EFFECT OF OXYGEN ENRICHMENT ON COMBUSTION AND EMISSIONS IN A SPARK IGNITION ENGINE

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ABSTRACT

Simulations of the performance of a spark ignition engine, when operated with oxygen enriched air are presented in this work. A zero-dimensional, one-zone thermodynamics model, which considers losses in crevices and heat transfer to the cylinder walls, was used. Such model predicts indicated engine parameters such as efficiency, fuel consumption and power, as well as in-cylinder pressure and temperature. The simulations were carried out varying the oxygen content, from 0% (atmospheric air), to pure oxygen (100% of O_2).

Several results obtained from the simulations were compared with experimental test on a 900 rpm ASTM-CFR[1] engine located in the engines laboratory of University of Antioquia (Medellín-Colombia) at an altitude of 1500 meters above sea level. The enriched oxygen tests were made by determining the higher indicated mean effective pressure as a function of the spark timing for a unique compression ratio, showing that maximum temperature, indicated power and efficiency all increase. CO and CO_2 emissions decreased, but NO_x emissions increased as oxygen was added into the air in the intake system.

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1. Introduction

The internal combustion engine is one of the most widely used applications produced by engineering development. However, it is a very limited machine: it has an effective efficiency of 30-35% [1]. This means that almost 70% of the chemical energy contained in the fuel is lost in the coolant, in the exhaust gases, as incomplete combustion of fuel and as radiation [2].

Previous studies have shown that engine performance is enhanced with oxygen enrichment in the intake air. The addition of oxygen produces an increase in engine's efficiency [3, 4] and a decrease in specific fuel consumption [3-5]. As the concentration of oxygen increases inside the cylinder, the amount of fuel injected must also increase in order to maintain stoichiometric conditions; this produces an increase in mean effective pressure, and therefore in power output [3-7].

On the other hand, strict pollutant emission regulations have forced engine manufacturers to develop new technologies that help control nitrogen oxides (NO_x), unburned hydrocarbons and carbon monoxide (*CO*) emissions. Oxygen enriched combustion is an effective technique for reducing unburned hydrocarbons and *CO* emissions [4, 6, 8, 9]. However, previous works have proven that oxygen enrichment significantly increases NO_x emissions due to the rise in combustion temperature [4, 6-9]. In order to obtain a full benefit with oxygen enrichment in internal combustion engines, special catalyst technology for high NO_x concentrations should be used.

The application of oxygen enrichment in the intake air in a spark ignition engine could be applied in older engines to increase their performance and also in order for them to comply with emission control policies. It also helps to compensate the loss of atmospheric oxygen at high altitudes due to the lower atmospheric pressures.

In this work, the addition of oxygen in the intake air was studied under high altitude conditions in order to evaluate the combustion process and the exhaust emissions.

2. Simulations and Testing

2.1. Simulations

A zero-dimensional, one-zone thermodynamic model, which considers losses in crevices and heat transfer to the cylinder walls, was used to simulate the engine performance. This model uses Wiebe's approximation to compute the fuel burning rate inside the combustion chamber. Inputs to the model are geometric characteristics of the engine, thermodynamic properties of the mixture, amount of air and fuel entering the chamber per cycle, atmospheric conditions, spark timing and combustion duration.

Oxygen enrichment was made by replacing air volume with oxygen volume at different proportions inside the chamber. Equation 1 shows said replacement on the stoichiometric reaction for the combustion of a mixture of 90% of gasoline and 10% of ethanol[2] in volume (*E10*) ($0.9C_8H_{15}+0.1C_2H_6O$).

$$\left(0.9C_8H_{15}+0.1C_2H_6O\right)+k\left(\alpha\left(O_2+3.76N_2\right)+\beta O_2\right)\rightarrow products \qquad 1$$

Where the products are all of the species that can be formed with the combination of Hydrogen (*H*), Carbon (*C*), Oxygen (*O*) and Nitrogen (*N*); including carbon dioxide (CO_2), water vapor (H_2O) and NO_x. The sum of α and β is always 1; so that in the case of 0% of oxygen substitution $\alpha=1$ and $\beta=0$, and in the case of 100% of oxygen substitution $\alpha=0$ and $\beta=1$. When the value of β rises, the amount of O_2 will increase as the amount of N_2 will decrease. The value of k in equation (1) is *10.875* and it represents the number of moles of oxygen needed to have stoichiometric combustion with one mole of the specified fuel.

