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Experimental Study of Exhaust Gas Composition from Combustion in Gasoline Engine with Polluted Air Intake

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Abstract

This research was an experimental study of exhaust gas composition from combustion in a gasoline engine with polluted air intake. The experimentations were tested at the engine's idle speed with removal of oxygen sensor. Pollution gases composing of carbon monoxide CO in range of 0 to 1.40 %vol., carbon dioxide CO_2 in range of 0 to 5.0 %vol., and unburned hydrocarbon HC in range of 0 to 400 ppm of which proportions were varying was diluted to intake air upstream to the tested engine. Compositions and temperature of the exhaust gas from the exhaust pipe were sampled and analyzed through Exhaust Gas Analyzer in order to determine the concentrations of CO, CO_2, HC, and excess O_2. Experimentation results revealed that increase of the HC, CO, and CO_2 concentrations to the intake air caused increase of the exhausted HC and CO concentration while the CO_2 concentration in the exhaust gas decreased. The results also showed that the variation of the excess O_2 in the exhaust gases did not relate to the varying concentrations of the diluted pollutants. Comparison of the exhaust gas composition predicted from the established mathematical model to the experimental results showed that implementation of the established model only provided the variation tendency of the exhausted CO and CO_2 consistent to the experimental results. Therefore, measurements of the actual exhaust gas composition were still necessary to ensure accuracy results.

***Keywords**:* Exhaust gases; Gasoline engine; Pollution; Exhaust gas analyzer; Combustion

1. Introduction

Exhaust gas composition depends on the relative proportions of fuel and air fed to the engine, fuel composition, and completeness of combustion process [1]. However, local chemistry of the burning process and the chamber geometry will also have a profound influence on the final composition of any exhaust gas [2]. In reality, dissociation reactions take place at elevated temperatures and pressured even under stoichiometric combustions, some free carbon monoxide (CO) and hydrogen (H_2) will be created, so that there would be some carbon monoxide (CO) in the existence and minor amount of oxygen (O_2) and hydrogen (H_2). As the air-fuel mixture is progressively richer than stoichiometric proportion, the exhaust gas would contain greater amounts of CO and H_2 while would still show little traces of free oxygen O_2. There are two principal dissociation reactions involved; 1) $CO + \frac{1}{2}O_2 \Leftrightarrow CO_2$ and 2) $H_2O + CO \Leftrightarrow H_2 + CO_2$. Maximum temperature of combustion is limited by the first reaction when it is proceeding as energy is released. The second reaction is often called the "water gas reaction". In addition, incompletely burning of the fuel and non-uniform air-fuel mixture fed to each cylinder are also affect the composition of exhaust gas. Although the combustion equations are useful for determining the combustion products, they do not correspond closely to the actual constituents. For all these reasons, the composition of the exhaust gases cannot be calculated and predicted easily. The best way to determine the composition of the engine exhaust gases is to measure directly.

Experimental work conducted by Martin A. Elliott, et al. [3] on the motor coaches had shown that driving condition had a marked effect on the emission rate of all constituents. The highest CO concentration in the exhaust gas occurred under idle condition. The largest NO_x concentration was at cruise and acceleration conditions and decreased below 60 ppm during idle and deceleration condition. The engine conditions giving rise to high HC concentration were observed at both deceleration and idle conditions; more than 34% of the supplied fuel was probably wasted during deceleration condition.

S.H. Graf, G.W. Gleeson, and W.H. Paul [4] reviewed correlations between the exhaust gas constituents of gasoline engines from various researchers and experimentations. The correlation between CO_2-O_2 was applicable for lean mixtures but for extremely rich mixtures it was advised to measure directly. There is a distinct correlation between CO-CO_2 and could be of practical used as a time-saving device in exhaust gas analysis. The correlation between CO-H_2 described that the ratio/slope of CO to H_2 in percentage by volume was non-linear over the range of values which were varying from 1.96 to 2.9.

Claudio Mazzoleni, et al. [5] showed that the concentration of HC, CO, NO, and particulate matters on an individual vehicle were poorly correlated. Therefore, one or more pollutants cannot be used as predictor for other pollutants, but it should be measured separately to ensure that the variability of the emissions was properly characterized.

