w tlen. Badanie miało na celu walidację funkcji Wiebe, która służy do poboru tlenu. Obliczenia przeprowadzono w warunkach pełnego obciążenia na czterech prędkościach obrotowych (2500, 3000, 3500 i 4000 rpm) dla różnych mieszanek benzyny wzbogaconej w tlen (4%, 8% i 12% w stosunku do masy tlenu) w AVL Boost, oprogramowaniu, które analizuje jeden wymiar silnika. Obliczeniowe i doświadczalne wyniki uzupełniają się wzajemnie i sprawdzają wykorzystanie AVL Boost, przy poborze tlenu do silnika. Emisja HC i CO spadła drastycznie wraz ze wzrostem stężenia tlenu. Nie zauważono jednak nagłej zmiany stężenia emisji NOx.

Słowa kluczowe: wzbogacenie tlenem, silnik z zapłonem iskrowym, parametry

1. Introduction

Increasing air pollution is one of the major problems being faced by the world today. The pollutants emitted from vehicles cause ecological problems such as the destruction of ozone layer, increase in greenhouse effect, acid rain, etc. This has led to a debate on use of additives to gasoline in order to reduce the exhaust emissions. Increasing the oxygen content leads to faster burn rates. Also, oxygen enriched air leads to shorter ignition delays and offers more potential for burning fuel.

Advances in computational methods and the availability of high speed computers have made it possible for the researchers to simulate and analyse combustion processes in an IC Engine. Experimental study requires enormous time, manpower, material and financial resources. However, the use of computational methods as a research tool to simulate the process has made it advantageous over experimental study [1].

The present study investigates the effect of oxygen enriched intake in a four-stroke spark ignited single cylinder IC Engine. This computational study was carried out at full load conditions at four engine speeds (2500, 3000, 3500 and 4000 rpm) for different blends of oxygen enriched gasoline (4%, 8% and 12% by mass of oxygen). Computational results are always approximate due to truncation errors. An experiment using a single-cylinder engine was carried out to validate the results obtained from AVL Boost. AVL simulation and experimental results were compared for Carbon Monoxide (CO), Unburned Hydrocarbon (HC) and Oxides of Nitrogen (NO_x) Emissions.

2. Literature Review

The literature survey is divided into two components.

1. Oxygen Enriched Intake

2. Simulation of an Internal Combustion Engine

2.1 Oxygen Enriched Intake

A number of studies are available on oxygen-enriched intake in diesel engines of which some are mentioned below. However such studies are very limited in spark ignited engine.

Yuh-Yih Wu and K. David Huang (2007) have carried out studies on oxygen enrichment in a spark ignited engine [2]. In their studies, a part of oxygen was added to the intake air when the engine is operated at wide open throttle. The combustion process can be enhanced by using an oxidant that contains a higher proportion of oxygen than that in normal air. The study aimed at determining the combustion characteristics and engine performance of such engine enhanced with oxidant. Engine testing was performed on a 50 cc four-stroke, spark-ignition engine with the oxygen concentration of intake air ranging from 21% to 25% by volume. The engine torque was found to increase with increasing oxygen concentration. The HC and CO emissions are decreased with oxygen enrichment, but the NOx emission was increased.

In a study by **Henry et al. (1993)**, a production spark ignition engine powered vehicle (3.1-L Chevrolet Lumina, model year 1990) was tested with oxygen-enriched intake air containing 25 and 28% oxygen by volume to determine if (1) the vehicle would run without difficulties and (2) there would be emissions benefits. Standard Federal Test Procedure (FTP) emissions test cycles were run satisfactorily without vehicle performance anomalies [3]. The results of catalytic converter-out (engine with a three-way catalytic converter in place) emissions showed that both CO and HC emissions were reduced significantly in all three phases of the emissions test cycle, compared with normal air (21 % oxygen). CO emissions from the engine (with the three-way catalytic converter removed) were significantly reduced in the cold-phase of the test cycle. The catalytic converter also had improved carbon monoxide conversion efficiency under the oxygen-enriched air conditions. Detailed results of hydrocarbon specification indicated large reductions in 1, 3-butadiene, formaldehyde, acetaldehyde, and benzene from the engine with the oxygen-enriched air.

A single-cylinder, 4-stroke, spark-ignition engine was used to evaluate the effect of oxygen enriched air on engine performance and exhaust emissions by **Timothy et al. (1993)** [4]. Evaluations were made with both gasoline and natural gas. The oxygen content of the intake air was varied between 20.9% (ambient air) and 25%. The effects of oxygen enrichment were evaluated in terms of power output, specific fuel consumption, fuel conversion efficiency, exhaust gas temperature, and exhaust emissions (carbon monoxide and hydrocarbons). Test results indicate that the use of oxygen enriched air produces a significant increase in power output, improved fuel conversion efficiency, lower specific fuel consumption, higher exhaust gas temperature and a substantial reduction in carbon monoxide and hydrocarbon emissions when the engine is fueled with either gasoline or natural gas. The feasibility of using a membrane gas separator to supply oxygen enriched air for vehicle applications was also considered and determined to be feasible.

Effect of Oxygen Enrichment on the Performance and Emissions of I.D.I. Diesel Engines was carried out as early as 1983 by **Jamil Ghojel et al. (1983**) [5]. The purpose of this study was to determine the effect of the partial pressure of O2 in the intake charge of an I.D.I. diesel engine on the various operating parameters and the exhaust emissions. The oxygen content in the intake was varied between 21% and 40% by volume. Engine performance and emissions were evaluated at constant engine speed and injection timing while fueling was varied. The research revealed that enriching the intake air with oxygen led to a large decrease in ignition delay and reduced combustion noise. The fuel economy, the power output and the exhaust temperature remained almost constant. HC and CO emissions decreased and smoke levels dropped substantially, while NOx emissions increased pro-rata with the O_2 added.