The variation of the oxygen composition modifies the value of the gas constant (*R*) as well as the value of the stoichiometric air to fuel-ratio (*A/F*). Table 1 lists the values that these parameters will have for each case of oxygen substitution.

Table 1. A/F and R values depending on the O_2 substitution percentage.

β	*R [kJ/kg·K]*	*A/F*
0	0.289	14.29
0.1	0.288	13.19
0.2	0.287	12.10
0.3	0.286	11.00
0.4	0.285	9.90
0.5	0.283	8.81
0.6	0.281	7.71
0.7	0.279	6.62
0.8	0.275	5.52
0.9	0.269	4.43
1	0.260	3.33

[2] Law in Colombia dictates that gasoline must have a 10% content of ethanol in volume.

The different pressure-volume diagrams obtained by simulations as the oxygen content in the mixture increases are shown in figure 1. The increase in maximum pressure is associated to an increase in the maximum temperature inside the cylinder [10]. The increase of the area below the curves is caused by a rise in the total work- thus in the power- generated by the engine [11]. Figures 2a and 2b show such increase in power and maximum temperature.

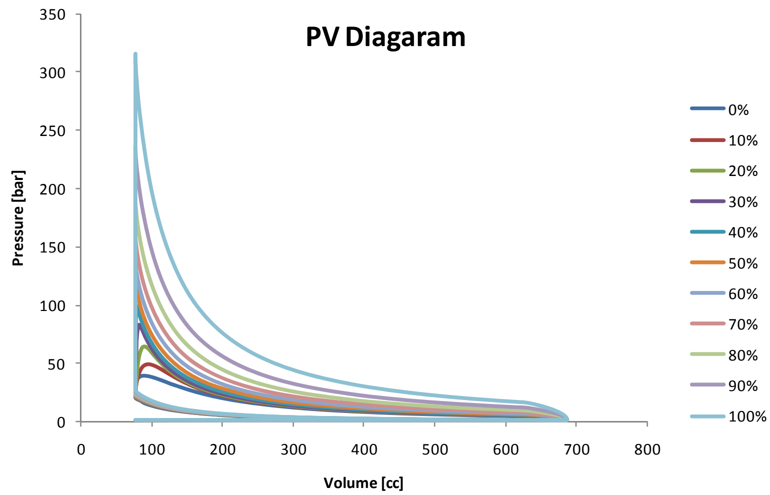

Figure 1. P-V cycles for each O_2 substitution case.