Effects of intake pollutant to the engine emission were mostly studied through varying of rate of EGR (Exhaust Gases Recirculation), while the effects of proportion of the pollutant concentration have not been studied as much. Applications of EGR could reduce a large amount of NO_x emission, but it leads to increase of CO and HC emissions [1, 6]. Increase of EGR rate results to slow combustion speeds which lead to partial burning or misfire that produces higher CO and HC [6].

This research is an experimental study of exhaust gas composition from combustion in a gasoline engine with polluted air intake and is tested at the engine's idle speed of 1,150 rpm with removal of oxygen sensor. Various proportion of pollution gas concentrations are diluted to the intake air upstream to the engine. The exhaust gas composition and temperature are sampled and analyzed through exhaust gas analyzer in order to determine the concentrations of CO, CO_2, HC, and excess oxygen O_2. Experimentation results are used to investigate the effects of each intake pollutant element to the exhaust gases emission. Comparisons to an established mathematical model and prior studies are also considered to further discussion.

2. Theory

An overall combustion reaction in the gasoline engine can be written as

$$Fuel + Oxidizer \rightarrow Products \quad (1)$$

Generally, the fuel is hydrocarbon fuel, the oxidizer normally is air (O_2+3.76N_2), and the products are CO_2, H_2O, CO, H_2, O_2, NO_x, N_2, unburned hydrocarbon (HC), and soot particles which are mainly solid carbon and usually can be omitted from the analysis. Among of the combustion products, CO, HC, NO_x, and CO_2 are considered as pollutants [2].

Air-fuel ratio is one of the most important parameter that affects the engine exhaust emissions. Variation in emissions with air-fuel ratio for any typical premixed gasoline engines is demonstrated in reference [7].

The actual combustion equations including the effects of dissociations for any generic hydrocarbon fuel containing alcohols $C_mH_nO_r$ in the internal combustion engine can be demonstrated explicitly as

$$\begin{aligned} C_mH_nO_r + \lambda_m(O_2 + 3.76N_2) \rightarrow \\ y_1O_2 + y_2N_2 + y_3CO_2 + y_4CO \\ + y_5H_aC_b + y_6H_2O + y_7H_2 + y_8NO_x \end{aligned} \quad (2)$$

where λ_m is the molecular air-fuel ratio, and y_1, y_2, y_3, y_4, y_5, y_6, y_7, y_8 are the number of mole of the combustion products, and a, b are the number of hydrogen atom and carbon atom in the unburned hydrocarbon, respectively.

To solve for the unknowns in Eq. (2), various assumptions are determined and it is required carbon balance, hydrogen balance, oxygen balance, nitrogen balance, and additional equations to complete the analysis.

3. Experimental Methodology

The experimentation using engine model: Toyota 5A-FE 1600 cc. which are tested at the engine's idle speed of 1,150 rpm. The oxygen sensor had been removed so as to run the engine at the constant fuel injection rate. The engine was turned into the safe mode operation; the manufacturer's set fuel injection rate. Two vehicles with and without catalytic converter are employed to generated pollution gases from combusting gasohol-91 fuel. The pollution gases composing of CO in range of 0-1.40 %vol., CO_2 in range of 0–5.0 %vol., and HC in range of 0–400 ppm of which proportion is varied and diluted to the intake fresh air in a mixing tank upstream to the tested engine. Compositions and temperature of the exhaust gases from the exhaust pipe before entering the catalytic converter are sampled and analyzed through Exhaust Gas Analyzer EMS Model 5002 in order to determine the concentrations of CO, CO_2, HC, and excess oxygen O_2.

3.1 Mathematical Modeling

To predict the exhaust gas composition, mathematical model is established. It is well aware that using the exhausted gas as EGR is purposely to reduce NO_x formation. However, the gasoline engines was typically operated in the fuel-rich condition or close to the stoichiometric condition, so that the amount of NO_x in the exhaust tails is comparatively much less than the others; CO, CO_2 and HC. Only trace amount of NO were recorded from all tests and the combustion products, NO_x was assumed to transform to N_2. Hence, the equation of combustion in the gasoline engine with polluted air can be modified from Eq. (2) as follow:

$$\begin{aligned} C_mH_nO_r + \lambda_m(x_1O_2 + x_2N_2 + x_3CO_2 + x_4CO + x_5HC) \rightarrow \\ y_1O_2 + y_2N_2 + y_3CO_2 + y_4CO \\ + y_5H_aC_b + y_6H_2O + y_7H_2 \end{aligned} \quad (3)$$

where the molecular air-fuel ratio λ_m is derived from experimental measurement at the engine's idle speed and x_1, x_2, x_3, x_4, x_5 are the mole fraction of the diluted air composing of dry pollutant gases and induced fresh air which are measured from the exhaust gas analyzer.