Similar studies of oxygen enrichment were carried out on diesel engine by **Hongsik Byun et al.(2006)** [6]. In this study, gas separation membranes with polystyrene(PS) and polydimethylsiloxane(PDMS) were prepared and the effects of enriched oxygen on the emission gas of a diesel engine were investigated. The diesel engines used in this study were single-cylinder ones. For the oxygen enriched inlet air, the spiral wound module was used after calculation of air flux requirements. The emission of a diesel engine of a larger size (11,149 cc of engine displacement) was also investigated in order to and out the possibility of this system to be used in commercial applications. When the oxygen separation membrane was used in the diesel engines, the smoke density of both diesel engines was remarkably reduced (35-73%). The oxygen concentration in the inlet air affects the composition of the emission gases. Especially, HC emissions decreased with the increase of oxygen concentration.

2.2 Simulation of an Internal Combustion Engine

Alla (2002) worked on computer simulation of four stroke spark ignition engine [7]. In this study, discussion about general introduction to computer simulation and zero dimensional model of spark ignition engine was carried out. The thermodynamic model was developed based on the first law of thermodynamics and ideal gas law. An arbitrary heat release formula was used to predict the cylinder pressure, which in turn was used to and the indicated work. Combustion modeling was carried out using Wiebe function. The heat transfer from the combustion mixture to cylinder wall was calculated using empirical correlation. The parameters which can affect the performance of four stroke spark ignition engines, such as equivalence ratio, spark timing, heat release rate, compression ratio, compression index and expansion index were studied.

Kodah et al. (2000) worked on engine simulation for the prediction of pressure within a spark ignition engine [8]. Combustion modeling was carried using Wiebe function approach, an exponential function to calculate the rate of fuel burned. The Eichelberge equation was used to calculate the heat-transfer rate between the cylinder gases and combustion chamber walls. The modified Mallard and Le Chatelier equation was used to calculate the laminar flame speed. The propagating flame surface was considered to be spherical as assumed in many earlier studies. The effects of the many operating conditions, such as compression ratio, engine speed, and spark timing were studied.

Al-Baghdadi (2006) developed a model for simulating the performance parameters of spark ignition engines fueled with a range of fuels (gasoline, ethanol or hydrogen) and their mixtures [9]. For modeling the combustion chamber was generally divided into burned and unburned zones separated by a flame front. The pressure was assumed to be uniform throughout the cylinder charge. The instantaneous heat interaction between the cylinder content (burned and unburned zones) and its walls was calculated by using the following semi-empirical expression for a4-stroke engine. The instantaneous energy flows into the crevices were calculated by using the following semi-empirical expression of **Gatowski et al. (1984)** for a spark ignition engine [10].

2.3 Observations from Literature Survey

The following are the observations from literature survey:

1. Worldwide emissions standards are getting stricter in the courses of time, and therefore there is a continuous effort to develop a new generation of clean internal combustion engines.

2. The increased oxygen concentration in the combustion chamber is expected to cause a considerable reduction of both CO and HC emissions.

3. At part loads, the addition of oxygen improves the combustion stability and prevents misfiring.

4. The more stable combustion reaction leads to an increased power output, a better fuel economy, and an improved thermal efficiency.

5. The oxygen addition also causes a large decrease in ignition delay, shortens the combustion duration, and thereby lowers the tendency to knock.

6. Simulation of combustion in engine using Wiebe function proved to be accurate.

7. Woschni's model was generally used for assessing the heat transfer in a combustion engine.

However, the literature survey concludes on the note that no research has been carried out to validate the use of Wiebe function for an engine with oxygen enriched intake. The present study tries to fill this void by carrying out simulation and experimental studies of a four stroke spark ignited engine with oxygen enriched intake at various speed conditions.

3. Simulation

AVL Boost is a package of computer codes which enables the user to model and simulate the various processes of an Internal Combustion Engine. In the current investigation, this software is used to analyze the effect of oxygen enriched intake on the performance and emissions of a SI Engine.

The pre-processing steps of AVL Boost enables the user to model a 1-Dimensional engine test bench setup using the predefined elements provided in the software toolbox. The various elements are joined by the desired connectors to establish the complete engine model using pipelines. The setup model is shown in Fig 3.1.

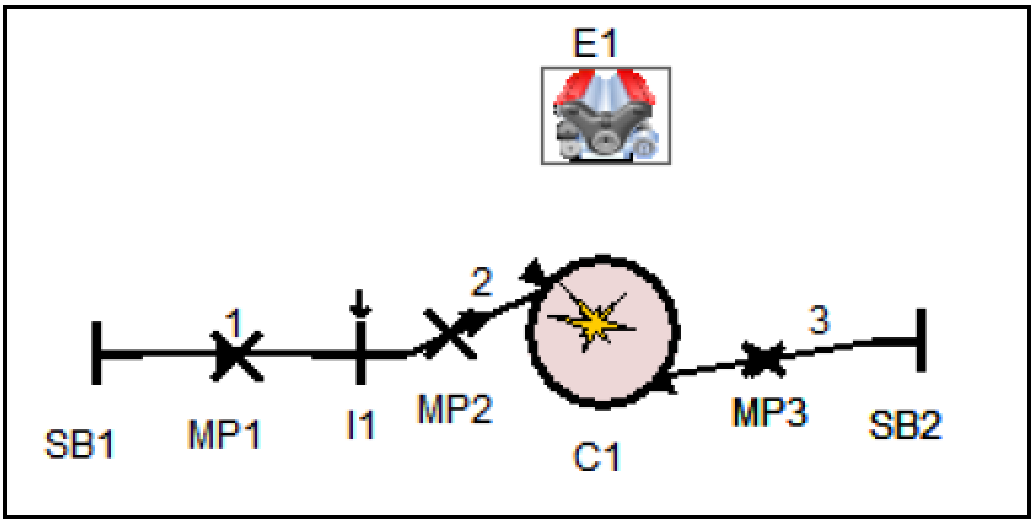

Fig 3.1 Simulation Setup

In the above figure E1 represents the Engine, C1 represents the Cylinder, MP1 to MP3 represents measuring points, SB1 and SB2 represents system boundary and I1 denotes the Fuel Injector.