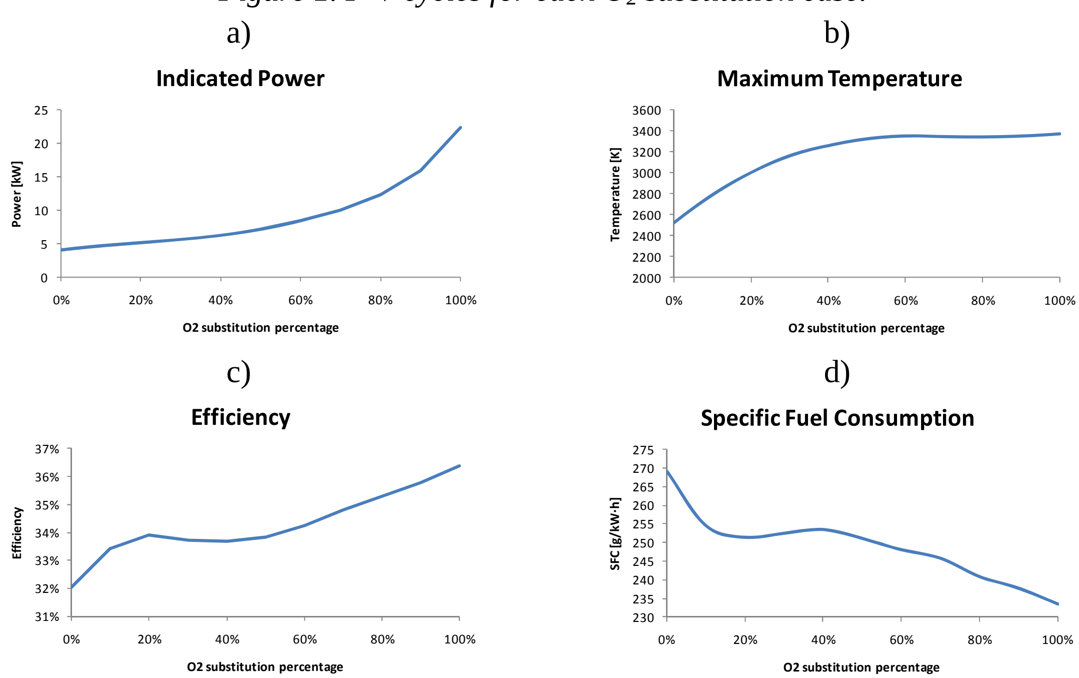

Figure 2. Engine performance with different O_2 concentrations. a) Indicated power delivered by the engine, b) Maximum temperature inside the combustion chamber, c) Thermal efficiency, d) Specific fuel consumption.

Figure 2 shows the performance of the engine when varying the O_2 concentration in the mixture. Figure 2c shows an increase in efficiency (which brings as a result the decreasing behavior of the specific fuel consumption, as shown in figure 2d). High O_2 concentration in the mixture produces a higher combustion speed [4], therefore it occurs in conditions that resemble those of constant-volume combustion. This helps increase the engine's thermal efficiency [11].

2.2. Experimental Setup and Procedure

2.2.1. Experimental Setup

An ASTM-CFR engine was used for the experimental testing. It is a one-cylinder engine, water cooled, with variable compression ratio, which operates at constant 900 rpm. An electronic fuel injection system has been adapted to the engine, which allows fuel flow control from a PC; it also has been fitted with all the necessary sensors and actuators to monitor and control the most important variables in real time. Engine specifications are listed in table 2.

Table 2. Geometric characteristics of the engine [12]

PARAMETER [UNITS]	VALUE
Number of cylinders	1
Stroke [mm]	114.3
Bore [mm]	82.5
Connecting rod length [mm]	254
Displacement [cm^3]	611.73
Compression ratio[3]	9:1
Intake valve opens [° *aTDC*[4]]	10
Intake valve closes [° *aBDC*[5]]	34
Exhaust valve opens [° *bBDC*[6]]	40
Exhaust valve closes [° *aTDC*[7]]	15

[3] Compression ratio in the engine is variable from 4:1 to 10:1, the tests described on this paper were performed at a constant compression ratio of 9:1.
[4] after Top Dead Center
[5] after Bottom Dead Center
[6] before Bottom Dead Center
[7] after Top Dead Center

The experimental setup is shown in figure 3. It consists of the CFR engine, equipped with the necessary sensors to perform a full combustion diagnosis and compute the indicated parameters for each case of O_2 en enrichment.