so that,

$$x_1 + x_2 + x_3 + x_4 + x_5 = 1 \quad (4)$$

To simplify the analysis, we assume that all moles of the unburned hydrocarbon H_aC_b in Eq. (3) have values of $a = b = 1$. Thus, there are 7 unknowns to be solved in Eq. (3), e.g., y_1, y_2, y_3, y_4, y_5, y_6, y_7 which are needed to be solved simultaneously through carbon balance, hydrogen balance, oxygen balance, nitrogen balance, and additional three equations as follows:

Carbon balance:

$$m + \lambda_m (x_3 + x_4 + x_5) = y_3 + y_4 \quad (5)$$

Hydrogen balance:

$$n + \lambda_m (x_5) = 2y_6 + 2y_7 \quad (6)$$

Oxygen balance:

$$r + \lambda_m (2x_1 + x_3 + 2x_4) = 2y_1 + y_3 + 2y_4 + y_6 \quad (7)$$

Nitrogen balance:

$$\lambda_m (x_2) = y_2 \quad (8)$$

An equation concerning to the equilibrium constant for the dissociation reaction of $H_2 + CO_2 \Leftrightarrow H_2O + CO$ can be written as

$$k_{H_2O+CO} = \frac{y_4 y_6}{y_3 y_7} \quad (9)$$

where the value of k_{H_2O+CO} is an empirical constant and is commonly recommended to be 3.5 or 3.8 [1].

Another two equations implemented to solve the solution derived from the experimental data between the exhaust gas CO_2-O_2 and the exhaust gas CO-CO_2 [4] are as below

$$[CO_2] = 14.023 - 0.674[O_2] \quad (10)$$

$$[CO] = 22.25 - 1.66[CO_2] \quad (11)$$

where [CO], [CO_2], and [O_2] are the percentage by volume of CO, CO_2, and O_2, respectively.

3.2 Experimental Apparatus

The photography of the experimental apparatus employed for this study is shown in Fig. 1. Details of the sampling points to be measured are demonstrated as schematic diagram in Fig. 2.

Fig. 1 Photography of Experimental Apparatus

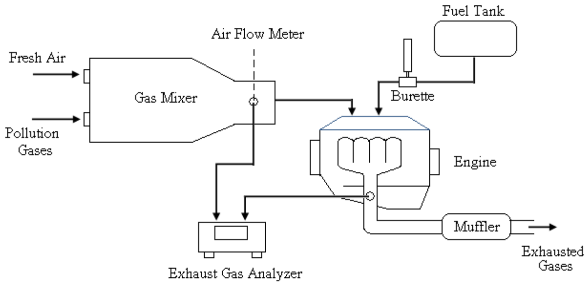


Fig. 2 Schematic diagram of the experimentations

4. Results and Discussion

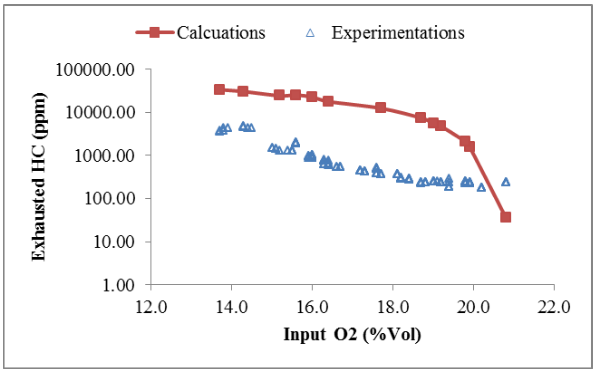
Experimental results are used to investigate the effects of each pollution gases to the exhaust gases emission combusted from the gasoline engine. And also, comparisons to the mathematical model and prior studies are considered to further discussion.

4.1 Effects of Intake Pollutants to the Exhaust Gas Composition

Figs. 3-6 show correlation of varying proportion of the polluted air and the experimental data derived from analysis of the dry exhaust gas composition, e.g., HC, CO, CO_2, and O_2 which are explained according to each intake elements.