The various configurations and parameters are set for each element. The system boundary conditions are specified. It is important to make a correct estimate of the boundary conditions as it directly affects the accuracy of the results.

For the current study Vibe two zone model was selected for the combustion analysis. This model divides the combustion chamber into unburned and burned gas regions as suggested by **Heywood J.B. (1988)** [11]**.** The first law of thermodynamics is applied to each of the zones to predict the rate of fuel consumed with respect to crank angle.

The following equations 3.1and 3.2 the Vibe two zone model [12]

$$\frac{dm_b u_b}{d\alpha} = -p_c \frac{dV_b}{d\alpha} + \frac{dQ_f}{d\alpha} - \frac{\sum dQ_{Wb}}{d\alpha} + \boldsymbol{h}_u \frac{dm_b}{d\alpha} - \boldsymbol{h}_{BB,b} \frac{dm_{BB,b}}{d\alpha} \qquad (3.1)$$

$$\frac{dm_u u_u}{d\alpha} = -p_c \frac{dV_u}{d\alpha} - \frac{\sum dQ_{Wu}}{d\alpha} - \boldsymbol{h}_u \frac{dm_b}{d\alpha} - \boldsymbol{h}_{BB,u} \frac{dm_{BB,u}}{d\alpha} \qquad (3.2)$$

Where

$dm_c u_c$	Denotes change of the internal energy in the cylinder
$p_c \frac{dV_c}{d\alpha}$	Denotes piston work
$\frac{dQ_f}{d\alpha}$	Denotes fuel heat input
$\frac{dQ_{Wc}}{d\alpha}$	Denotes wall heat losses
$\boldsymbol{h}_u \frac{dm_c}{d\alpha}$	Denotes enthalpy flow from the unburned to the burned zone
$\boldsymbol{h}_{BB,c} \frac{dm_{BB,c}}{d\alpha}$	Denotes enthalpy due to blowby

u and b in the subscripts denote unburned and burned gas

Prediction of NOx generated by combustion was based on the model by Pattas and Häfner which incorporates the well-known Zeldovich mechanism as suggested by **Bowman C.T (1975)** [13]**.** The rate of NOx production was estimated by using the following equation 3.3:

$$r_{NO} = C_{PPM} . C_{KM} . (2.0) . \frac{(1-\alpha^2) r_1}{1+\alpha . AK_2} \frac{r_4}{1+AK_4} \qquad (3.3)$$

$$\alpha = \frac{\frac{c_{NO,act}}{c_{NO,equ} . 1}}{C_{PPM}} \qquad (3.4)$$

$$AK_2 = \frac{r_1}{r_2 + r_3} \qquad (3.5)$$

$$AK_4 = \frac{r_4}{r_5 + r_6} \qquad (3.6)$$

Where

C_{PPM}	Denotes Post Processing Multiplier
C_{KM}	Denotes Kinetic Multiplier

c	Denotes molar concentration in equilibrium
r_i	Denotes reactions rates of Zeldovich mechanism

The amount of CO emissions was predicted using the following equation 3.7 which was taken from a model presented by **Onorati et al. (2001)** [14]**.**

$$r_{CO} = C_{Const} \cdot (1 - \alpha) \cdot (r_1 + r_2) \tag{3.7}$$

$$\alpha = \frac{c_{CO,act}}{c_{CO,equ}} \tag{3.8}$$

Where

c	Denotes molar concentration in equilibrium
r_i	Denotes reactions rates based on the model

The process of formation of unburned hydrocarbons in the crevices is described by assuming that, the pressure in the cylinder and in the crevices is the same and that the temperature of the mass in the crevice volumes is equal to the piston temperature. This assumption was made in the model by **D'Errico et al. (2002)** [15]**.**

The mass in the crevices at any time period is given by equation 3.9:

$$m_{crevice} = \frac{p \cdot V_{crevice} \cdot M}{R \cdot T_{piston}} \tag{3.9}$$

Where

$m_{crevice}$	Denotes mass of unburned charge in the crevices
p	Denotes cylinder pressure
$V_{crevice}$	Denotes total crevice volume
M	Denotes unburned molecular weight
R	Denotes gas constant
T_{piston}	Denotes piston temperature

4. Experimentation

In order to validate the simulation results, experimentation was carried out in Lombardini LGA-340 gasoline engine (340cc, single cylinder, 4 stroke, SI engine). The technical specification of the engine is provided in Table 4.1.