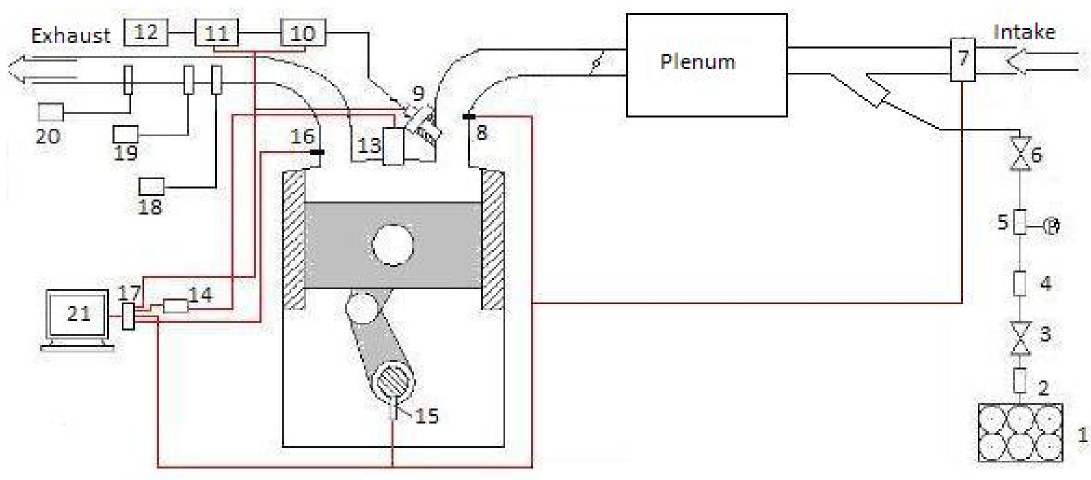

Figure 3. Experimental setup(adapted from [11]*). (1) Oxygen supply, (2) Backfire arrestor, (3) Pressure control valve, (4) Oxygen flow meter, (5) Pressure meter, (6) Oxygen flow control valve, (7) Air mass flow meter, (8) Intake manifold temperature sensor, (9) Fuel injector, (10) Fuel mass flow meter, (11) Fuel pump, (12) Fuel tank, (13) In-cylinder pressure transducer, (14) Charge amplifier for the pressure transducer, (15) Optical encoder coupled to the crankshaft, (16) Exhaust manifold temperature sensor, (17) Data acquisition system, (19) CO_2 and CO concentration analyzer, (19) NO_x concentration analyzer, (20) Hydrocarbon concentration analyzer, (21) Computer.*

Oxygen flow and air flow are measured before both gases mix together in the plenum. The plenum helps eliminate the flow pulsating effect induced by the cylinder suction [13]. The plenum's volume is over 200 times greater than the engine's displacement, which guarantees flow homogenization.

The piezoelectric pressure transducer is screwed in the cylinder's head. The transducer is wired to a charge amplifier which sends the pressure signal directly to the data acquisition system and then to the computer. This signal is stored in the computer's memory for an off-line analysis. The 1024 pulse/revolution optical encoder is coupled to the crankshaft where it measures the crank angle and triggers the sample of combustion pressure.

Due to cyclic dispersion in consecutive engine cycles, the mean of 300 consecutive pressure cycle samples was registered in order to minimize measurement error [13].

2.2.2. Experimental procedure

All tests were performed at a constant 900 rpm engine speed and a compression ratio of 9:1, varying the spark timing and O_2 concentration in the mixture. Spark timing was measured with a digital strobe gun. O_2 concentration was controlled by the flow valve and the flow meter, and the gas was always delivered at a pressure of 1 bar.

The tests were made at spark timings of 1° *aTDC* and 1°, 5° and 10° *bTDC*. The performance of the engine without any O_2 enrichment was first measured and considered as the comparison base line. Then the volumetric fraction of O_2 in the mixture was increased in 1, 2, 3, 4 and 5% as the air proportion was simultaneously decreased.

For each O_2 increment, the amount of fuel injected per cycle was also increased, as shown in figure 4, so that there would always be stoichiometric combustion ($\lambda=1$).

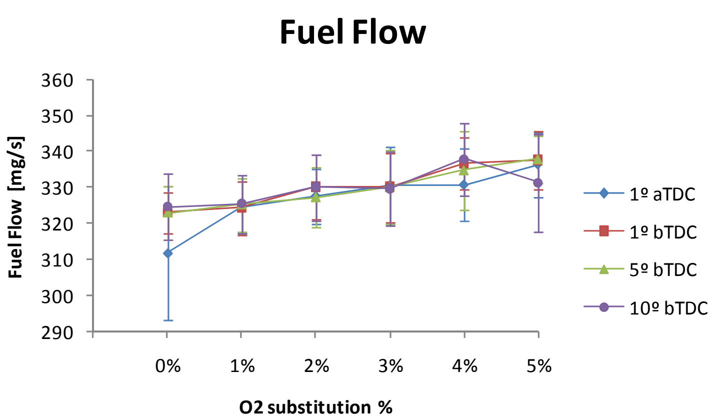

Figure 4. Fuel flow for each O_2 increment.

3. Results

3.1. Engine Performance

Experimental measurements on the engine are shown in figure 4. A power increase can be observed, as well as an increase in efficiency and maximum temperature. Specific fuel consumption lowers as the mixture has more O_2 content.

For high O_2 percentages (4 and 5%), and in the spark timings of 5 and 10° *bTDC*, the presence of knocking in the engine was found. This phenomena was generated by high in-cylinder temperatures [14].