Amount of the exhausted HC are unburned fuel components which occur in the exhaust emission after incomplete combustion. Figs. 3(a)-3(d) demonstrate the variation of the exhausted HC to each intake polluted air element O_2, CO_2, CO, and HC, respectively. Decrease of the intake O_2 or increase of the intake CO_2 cause rise of the exhausted HC obviously until to certain values 14% of O_2 and 5% of CO_2, the tested engine are instability due to misfiring. Variation of the exhausted HC to the intake CO and the intake HC do not show evident correlations. However, the solutions from the established mathematical model are extremely higher than the experimental results as shown on logarithm scale of the exhausted HC. These lower amounts of measured HC concentration may be due to only evaporated HC emissions were measured by the exhaust gas analyzer while the condensed HC in the sampling line between the sampling point to the measurement point could not be measured in the exhaust gas analyzer. Therefore, installation of a heated sampling device is important for sampling unburned HC emissions. It allows the exhaust gas to be ducted from the sampling point to the measuring point across an electrically heated line. This approach could eliminate system failure caused by condensation in the sampling line [8].

Figs. 4(a)-4(d) demonstrate the variation of the exhausted CO to each intake polluted air element O_2, CO_2, CO, and HC, respectively. Increase of all the intake pollutants CO_2, CO and HC result to rise of the



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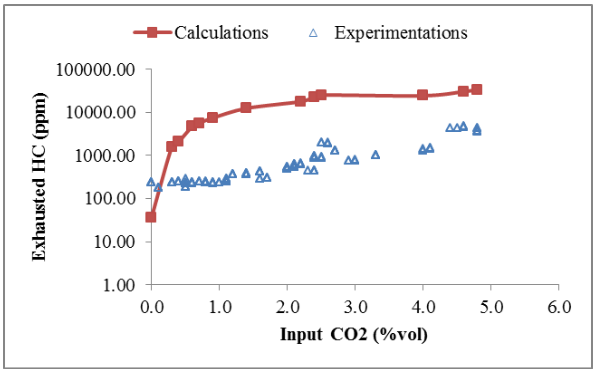

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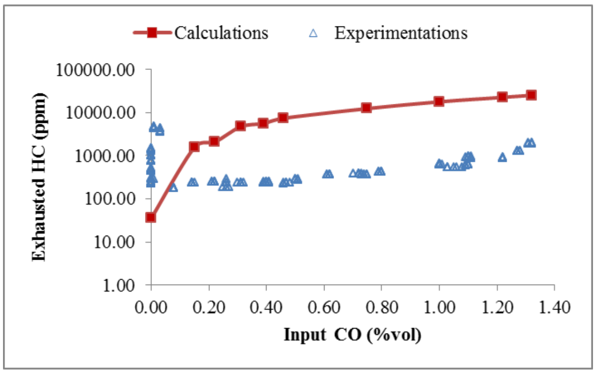

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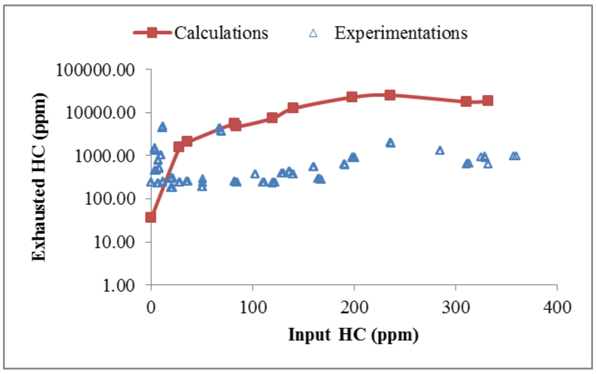
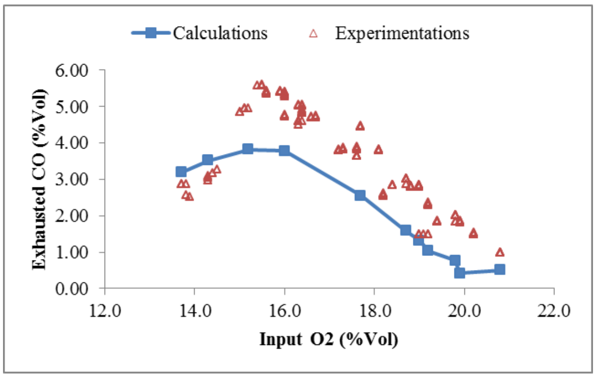