Table 4.1 Technical Specifications of the Engine

ENGINE PARAMETER	DETAILS
Cylinder	Single
Bore	82 mm
Stroke	64 mm
Displacement	338 cc
Compression Ratio	8:1
Maximum rpm at no load	6200 rpm
Power Rating	9 kW at 4400 rpm
Maximum Torque	20.2 Nm at 2800 rpm

The engine was previously modified from a carburettor inlet to a port fuel injected engine. This modification ensures higher volumetric efficiency. A test benches involving an eddy current-type dynamometer, exhaust emission analyzer, fuel metering device and auxiliary equipment is prepared as described in Fig 4.1. The engine is coupled with its original shaft to the SAJ make eddy current dynamometer to control and measure engine speed and torque output. The control panel of the dynamometer is placed at a safe but easily accessible distance from the setup. A mass air flow (MAF) sensor is placed in the inlet manifold to help control stoichiometric air-fuel ratio. Another rotameter is placed in the inlet pipe line of oxygen to control the mass fraction of oxygen. A spark plug with pressure transducer is connected to the data acquisition system (DAS) as shown in the figure. The developed electronic control unit (ECU) is interfaced with the computer by using RS-232 port. The exhaust emissions from the test engine are measured by exhaust gas analyzer which is placed in the way of engine exhaust system.

The engine is run for the similar parameters as performed in the simulation studies. The readings are compared with the results obtained from the simulation studies.

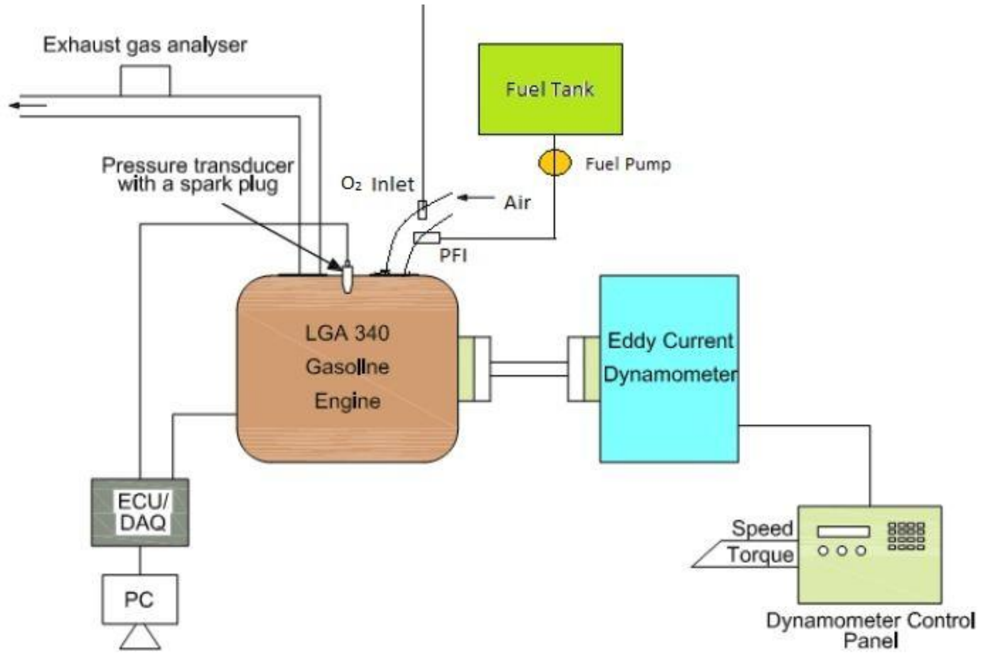

Fig 4.1 Schematic Diagram of Experimental Apparatus

5. Results and Discussion

The present study concentrated on the emission characteristics of the Oxygen enriched gasoline blends. Different concentrations of the blends (4% Oxygen (O4), 8% Oxygen (O8) and 12% Oxygen (O12) by mass) were analysed using AVL BOOST codes and were validated experimentally at full load conditions for the speeds ranging from 2500-4000 rpm in the steps of 500 rpm. The results are divided into different sections based on the parameter analysed.

5.1 Carbon Monoxide Emissions (CO)

Carbon Monoxide (CO) emission is a strong function of equivalence ratio. The influence of other parameters on the emissions of CO is very low and the percentage of CO emitted from the engine was almost constant with increasing speed at full load condition.

Both computational and experimental results show that the change in percentage of CO emissions with varying speed is constant at full load conditions for all the cases. CO emissions decrease with increase in oxygen concentration at constant speed due to the presence of excess oxygen leading to complete combustion. Computational and Experimental results of CO emissions for four blends at constant speed are shown in Fig 5.1 to 5.4.