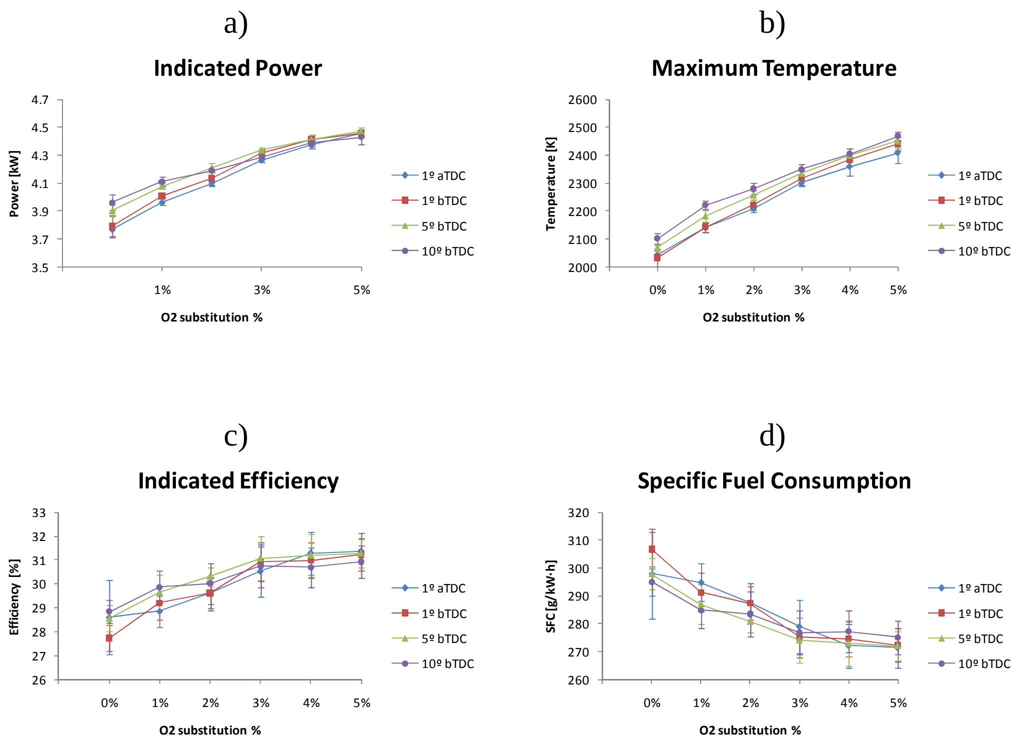

Figure 4. Experimental Results. a) Indicated power delivered by the engine, b) Maximum temperature inside the combustion chamber, c) Indicated thermal efficiency, d) Specific fuel consumption.

3.2. Emissions

Figure 5 shows the concentration of pollutants in the flue gases. A rise in CO_2 and NO_x emissions can be noted as well as a decrease in *CO* and hydrocarbons in the exhaust. NOx emissions were measured before the catalyst system.

There is a high dependency between maximum temperature and NO_x formation [15]. This explains such a large increase in this pollutant emission as the temperature rises.

The increase in CO_2 emissions is mostly a consequence of the rise of the amount of fuel burned as the O_2 content increases.

The reduction of hydrocarbon emissions can be attributed to the rise in exhaust gas temperature (figure 6), which enhances post combustion oxidation [4].