(d)

Fig. 3 Variation of Exhausted HC to Intake Elements



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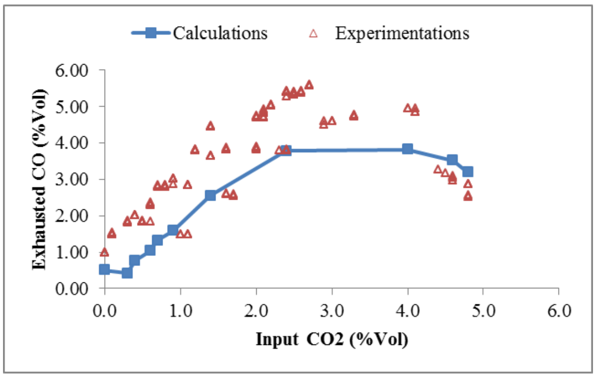

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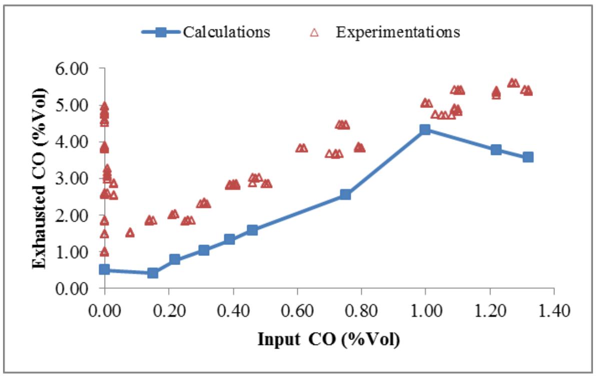

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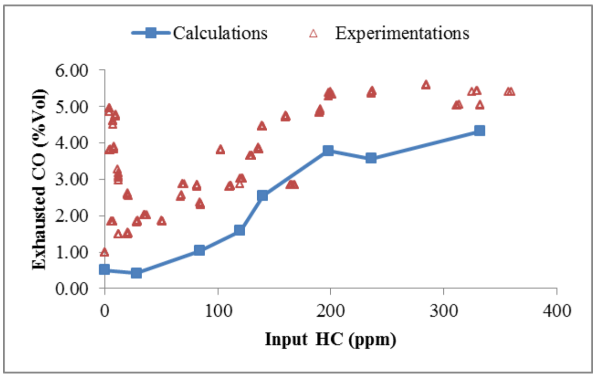

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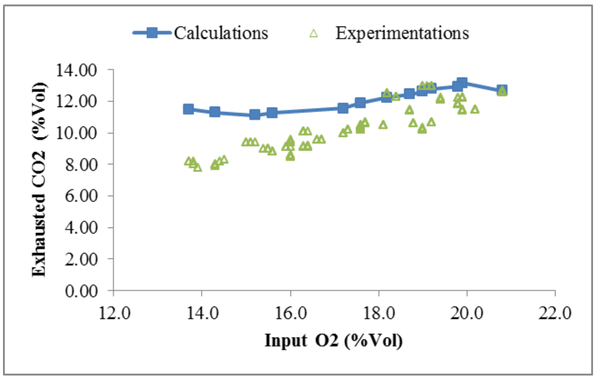
Fig. 4 Variation of Exhausted CO to Intake Elements



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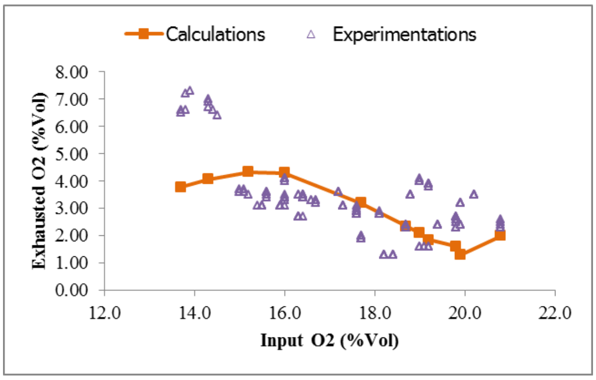