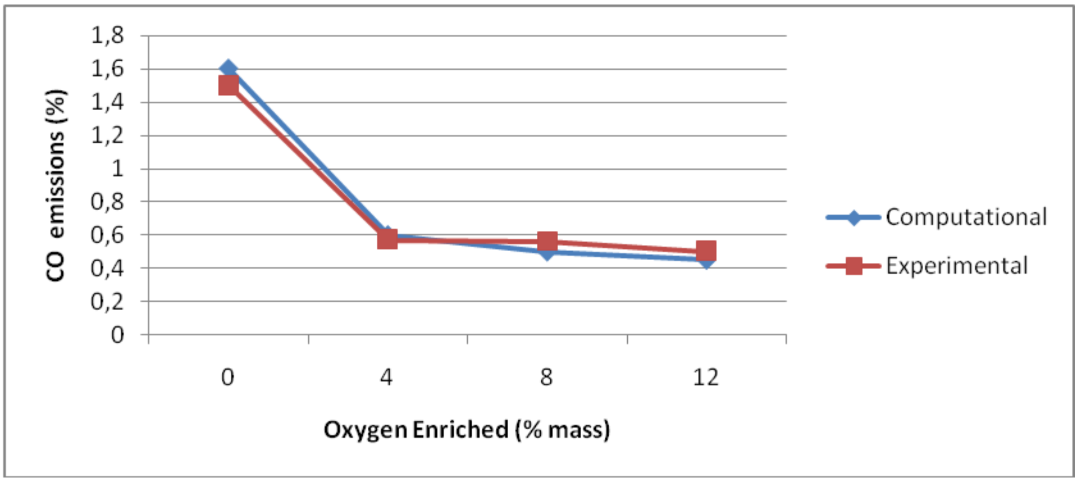

Fig 5.1 CO emissions for different blends at constant speed of 2500 rpm

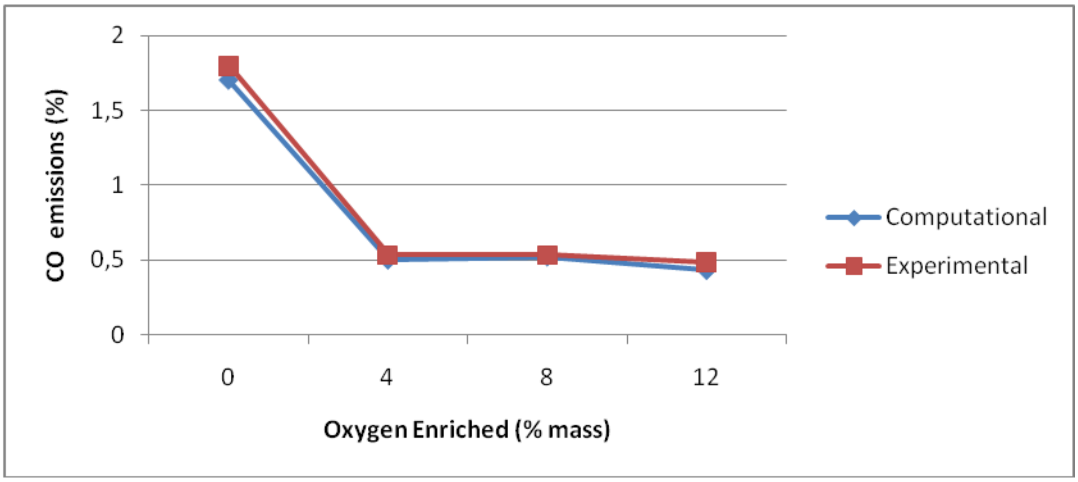

Fig 5.2 CO emissions for different blends at constant speed of 3000 rpm

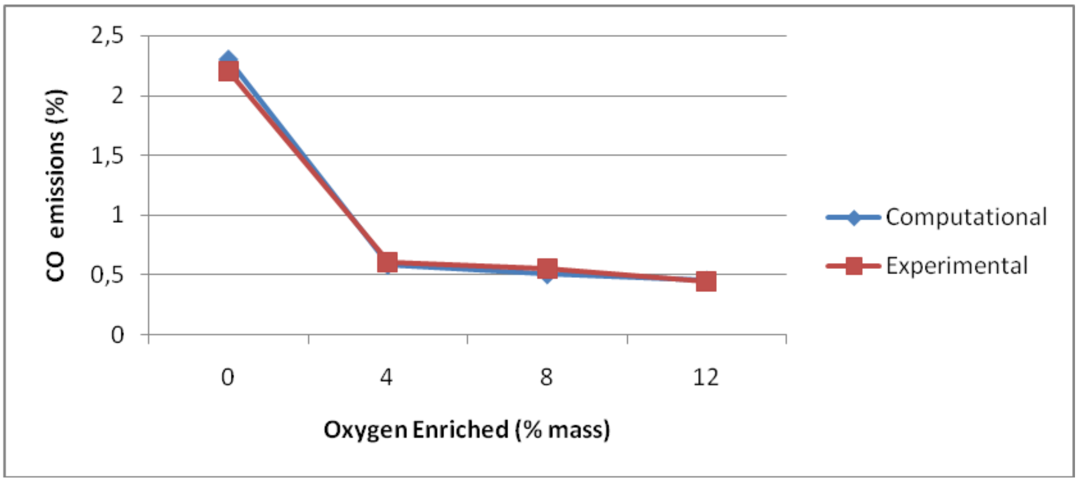

Fig 5.3 CO emissions for different blends at constant speed of 3500 rpm

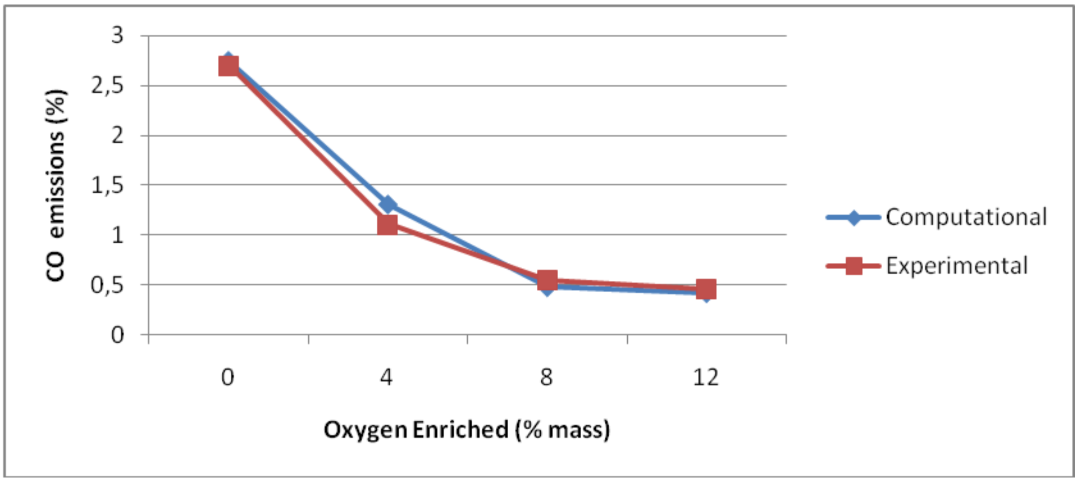

Fig 5.4 CO emissions for different blends at constant speed of 4000 rpm

5.2 Nitrogen Oxide Emissions (NOx)

NOx emissions are mainly affected by the equivalence ratio, peak temperature, ignition timing and oxygen concentration in the fuel. In the present study, ignition timing was held constant. The simulation and experimental results have shown that with the increase in oxygen concentration, NOx emissions increase because of increase in peak temperature. Computational and Experimental results of NOx emissions for four blends at constant speed are shown in Fig 5.5 to 5.8.