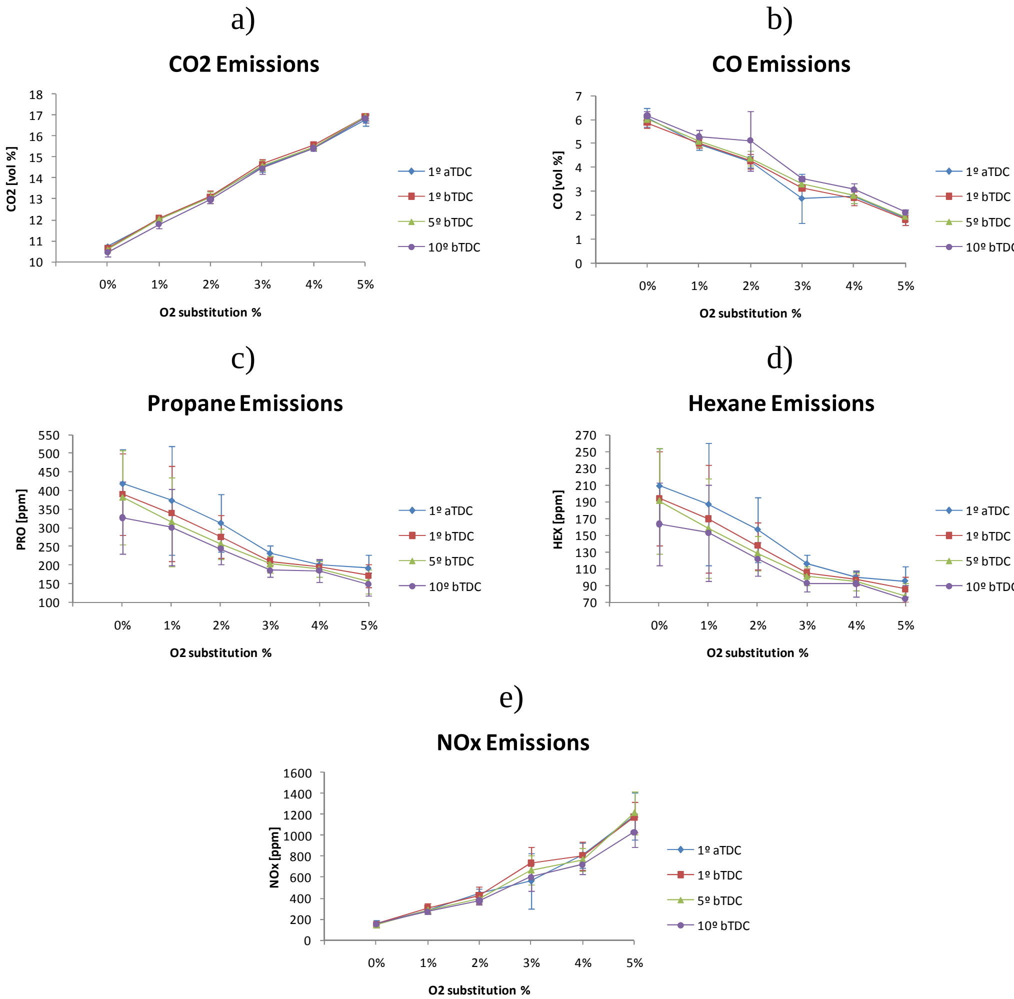

Figure 5. Pollutant Emissions. a) CO_2, b) CO, c) Propane, d) Hexane, e) NO_x.

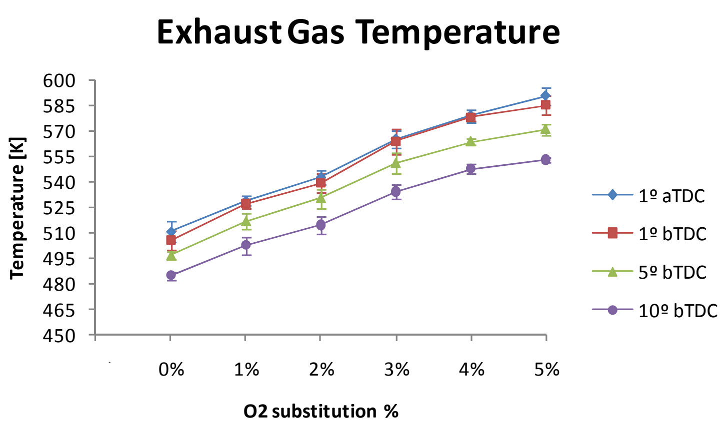

Figure 6. Exhaust gas temperature.

4. Conclusions

Simulations of an engine operating with oxygen-enriched air were carried increasing the O_2 content in the mixture from atmospheric air to pure oxygen. A rise in in-cylinder temperature, indicated power and indicated efficiency was found; as well as a decrease in specific fuel consumption.

Experimental tests were carried out, varying oxygen's volumetric fraction from 0% to 5%, being 0% the atmospheric intake air. It was not possible to test with higher O_2 content due to the limitations of the cooling system of the engine, which was not capable of withstanding the high temperatures produced by oxygen enrichment in higher percentages. The following conclusions were obtained:

1. The rise in the amount of O_2 in the oxidant produces an increase in power, temperature and efficiency; there is also a decrease in specific fuel consumption. However, the presence of high O_2 concentrations produces engine knocking if spark timing is not controlled.
2. CO_2 emissions increase because the amount of fuel increases in order to maintain stoichiometric conditions.
3. NO_x emissions increase due to the rise in combustion temperature.
4. *CO* and hydrocarbons emissions decrease because of the higher exhaust gas temperatures.
5. The performance behavior of the experimental results is comparable with that of the simulation results.

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