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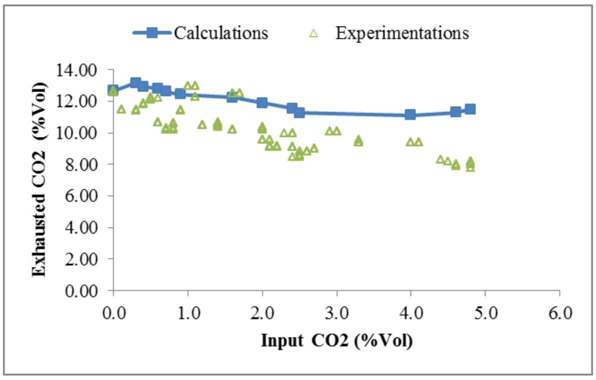

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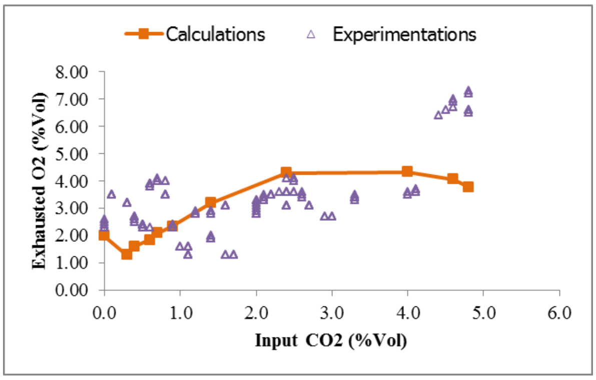

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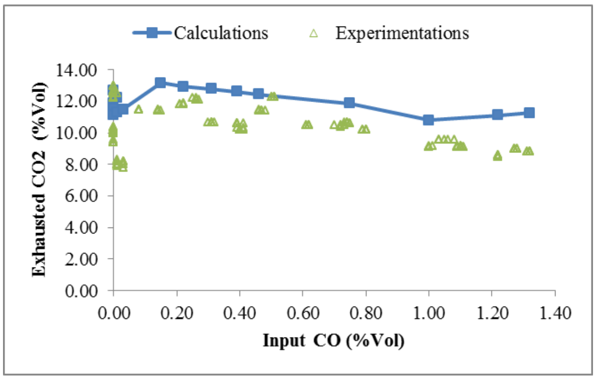

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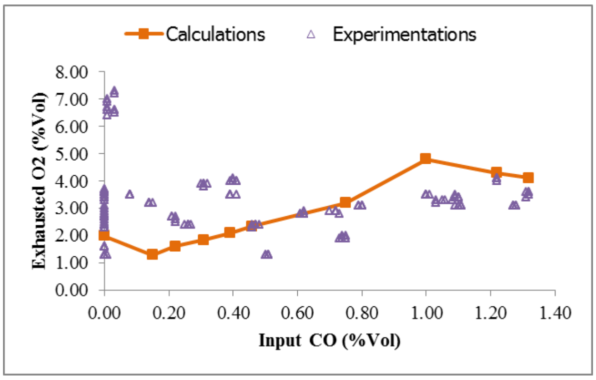

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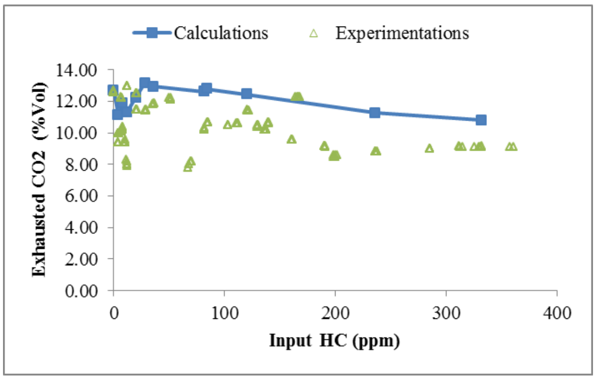

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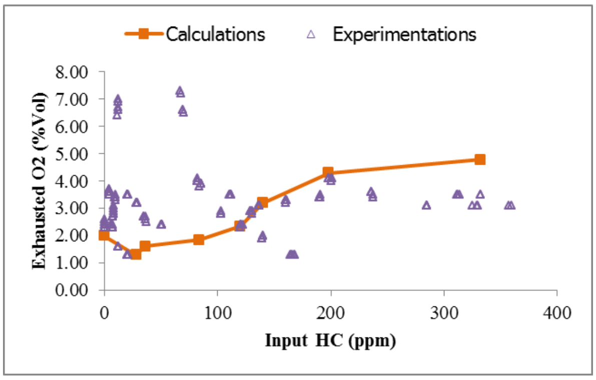