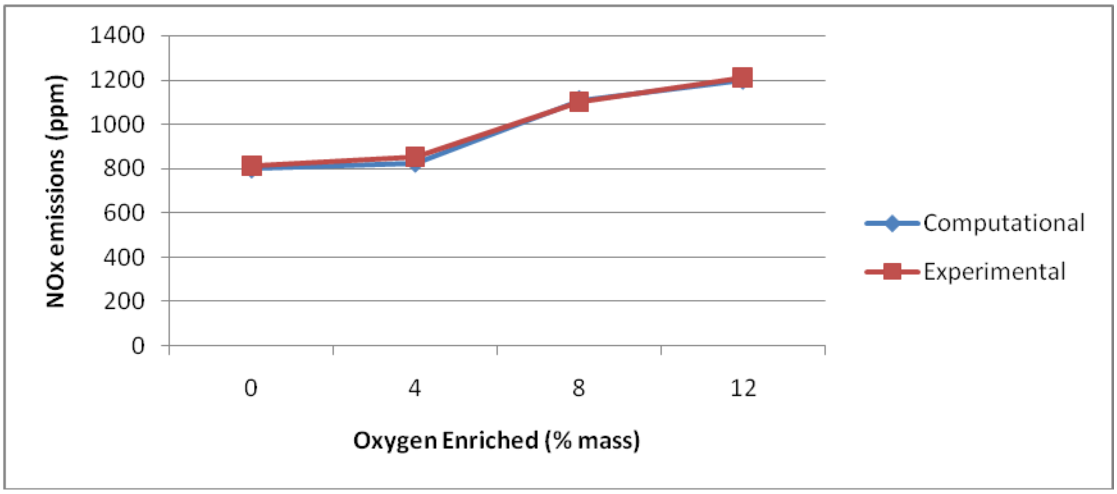

Fig 5.5 NOx emissions for different blends at constant speed of 2500 rpm

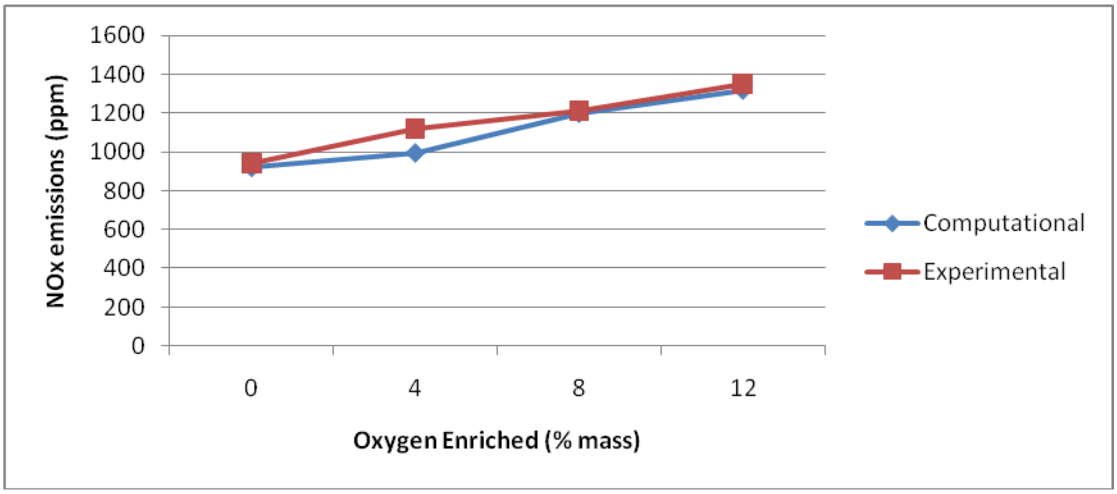

Fig 5.6 NOx emissions for different blends at constant speed of 3000 rpm

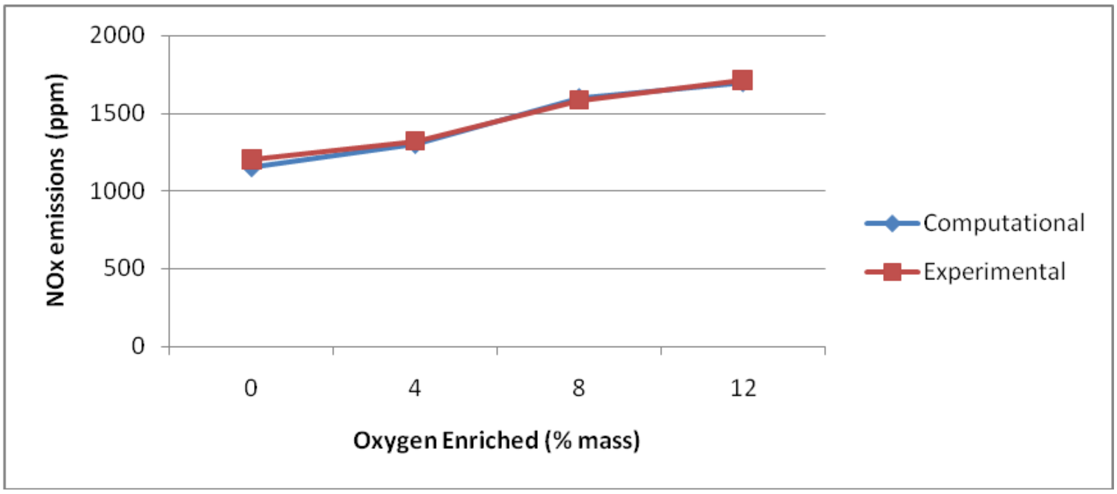

Fig 5.7 NOx emissions for different blends at constant speed of 3500 rpm

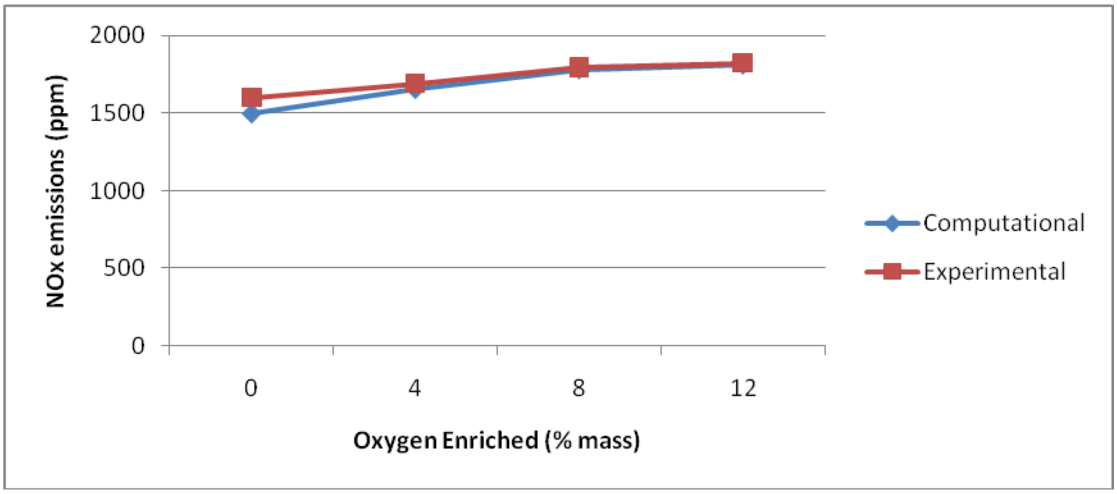

Fig 5.8 NOx emissions for different blends at constant speed of 4000 rpm

5.3 Unburned Hydrocarbon Emissions (HC)

Unburned hydrocarbons are result of incomplete combustion of charge inside the cylinder. Primary sources of HC emissions are the charge in the crevice volume which is not burned due to flame quenching at the entrance and the fuel vapours absorbed by the oil layers that are not burned during the combustion process .

It is clearly seen from results that with increase in percentage of oxygen, HC emissions decrease. However, in this case the experimentally obtained results showed a maximum deviation of about 20 % from the simulation results. This is because AVL BOOST code predicts combustion only based on thermodynamic properties. Since oxygen enrichment is not readily available in AVL database, specific fuel properties are not considered. The faster burn rates due to oxygen enrichment are not considered by the software which leads to this drastic deviation. Computational and Experimental results of HC emissions for four blends at constant speed are shown in Fig 5.9 to 5.12.