(d)

Fig. 5 Variation of Exhausted CO_2 to Intake Elements

Fig. 6 Variation of Exhausted O_2 to Intake Elements exhausted CO proportionally which means incomplete combustion of the engine. Such results are consistent to decrease of the intake O_2 which causes the richer air-fuel mixture; hence, there is not enough oxygen to oxidize all the carbon molecules sufficiently into CO_2. The instability of engine are also shown in Figs 4(a)-4(b) as the concentrations of the exhausted CO are dropped while the concentrations of the intake O_2 and CO_2 are lower to 14% and higher than 5%, respectively. The calculated values seemed to provide good predictive tendency between the exhausted CO and each intake. However, in all of the tested range, the actual concentrations of the emission are all higher than the calculation values.

As the rise of the exhausted HC and CO means incomplete combustion, the concentration of the exhausted CO_2 imply to completeness of the combustion. Figs. 5(a)-5(d) describe the variation of the exhausted CO_2 to each intake polluted air element. The exhausted CO_2 tends to decrease continuously as the concentrations of the intake CO_2, CO, and HC are increased, while such variation is inversely proportion to the increase of the intake O_2. The calculation values are seemed to provide good predictive tendency between the exhausted CO_2 and each intake. However, in all of the tested range, the actual concentrations of CO_2 are all lower than the calculation values. The instability of engine are also shown in Figs 4(a)-4(b) as the concentrations of the exhausted CO are dropped while the concentrations of the intake O_2 and CO_2 are lower to 14% and higher than 5%, respectively. The calculated values seemed to provide good predictive tendency between the exhausted CO and each intake. However, in all of the tested range, the actual concentrations of the emission are all higher than the calculation values.

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Figs. 6(a)-6(d) illustrate the variation of the excess O_2 in the exhaust gas to each intake polluted air element O_2, CO_2, CO, and HC, respectively. The experimental results show that poor correlations are found between the excess O_2 and the varying concentrations of the intake elements as well as the available calculation values.

As the amount of the intake air decreases, the combustion temperature is also decreased. Fig. 7 shows the exhaust gas temperature drop as the concentration of the intake O_2 is decreasing linearly.

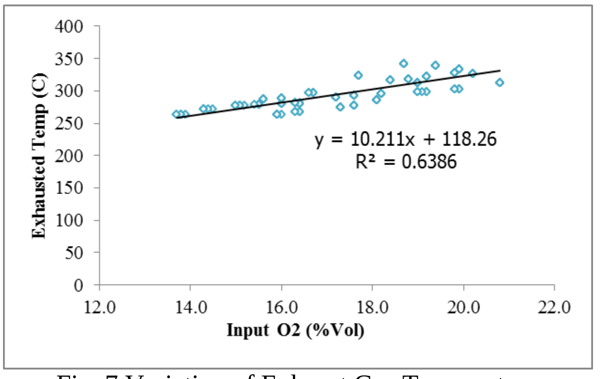

Fig. 7 Variation of Exhaust Gas Temperature to the Intake Oxygen

4.2 Correlation of Exhaust Gas Composition

Comparisons of the experimental results to the available correlation of the exhausted O_2 and CO_2, and the exhausted CO and CO_2 from the prior study in normal fresh air intake [4] are demonstrated as shown in Figs. 8-9. The correlations can be approximated to a linear equation as the described relations in the figure.

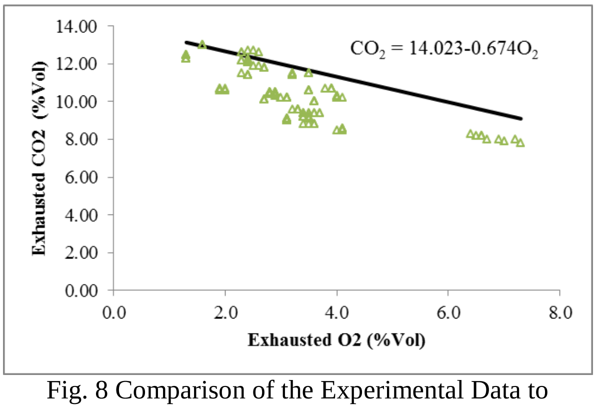

Fig. 8 Comparison of the Experimental Data to the Correlation of the Exhausted O_2 and the Exhausted CO_2