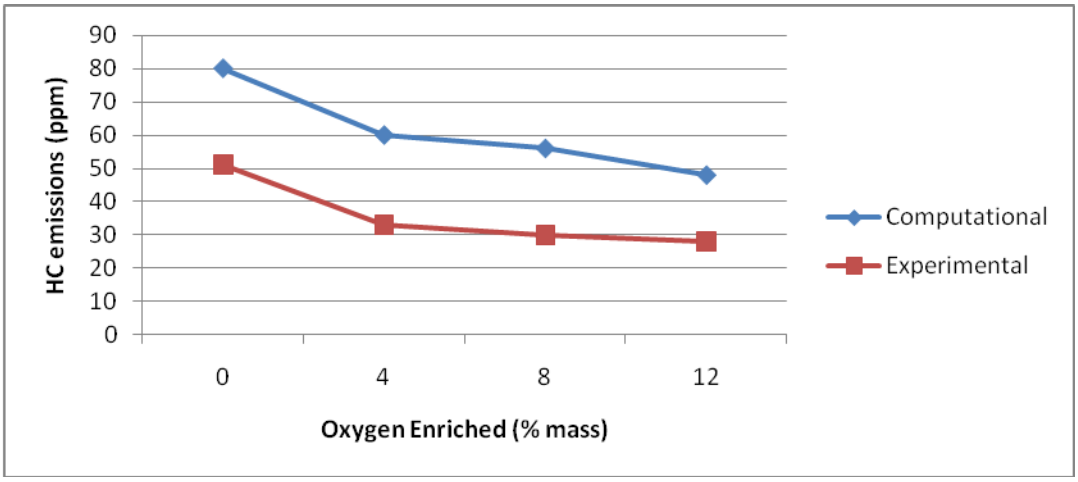

Fig 5.9 HC emissions for different blends at constant speed of 2500 rpm

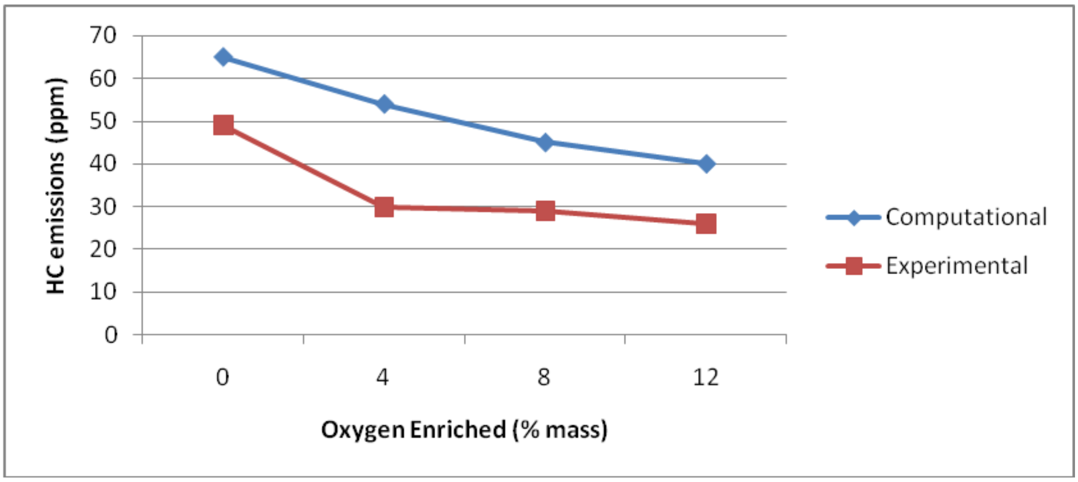

Fig 5.10 HC emissions for different blends at constant speed of 3000 rpm

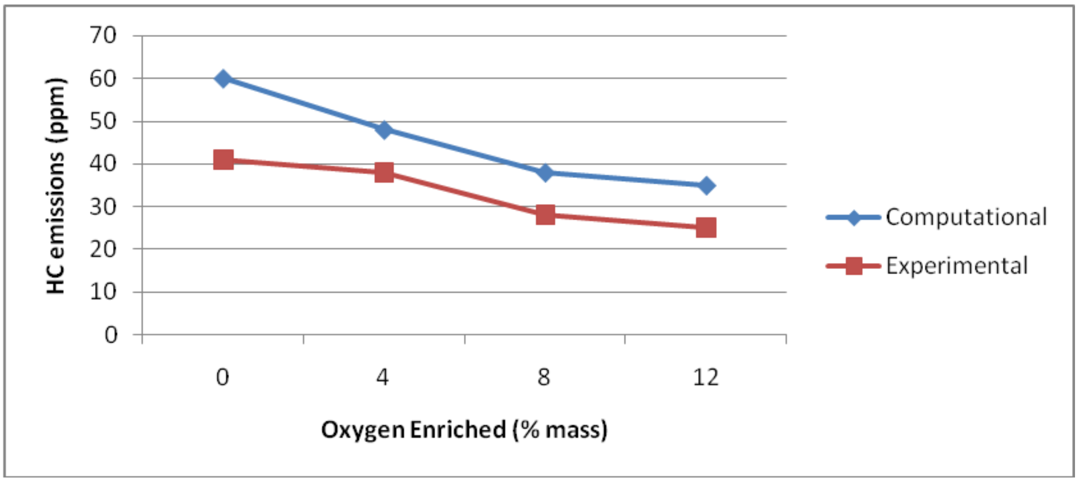

Fig 5.11 HC emissions for different blends at constant speed of 3500 rpm

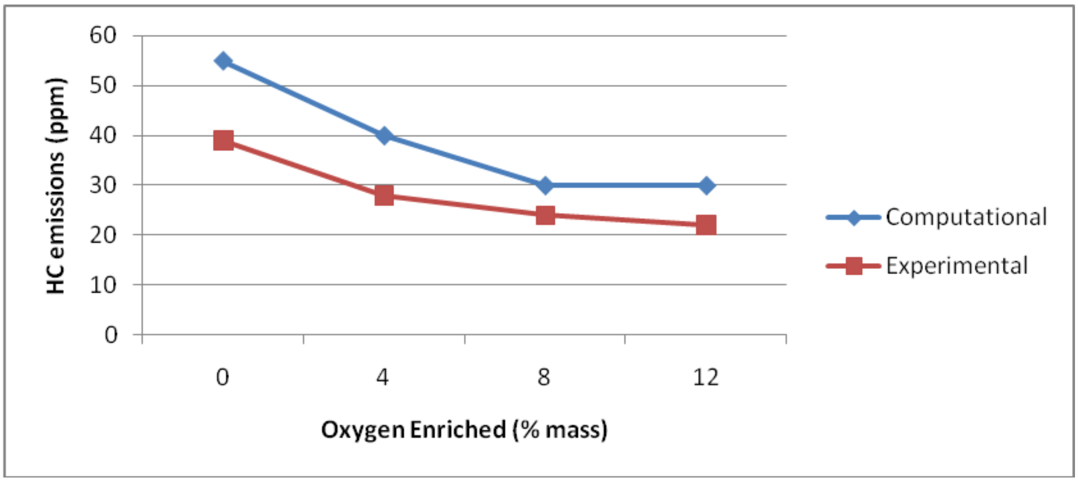

Fig 5.12 HC emissions for different blends at constant speed of 4000 rpm

6. Conclusions

The following conclusions can be made from the above results:

1. Simulation and experimental results complement each other validating the use of Wiebe function for oxygen enriched intake in a spark ignition engine.

2. CO and HC emissions decrease in oxygen enriched blends due to the presence of excess oxygen leading to complete combustion. Prediction of CO emissions in software was accurate whereas HC emissions showed a visible deviation, indicating that improvements are needed in this sector in the software.

3. NOx emissions increase in oxygen enriched blends because of increase in peak temperature due to better combustion.

4. Oxygen enrichment was possible only up to 12% by mass. Higher concentrations of oxygen led to severe engine overheating problems. Hence, higher concentrations were not used.

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