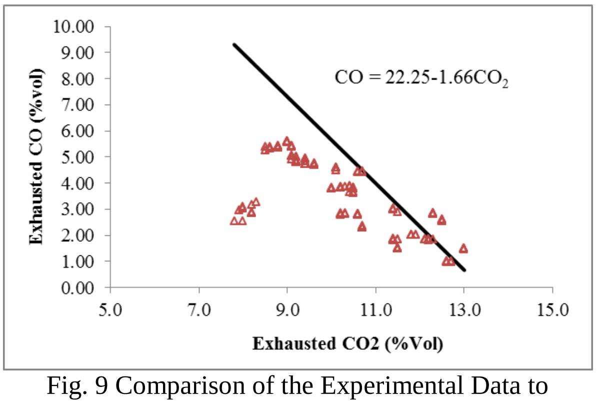

Fig. 9 Comparison of the Experimental Data to the Correlation of the Exhausted CO_2 and the Exhausted CO

In Fig. 8, for normal fresh air intake, the concentration of the exhausted CO_2 decreases linearly as the exhausted O_2 increases. For the polluted air intake, such relation is also consistent but the decreasing trend of the exhausted CO_2 is lower than the normal fresh air intake. This means the completeness of combustion is lower than the fresh air intake.

The amount of $CO+CO_2$ in the exhaust gas implies total carbon to be burned in the engine. In Fig. 9, for normal fresh air intake, the concentration of the exhausted CO decreases as the exhausted CO_2 increases. For the polluted air intake, such relation is also consistent but the decreasing trend of the exhausted CO is lower than the normal fresh air intake as evident in the experimental results that high concentration of HC is observed.

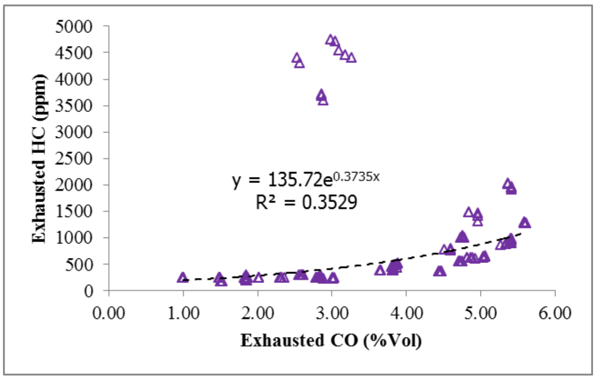

Fig. 10 Correlation of the Exhausted Carbon Monoxide and the Exhausted HC

Fig. 10 demonstrates that the concentration of the exhausted CO and the exhausted HC has no obvious relation which is consistent to the prior study.

5. Conclusion

The study of the exhaust gas composition from the combustion in a gasoline engine with various proportion of the polluted air intake was diluted upstream to the engine at the idle speed. The exhaust gas composition and temperature were sampled and analyzed through the exhaust gas analyzer in order to determine the concentrations of CO, CO_2, HC, and excess oxygen O_2. Experimentation results was used to investigate the effects of each intake pollutant element to the exhaust gases emission and compare to the established mathematical model and the prior studies, therefore, it could be summarized that

All the pollutants diluted into the intake air causes the increase of HC and CO concentrations in the exhaust gas composition while the CO_2 concentration decreased due to incompleteness of the combustion in the engine. Experimental results showed that the variation of the excess O_2 in the exhaust gas did not reveal any relation to the varying concentrations of the diluted pollutants.

The exhaust gas temperature decreased as the fresh air intake was diluted by the pollutants due to incomplete combustion as mentioned above.

The established mathematical model was able to be used only as a predictor to the trend of the concentration of CO and CO_2 in the exhaust gas composition, but prediction of the HC concentration in the exhaust gas did not provide proper results due to extremely different values to the experimental results. However, the calculations of the CO concentration were usually lower than the experimental results, and the calculations of the CO_2 concentration were usually higher than the experimental results. Because of scattering in the experimental data of the exhausted O_2 concentration, the model may not provide the results consistent to the experimental results accurately.

The exhausted CO_2 and O_2, and the exhausted CO and CO_2 had correlations consistent to the prior study, while the exhausted CO and HC shown poor relation. Therefore, separately measured of the exhaust gas composition should be conducted to ensure the variability of the emissions.

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